MODERN CONSTRUCTION HANDBOOK

ANDREW WATTS

THIRD EDITION

AMBRA | V

CONTENTS

INTRODUCTION

This book aims to set out the construction systems use in the design of contemporary buildings, grouping the systems as distinct chapters covering walls, roofs, structure and environment. The book begins with a chapter on building materials, and ends with applications of the systems described in the chapters which follow. This format varies slightly from the second edition, where the last chapter was called 'Future', which has been renamed 'Applications' in this edition to reflect the fact that systems presented as concepts in the previous edition have now been used in completed buildings.

Where 20th Century architecture admired simple geometric forms and their rectilinear-based combination, material systems of the early 21st Century can be used to interact with the existing built environment rather than completely replace that previous environment. This approach is one enjoyed before the mass industrialisation of building production in the early 20th century. This book aims to demonstrate that pre-industrial buildings, that form a part of our current urban environments, can find continuity with the digital fabrication and mass customisation techniques of the 21st century.

The organisation of the material in the Modern Construction Handbook, which has been refined for this third edition, has undergone several stages of development, based on the idea of grouping construction systems by the material used rather than by their 'function', which is one of the most widely used construction-based classification systems. The materials-based approach specific to this book allows the text to draw parallels between building 'systems' that are based on the same primary material, since the development and use of those systems is informed mainly by the physical properties specific to each material and the way the material is worked, manufactured or formed for use as a building material. Known classification systems create a mix between manufacturer-led names for systems, such as 'structural glazing', where the glass is often not structural at all, and 'rainscreen cladding', which covers almost any decorative outer layer that has open joints. Rather than basing classification on that of existing categories, the approach was to start from scratch and test material-based categories against one another. In the first edition, this evolved into categories of walls, roofs, structure, environment and fittings. Another category of materials preceded this, since an understanding of the physical nature of materials is essential in construction-led architecture.

An essential aspect of contemporary construction is the wide range of construction systems which are non-loadbearing. Almost all contemporary construction is based on the structural frame; typically either steel or concrete, with the modest, but growing, use of timber frames as a lower embodied energy alternative. As examples of loadbearing construction are rare, the use of categories of 'loadbearing' and 'non-loadbearing' was not appropriate due to the imbalance of the categories. What emerged was that construction systems for the majority of building construction are independent, with few systems relating to one another. Much of the skill of contemporary detailing is in knowing how to bring those systems together which are fabricated or manufactured in isolation of one another.

The linking of building systems so that they might be able to interface more easily has long been an aspiration of manufacturers, but the current situation is one where few systems co-ordinate easily with one another. This suggested that the taxonomy of building systems in the first edition should be based on a robust set of genuinely different generic types that would have to be identified independently of current systems of classification, such as those described in designers' specifications. The structure of architecture-based specifications identifies components and assemblies in inter-related sections, where each sub-item in the assembly is identified independently, such as 'curtain walling', which itself comprises several generic external wall types set out in this book. Specifications then link items such as 'curtain walling' to their constituent materials of glass, seals, paint finishes and so on under quite different headings. While the system is useful in describing a building for use by a contractor, particularly with regard to national standards, including those for performance testing, specifications do not relate the parts in a way that can be easily used at the design stage to understand generic facade assemblies. The approach taken in the classification system in the Modern Construction Handbook was to group items in a way known to building design teams: structure, walls, roofs, and services.

The construction of buildings has, historically, been based on a varying relationship between loadbearing structure, walls and roofs, and this forms the basis of classification in this book. In some buildings, walls, roofs and structure are a single entity as in medieval cathedrals, with the exception of their additional timber roofs, used to protect the structural ceiling. In framed construction the walls and roofs can be continuous over a single supporting structure, while in many cases of 20th century construction, walls, roofs and structure are quite separate, and are then subdivided within each category to provide a 'collage' form of construction where systems are overlaid in the manner of a visual collage.

Most of the primary building materials can be used to make loadbearing structures, where they serve as both structure and enclosure. Other uses of materials for walls and roofs are non-loadbearing cladding. However, sometimes where different material systems are formed in the same material in a building, there is still some structural interdependency. Where quite different material systems are mixed, such as in a concrete frame and enclosure, a different inter-dependency emerges, that of allowing each material to be expressed separately.

The inclusion of fittings in the taxonomy of the first edition proved difficult, with smaller scale items of stairs, lifts, internal finishes and doors placed within the group. The term 'internal fittings' was too restricting, as some of these components could be used externally. This was the least satisfying part of the first edition. In this third edition this issue has been resolved by including stairs in the structure chapter, doors in the walls chapter, and internal finishes in the first section on materials. Lifts are now described in the environment chapter, since they are usually considered to be part of the mechanical systems, the layout of which is designed by a specialist consultant. As a result of this last decision it could be seen that the environment section could include both systems that reduce energy consumption by the use of low energy passive strategies, as well as high energy active strategies, such as mechanical ventilation, and lifts can be seen as part of this strategy to make tall buildings usable.

In environmental terms, the use of several layers of envelope and structure in a single building can create a much richer set of internal spaces than those provided by the single skin envelope. The outer wall can be made of a double skin, or even as a deep zone within the building which is an inhabitable equivalent of the 'twin wall' or 'double skin' facade. This has helped to inform both material systems, not all of which need to be sealed, as well as the environment chapter where passive cooling, heating and ventilation can be used to reduce overall energy consumption, as well as create a stronger link between the built environment of the city and the building itself. The materials for roads and public spaces do not form part of the scope of this book, of course.

Each generic system is described first in terms of the properties of the material, then how they are used as a material system, and last how that material system 'behaves', or can be made to 'behave', to form a building by examining its detailing. Possible developments of some of these material systems are set out in the future chapter to show how the principles can be extrapolated for use on new projects.

Generic systems are discussed in terms of how they are assembled, and how they work from a structural and/or enclosure point of view. These paragraphs on 'system design' show how the generic example works. The way the system is applied to different geometries is explained in 'system details'. The geometries show how the system can be set out on different mathematically-based surfaces, and how the system can meet at corners and junctions. Two other books in the Modern Construction Series, titled Modern Construction Facades and Modern Construction Roofs, show how specific details can be created, which forms the basis of an understanding of what is needed to be accommodated in different geometries. The chapter on 'future' systems adds a parametric component to some of the examples, thus highlighting the range of possibilities that might exist for some of the examples shown.

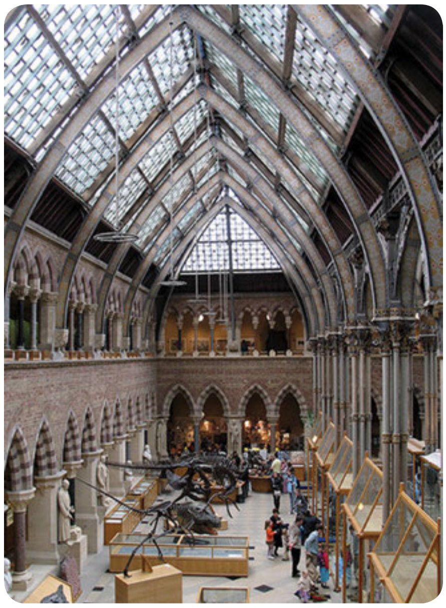
The materials chapter in this third edition presents essays on how the tectonics of material systems was used historically and how digital tools are bringing flexibility back into building construction, something which was considered to be too expensive until the arrival of CAD/CAM (computer aided design/computer aided manufacturing), mentioned as a development bringing change in the first edition. This return to an almost pre-industrial approach to design allows new buildings to develop a much closer empathy with existing buildings, even if the technologies used are very different. The non-rectilinear nature of some of the material systems allows them to engage more robustly and elegantly with existing fabric, both pre-industrial and that of 20th century Modernism in architecture.

Qualifying comments

The building techniques discussed and the built examples shown are designed to last for an extended period with a relatively high performance. Consequently, buildings for exhibitions and for temporary use are excluded. In addressing an international readership, references to national legislation, building regulations, codes of practice and national standards have specifically not been included. This book explains the principles of accepted building techniques currently in use. Building codes throughout the world are undergoing increased harmonisation because of increased economic and intellectual globalisation. Building components and assemblies from many different countries are often used in a single building. Since building codes are written to protect users of buildings by providing for their health and safety, good construction practice will always uphold these codes as well as assist their advancement. The components, assemblies and details shown in this book describe many of the building techniques used by the building industry today, but this book does not necessarily endorse or justify their use since techniques in building are in a continual state of change and development.

Wells Cathedral, Wells, U.K.

Natural History Museum, Oxford, U.K.
Architect: Deane and Woodward

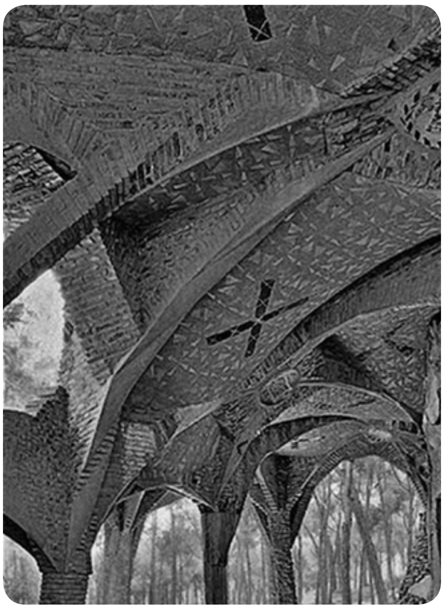


Natural History Museum, Oxford, U.K.
Architect: Deane and Woodward

In terms of construction, Modernist architecture can be considered to be an approach that was not an inevitable development of 19th century architecture but rather a response to an industrialisation governed by mass production of building components such as steel sections for frames, bricks, blocks, metal coil, timber boards and sections. The use of repeated, rectilinear structural bays, both in plan and elevation, can be seen as a response to the way the raw products used in building are manufactured, including the straight lines of cut timber and plywood used for concrete formwork.

20th century Modernist architecture can be considered in terms of its response to mass production techniques through the use of the structural frame. Building components and assemblies were used as repeated identical elements in building compositions. The use of steel or concrete frames led to building envelopes being enclosed in non-loadbearing cladding. The use of repeated, rectilinear bays can be seen as a response to manufacture, including the straight lines of cut timber and plywood used for concrete formwork. Consequently, as a result of the widespread use of the structural frame in much of 20th century Modernist architecture, the separation of structure and external wall has dominated, where the facade is reduced to non-loadbearing walls. This approach has been a result of the development of structural forms, originally destined for large scale buildings, which have found use in much smaller scale constructions, even being used in individual houses in continental Europe. The use of loadbearing structures for larger scale buildings resulted in facades with 'punched' window openings that gave a 'massive' quality to buildings. In contrast, the use of the separate structural frame was able to create a visual lightness and transparency that gave greater freedom to designers. However, the integration of skin and structure into loadbearing facades can also allow much greater freedom in the design of the external envelope to suit the requirements of the spaces immediately behind. In the context of the existing built environment, a new building can almost 'grow' out of the adjacent existing building using the same materials but with a different material system.

The use of a structural frame clad with non-loadbearing walls has led to an aesthetic typically concerned with either forming a 'collage' of different components, or as a repeated module of the same component. However, loadbearing construction can embrace a design approach of structural and environmental integration: the use of envelope and structure combined to create space in the facade and continuity in groundscape or urban context. Both loadbearing and deep rainscreens are possible solutions for this approach. The recent introduction of computer controlled tools has taken away the imperative of mass production, offering instead possibilities of 'mass customisation' where many components of different size can be produced quickly to a high quality. Consequently, architectural production is no longer determined by the need for repeated rectilinear units used in Modernist designs. In terms of the relationship between structure and external envelope, the introduction of mass customisation suggests that systems for both facades and structures could become more complex and



Colonia Güell, Barcelona, Spain.
Architect: Antonio Gaudi

Sagrada-Familia, Barcelona, Spain.
Architect: Antonio Gaudi

Sagrada-Familia, Barcelona, Spain.
Architect: Antonio Gaudi

interdependent, while remaining economic by the standards of contemporary building construction.

A tradition of the integration of structure and envelope

The integration of structure and envelope can be seen in the Gothic tradition: facades forming external spaces created by the framing effect of flying buttresses of medieval cathedrals. Such structures also communicate a sense of the communal effort required to construct the building: The walls, which seem to integrate frame and infill wall into a single constructional entity, sweep inwards at roof level to create stone vaults that form a continuity with the walls. Only a timber roof is required to protect the stone ceiling from the effects of the weather. The timber roof is not a 'conceptual' part of the masonry structure, but rather a necessary addition that ensures the construction provides a weathertight enclosure. Gothic Revival buildings of the 19th century, such as the Oxford Museum in England, combine medieval methods of loadbearing construction with industrially manufactured iron ribs that form a vaulted roof structure infilled with glazing. What can be seen as a civic expression of the manual work of many craftsmen and labourers of the medieval world, was replaced by an architectural expression of the use of mass-produced building components that were used as the raw material for the specialist fabrication of entire parts in small workshops, rather than that of work being all performed on site. Gothic Revival buildings such as the Oxford Museum are built with a mixture of loadbearing and framed construction.

In the early 20th century the architect Antonio Gaudi saw that an advantage of loadbearing construction was that individual blocks of stone, bricks or concrete blocks could be corbelled inwards or outwards from the vertical plane of the external wall to create a complex vertical section as well as a complex plan. Gaudi's use of brickwork was based on his own structural investigations, as implemented at the Sagrada Familia in Barcelona. In the years that followed, the buildings of Oscar Niemeyer integrated structure and skin in projects of varying brief, from housing to churches to public buildings, exploring the possibilities inherent in reinforced concrete rather than following the imperatives of the rectilinear structural frame. In the 1950s, Eero Saarinen used loadbearing concrete in the TWA Terminal at John F Kennedy Airport in New York, a building which integrates the language of structure and enclosure with that of partitions, counters, desks and furniture. The furniture is curved to make it comfortable for the curved human physique, linking the form of what inhabits the building to inform the construction of the building itself. This building can be regarded as an integration of building, interior spaces and furniture that marked the buildings of medieval Oxford. A building designed by Eero Saarinen, the Milwaukee Art Museum, was recently extended to a design by Santiago Calatrava in a structure that creates a loadbearing, or skeletal, structure, reminiscent of earlier buildings by Oscar Niemeyer. Calatrava's interest in animal skeletons goes one step beyond the interest in the structure of Saarinen.

Aerial view, Oxford, U.K.

Parametric modelling

This need for variation in more complex arrangements of linked spaces is tackled more comprehensively in projects by Zaha Hadid, whose work is informed by an interest in parametric design, where spaces can be linked by rhythm, and links achieved through the assistance of computer software, so that many more iterations can be investigated and explored than are possible by hand, by conventional 2D CAD, or even by conventional physical modelling. Parametric modelling provides an interrelationship between parts of the building as well as the urban space surrounding it, making the cityscape one of interdependence as, once again, can be found in medieval Oxford. The office of Frank Gehry has taken the use of parametric modelling as a tool for generating building forms that would not be possible in a practical sense without computer software and its link to computer aided manufacturing. Gehry is concerned that architects produce buildings that are generated by the need to be resolved in 2D as drawings, and that buildings can be seen as mere 'built drawings' rather than being conceived as 'buildings' in the first place. Gehry is less interested in loadbearing construction than in the built forms that can be generated from a few material systems which are liberated from the constraints of mass production towards an eventual approach of mass customisation.

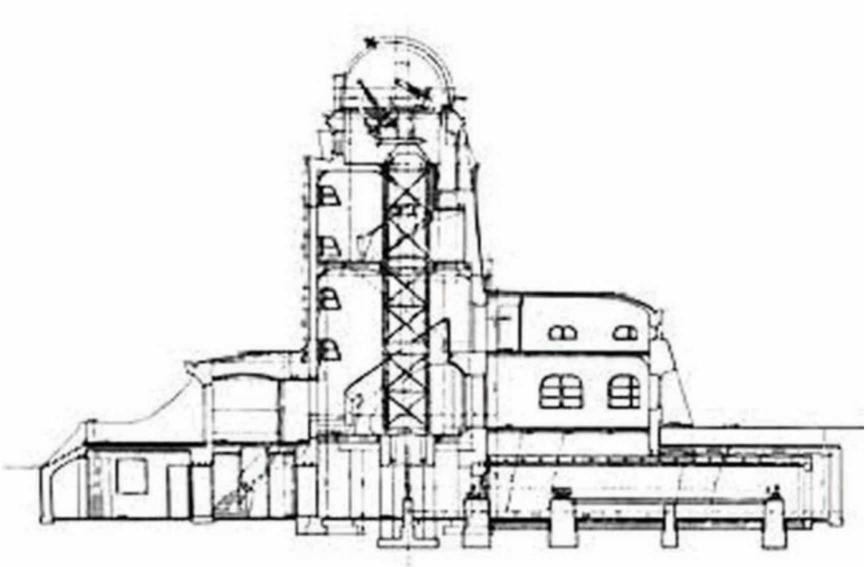
Modernism and construction

Modernism developed from aspects of architecture of the early 20th century, influenced by mass production techniques from about 1920 onwards. In contrast, the approach taken by architects such as Eric Mendelsohn in Germany during the 1920s considered ways of integrating different aspects of programmes informed strongly by the way the building was constructed. The Einsteinturm in Potsdam, Germany, by Eric Mendelsohn integrated the needs of a research centre comprising spaces for study and discussion, with the complimentary requirement for an astronomical telescope to be accommodated in the building. Rather than express the 'primary' aspect of the telescope and fitting the 'secondary' research spaces into it, the design allows both aspects of the design to combine as a more balanced composition. This was achieved by designing the spaces from the outside in, creating an envelope to suit the general enclosure of spaces, effectively wrapped around the telescope. The structure supporting the telescope is set inside the building, requiring a quite different support for the observation floor. The space between the outer envelope and the inner telescope structure is inhabited by the circulation space serving both telescope and study spaces. The telescope can be considered to be designed from the inside out, while the study spaces are designed from the outside in. The interstitial zone between the inner and outer structure is inhabited by the staircase which rises through the building. In another project, the staircase itself could have been part of the overall building structure, but here the stair is supported primarily by both inner and outer structures on its sides. The building's external envelope is built from brick, covered in render. While the building could have been formed in concrete, the construction method of corbelling brickwork in and out of vertical plane is ideally suited as a method to construct a form of this geometry.

In our own time, the rise of digital tools permits this more complex approach to tectonics that was dominated in the 20th century by the use of the structural frame.

As set out in the previous essay, a characteristic of the construction of Modernist architecture has been the separation

Einstein Tower, Potsdam, Germany. Architect: Erich Mendelsohn



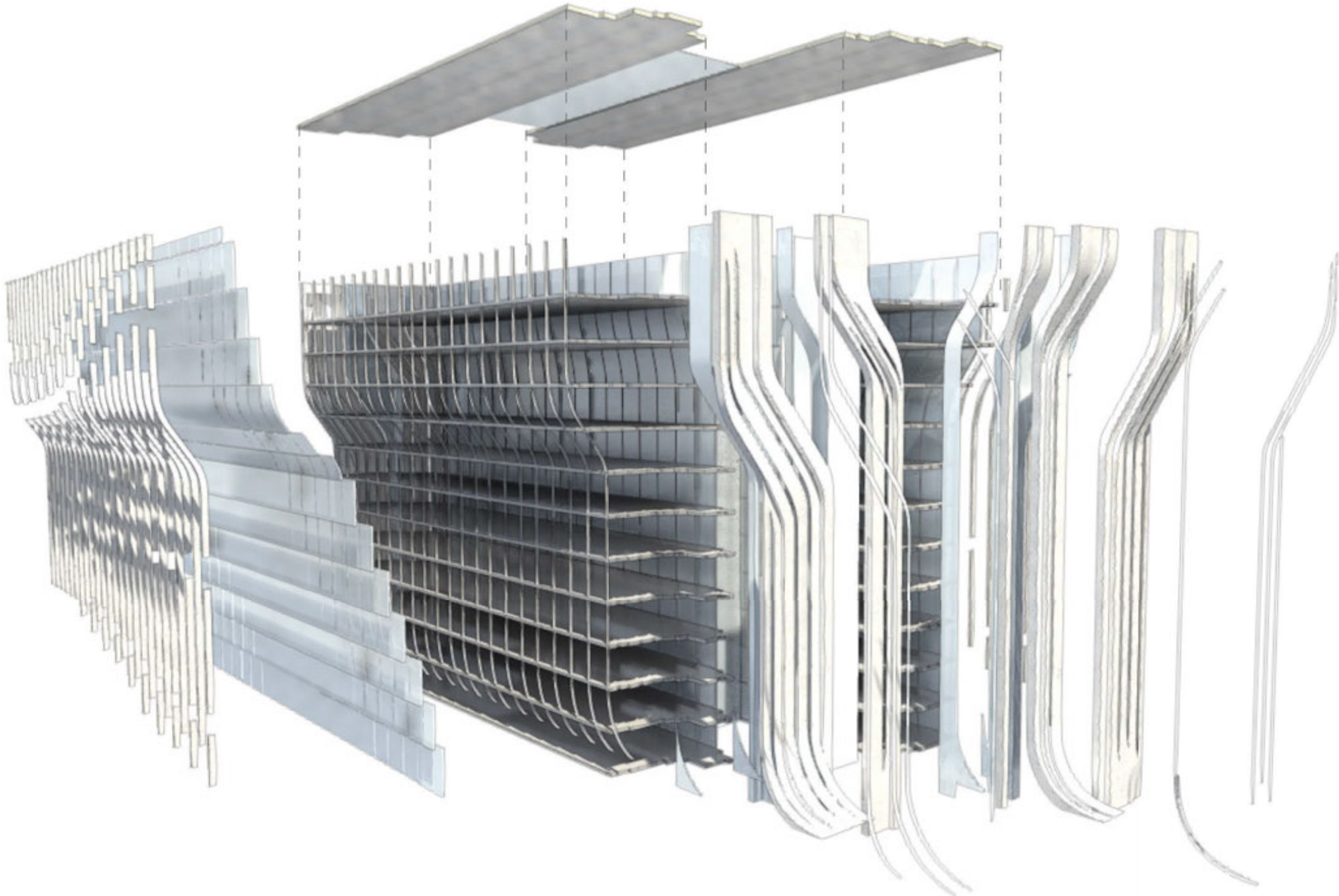
Einstein Tower, Potsdam, Germany. Architect: Erich Mendelsohn

of structure and external envelope, where the facade is reduced to non-loadbearing 'cladding' as a result of the development of structural frames, originally destined for large scale buildings. In contrast, the use of digital tools and mass customisation methods can be used to create a partial or full integration of skin and structure as loadbearing facades. This revived loadbearing approach can allow a much greater control of the design of the envelope to suit the requirements of the spaces immediately behind, rather than using the repeated bays of structural frames built using established methods of mass production. In this loadbearing-based approach, the choice of material used may be taken from the immediate physical context of the built environment, and may also depart geometrically from its context, as in the case of Zaha Hadid's design for an extension to the Louvre Museum in Paris. The design provides continuity of material and context without compromising the performance of the building in terms of use, organisation and spaces created within the building while responding to environmental imperatives of reducing energy consumption within the building. The new structure can almost be seen as 'growing' out of the adjacent existing building and the adjacent groundscape, using the same material but employing a different material system. The material system can be chosen or developed to suit the design needs of the spaces immediately behind the external envelope.

Within building designs, spaces can be created in an outward direction from the internal spaces of the building. Where spaces are required to have a high level of technical performance, or specific light conditions that are to be created, this can be achieved without immediate reference to the external envelope but rather to the building structure. An interstitial zone between internal spaces and external facade structures creates an opportunity for a buffer zone between them, which could be used as an inhabited space or for circulation around the building, as was mentioned in the previous text on the Einsteinturm by Eric Mendelsohn. The recently completed Mercedes-Benz Museum in Stuttgart by UN Studio has interstitial zones used for circulation, while interstitial zones which are inhabited can be seen in the Phaeno Science Center in Wolfsburg, Germany, by Zaha Hadid.

The integration of skin and structure into a loadbearing facade has obvious difficulties. The conventional 'layered' approach of cladding applied to structural forms in Modernist construction has the advantage of superimposing waterproofing, thermal insulation and vapour barriers to form a sequential wall build-up. In loadbearing facades it is more difficult to integrate these different functions into a single structural wall. However, allowing lines of structure to deviate from the rectilinear rather than being used to suit primarily rectilinear facade cladding, allows structure to interact with non-rectilinear spaces within buildings. Current Modernist architecture responds to the needs of mass production, a set of design imperatives of repeatability and a rectilinear approach based on mass production rather than the possibilities provided by digital tools of design and production available with mass customisation.

The renewed interest in the structural design of the external loadbearing wall creates at once a new design vocabulary for architecture and a return to an expression of the joy of making buildings, as demonstrated in individual craftsmanship, an approach that can be seen to have been shared widely in construction before early prefabrication techniques were introduced in the 1920s. This approach to design is informed by a balance of the specific use of the material system used to form

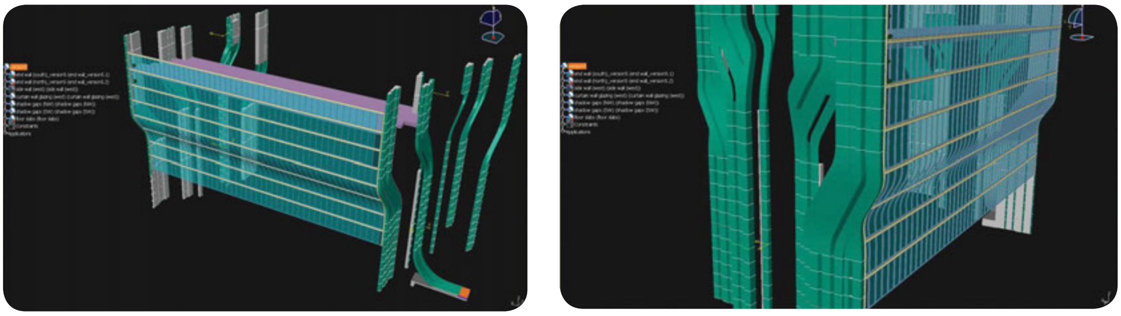


Example of parametric modelling

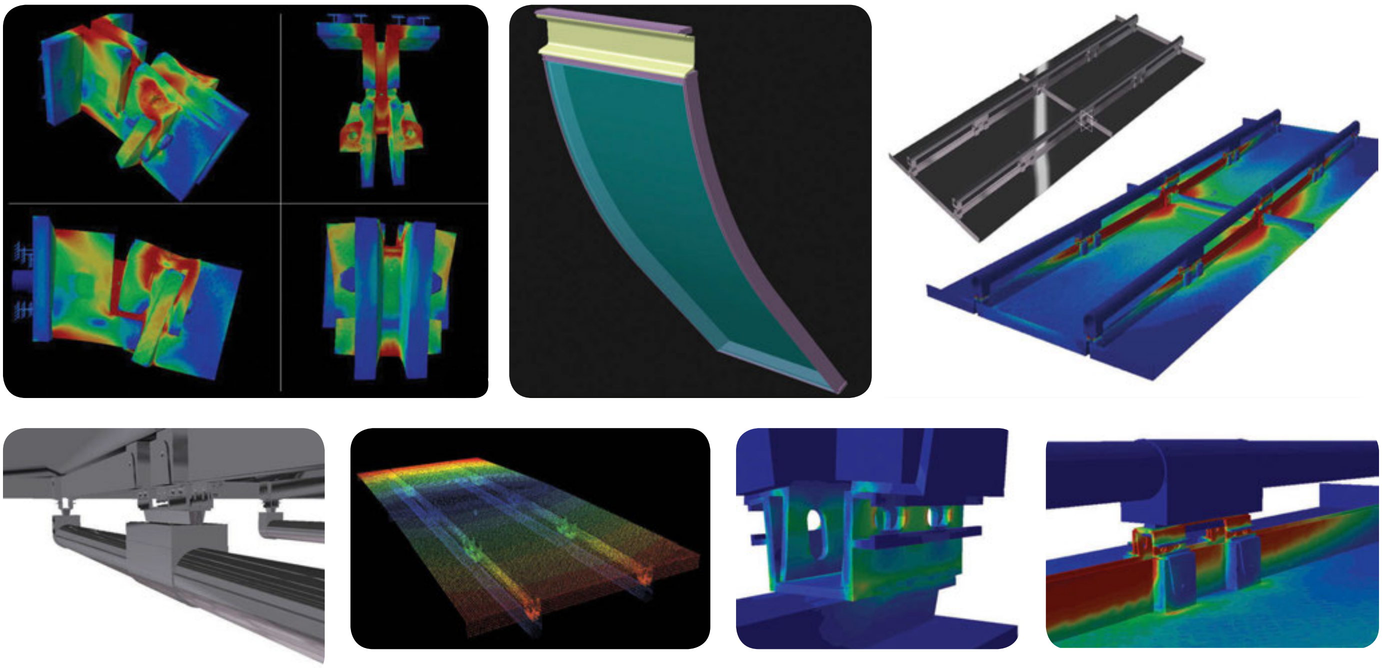
the building, with the sequence of movement around the building and the spaces created within. The expression of construction and circulation as 'designed' elements harnessed to the 'objective' design requirements of spatial organisation related to programme and site context, can be a powerful partnership of principles. This approach could allow construction to move on from 20th century industrial imperatives of the mass production of identical components towards a new period of craftsmanship as a result of mass customisation.

A design approach of designing inwards from the facade of the building, and outwards from the internal spaces of the building, could allow structure to create interstitial space between inside and outside. This approach can also create environmental 'buffer' spaces, which are not maintained at the internal temperature of the building but serve as a buffer between inside and outside temperature conditions. These spaces would not require the same amount of tempered air, but would provide an opportunity for natural ventilation, all key to reducing carbon dioxide emissions in buildings. From the point of view of construction, this approach is more complex than 20th century construction, but could be achieved with digital tools for design and fabrication, the tools of mass customisation. The possibility of mass customisation of components allows a departure from the repeated rectilinear component so that components can be more geometrically complex, either as individual components or as complete building assemblies. Recent developments in building forms have been seen in both twisted and folded geometries.

Twisted building forms achieve geometric complexity by using curves, typically across a surface of constant curvature in order to make it easier to build in a construction market that is used to mass production techniques of building construction. Geometric complexity can also be achieved with folds, where conventional flat surfaces, which are straightforward to build, can be formed into unconventional facade forms. The recent examples are those by Santiago Calatrava, Frank Gehry and UN Studio in twisted forms, and OMA, Zaha Hadid and LAB Architecture in folded forms. The approach of folded and twisted building forms is a way of introducing complex geometry while maintaining contemporary principles of 'repeatability' in order to make them economic to build using a conventional approach to construction. In this sense the approach of twisted and folded forms is an intermediary one between the rectilinear repetition of Modernist construction and the emerging construction methods described here. The current approach to folded and twisted facades requires geometric discipline in order to



Examples of parametric models



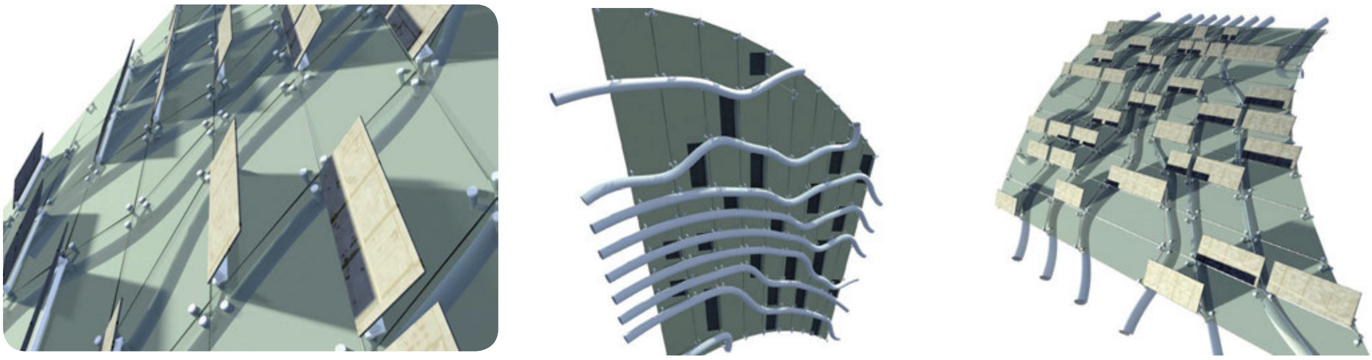
maintain the repeatability of components, mainly facade panels, used in conventional construction techniques. With the greater introduction of digital fabrication tools, the need to maintain a geometric discipline will slowly disappear, perhaps making design choices more dependent on the principles of design performance imperative in buildings such as the Einsteinturm discussed in the last essay. Greater freedom of design from digital tools will provide greater control and greater responsibility from the designer to use the technology wisely.

Design methodology

Current architectural design has a preference for rectilinear spaces linked in a spatial organisation which is also primarily rectilinear, though dependent upon site conditions, based around the use of rectilinear structural frames. The design generated is then given an outward facade expression of materials formed with openings or wraps as an interface between the internal arrangement of the building at its immediate site context.

An alternative design methodology is to add the use of material systems to that mix: construction as an additional driving factor. This may be digital, as with the possibilities for invention that the tools bring, or may be used for the continued cladding of structural frames. This leads the design into a direct connection with traditional loadbearing construction, but moving it forward with changing methods of industrial production. Digital tools allow the performance of a design to be explored and optimised, and be developed in order for an individual or a team to tackle the fabrication of the component which has not been made in a particular way before. Alternatively, a design may use historical models, either to endorse the construction methods of existing buildings, to mix old and new to create something new, or even to advance what is already constructed by physically adjusting it by using the same material but a different material system.

The Modern Construction Handbook sets out these construction techniques, both traditionally-based and contemporary, all of which evolved during the industrialisation of the 19th century. Essential to this use of material systems is an understanding of the physical characteristics of materials as manufactured and used in a system in addition to their essential physical properties. This book also sets out the construction systems essential to contemporary architectural production, categorised in terms of envelope, structure and environment. The book begins with a setting out of materials and how they are used as material systems and ends with proposals for new material systems as an extrapolation of what is possible in the present and how it could be used in the future.



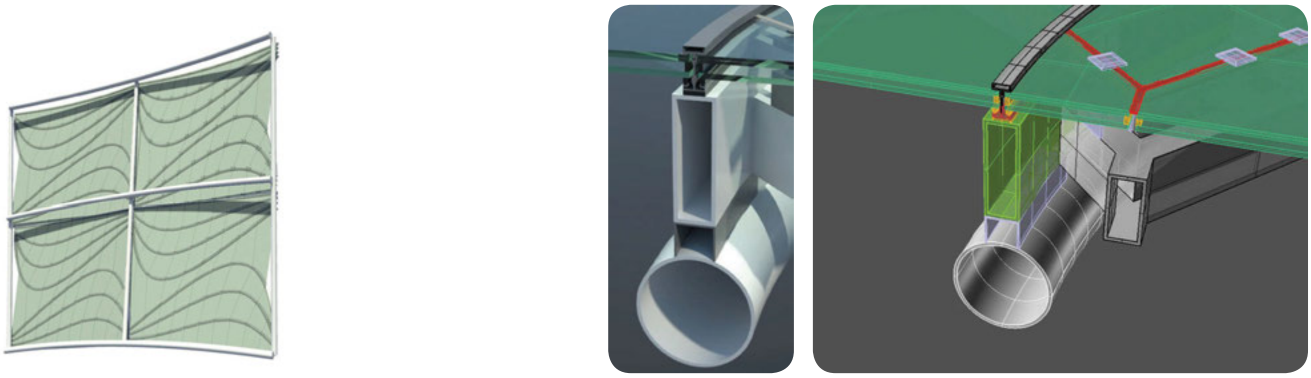
Parametrically modelled glazed structural facade

The use of parametric design in architecture has been centred around the use of software that was originally developed for other industries. Its primary use in architecture has been to generate digital models for building structures and external envelope which have a complex geometry. The word 'complex' is used to denote geometries which are not rectilinear, and therefore cannot be described by plans and sections which can be extruded in a straight line through the form of the building. Building designs which do not conform to the rectilinear forms characteristic of Modernism are difficult to describe as 2D plans, sections and elevations in a way which can be communicated to those who will construct the building. Even 2D plans, while still a useful tool, still cannot be used to establish the edge of the external envelope if the external wall is not vertical, as the position of that wall applies only at the horizontal plane at which the plan is set, typically at floor level for a form of complex geometry. Typically, glazing is set above the floor level, where plans are typically drawn, but any dimensions on the plan at this point are set at a level difficult to establish on site in buildings of complex geometry.

A well-known example of complex geometry using flat facades that do not conform to the rectilinear forms of most contemporary architecture is Federation Square in Melbourne, Australia. The external walls were designed in the form of 'wraps' of open jointed rainscreens and solar shading screens set forward of a waterproofed backing wall. Rainscreen facade panels comprise a pattern of repeated triangular panels in a pinwheel grid, where a set of five triangular panels forms a shape identical in proportion to the smallest triangle from which it is formed. In projects such as these, facades are described in a way that can communicate to contractors the nature of a complex three dimensional form on paper. Elevations of such buildings are set out as unfolded or 'developed' facades from a 3D digital model. This describes the scope of the facades and the total material needed as 'kit of parts' drawings resembling that of an Airfix model kit. In addition, 2D details describe the 'system' as a wall method that could be used to describe how the facades go together, regardless of its actual application around the building. Drawings specifically for the facade systems are needed since the facade construction method is devised individually for such projects. Details of facade conditions at edges, corners, interfaces and junctions with other parts of the building construction are prepared in the traditional way.

Drawings describing the design of complex geometry of the external envelope are of different types: 'kit of parts' drawings, 'system' drawings, details and setting-out drawings. This method differs significantly from the traditional approach of plans, sections, elevations, typical details and so on, as nothing is typical or dimensionally constant in the external walls. The relationship of inner and outer skin varies, so a set of 'rules' is set out in the system drawings, then applied to the 'kit of parts' drawings and the setting out drawings.

At Federation Square for example, the inner and outer layers are set out in a loose-fit relationship between inner and outer skin. In projects where forms are either facetted or curved to create an architecture of complex geometry, the means of controlling the geometry of the building become more crucial. In single skin buildings where the building has a complex form, the exact fit of the different components during construction is critical. In developing such building forms and implementing them, the forms need to establish criteria which are fixed, such as floor area of the different spaces comprising the building, site constraints and criteria which are not fixed. Some building designs for complex forms evolve as a result of more information being known about the building, allowing more of the design to be fixed. Consequently, the different criteria of the design can be set as 'parameters' which can be related as a matrix in the form of a spreadsheet. The spreadsheet can be linked to the process of modelling the building forms digitally in a parametric design software. Working parametrically allows the design to establish what is 'fixed' and what will be 'variable' in the design development. This approach allows a digital design method to evolve. In facade design, the behaviour of the model as a set of surfaces can be understood by number, size, geometry and so on. The relationship of the parameters in the



Detailed images of construction system from the same parametric model

design allows the digital model to evolve through an engineering-based method of iteration, rather than start the digital design model again each time a new option is explored. This approach requires some discipline and clarity in the design approach at the outset, which often makes the parametric design method more suited to design development than initial design research. However, parametric plug-ins are becoming available for early stage design software, ensuring that the parametric approach is gaining influence throughout the design process.

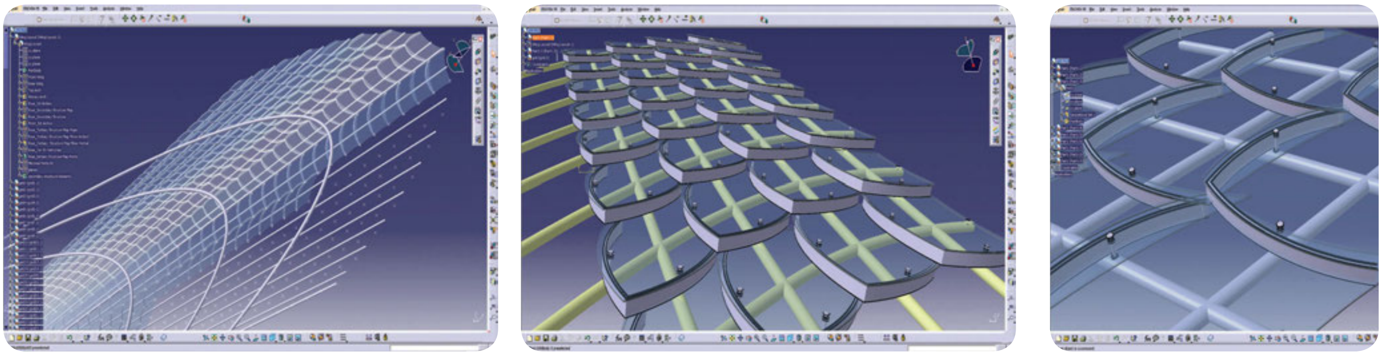
In facade design, where the parametric approach is becoming a primary tool in architecture, the aims vary during the different stages of design development. Outcomes of parametric design can range from establishing a rationalised or optimised geometry, reducing the number of panel types, restricting the facade assembly so that it conforms only to the design limits imposed by the material systems or facade systems being used, ensuring that the floor plates provide a fixed total amount of floor area, or ensuring that the relationship with the primary supporting structure is maintained without exceeding maximum spans. All these different requirements can be put into the model at the beginning, with changes in the digital model showing the corresponding effect between them all. Facade design of complex forms is often driven by a desire to optimise the construction; often by simplifying it by providing as simple a solution as possible without losing the strength of vision or strength of architectural expression in the design. Even in higher budget projects, the need to omit unnecessary complexity of construction and diversity in panel size is important to both reduce costs and attract the most highly qualified companies to work on the project.

The possibilities of parametrically-based design go beyond the need for evolving a single digital model for the main components of building structure and external envelope. With more and more parts of the design forming a single model, the use of a building information model or 'BIM' that sets out all the components required to make a building, is becoming a reality. Whereas large scale manufacturing of aircraft, cars, boats and so on have already used this working method for some years, the use of BIMs in building design is just becoming the norm in higher profile projects. Building information models are now becoming parametric, with the possibility of introducing complex geometry into the process.

While this approach is aimed primarily at bringing greater control and knowledge to the design of individual buildings, the possibilities are being seen more widely in both fields of architectural design and urban design. Where buildings have been designed as a 'collage' of components which are juxtaposed or stacked together in a loose-fit manner, more contemporary architectural design is basing itself on a greater integration of structure, envelope, environment, space and light as ingredients in a richer mix.

This greater level of interdependency of design allows buildings to become better constructed at the scale of the window, the bay, the wall, the building and the street to form a continuity. Where the provision of buildings, roads, natural landscape and services infrastructure are considered quite separately in our industrialised society, the re-integration of these essential components of our cities could eventually become part of linked parametric models. The interdependency of building, street, and the natural landscape that was a critical generator of the built forms of the pre-industrial world, where the use of energy for both transportation within towns and cities and the response to the built environment played much bigger roles in the generation of urban form.

An essential aspect of parametric design with digital models is to establish what is important in the design and what is much less important; understanding what design 'problem' is being set, and what might be the ways of exploring that design. This approach allows buildings to become a much more closely dependent set of spaces, and building construction becoming a closer expression of the ideas of space, light and form constructed within the constraints of a particular material system. A parametric approach will also allow much greater



Parametrically modelled lapped glazed panel-covered facade

interdependency of buildings working together as part of a single 'organism' – the urban environment of buildings, streets and public spaces. It is perhaps in the design of public space, and the elimination of residual or ill-defined space that could be the next major use of parametric design in digital models.

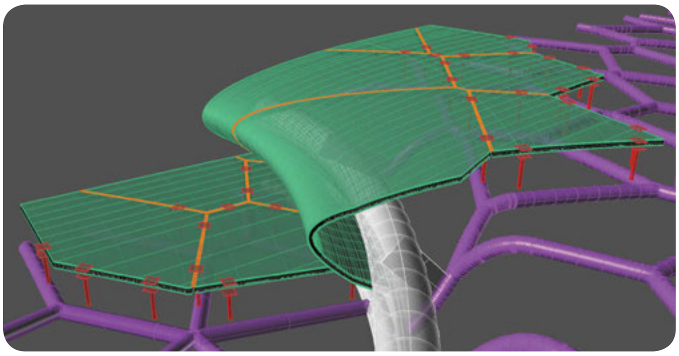
Parametric working method

An essential aspect of working with parametric design is the ability to develop different parts of the building design in parallel rather than working sequentially from outline design, scheme design, detailed design and so on. Rather than viewing design as a series of stages to complete and move on from without significantly changing or informing what has already been accomplished in the design, the design of a building is tackled not as something developing as a result of a series of decisions which influence the next decision in turn (from primary concerns to secondary concerns and so on) but rather of material systems which interact and influence one another. A material system for structure, walls, roofs and environmental design can be developed in parallel, for these choices are as important as the internal organisation of the building, the spatial arrangement and relationship to the site. This brings the choice of materials and the way they are used, or 'tectonics' back to the centre of architectural design, rather than material and construction-related issues being chosen as standard construction methods afterwards. The result of involving issues of materials and construction at a later stage is that the forms of construction used can become no more than an outer 'clothing' that is deemed appropriate to the site context and the brief, that it should somehow behave well in an architectural sense. The limitation of this approach is that the outer skin has little to do with the structure and envelope materials behind it, often forming the outer rainscreen or covering of a construction system that is based on procurement expediency rather than design. Consequently, there is a need for material systems to be involved at early stages of the design process. Construction methods used for these essential parts of building design are set out as material systems in the chapters of this book; each described from a common platform of how the principle material is used to form a system for wall, roof or structure, and how these might be applied to specific strategies of environmental design.

Embodied energy and digital design

Two trends in building construction which are driving change in architectural design are concerns about the environment, and the introduction of computer controlled manufacturing. The effect of building construction on the environment has been of concern since at least the 1960s. The effect in building construction is a growing awareness of the energy required to construct buildings, or 'embodied energy', and secondly the energy required to operate the building when in use. The embodied energy part of the equation is concerned with both the amount of energy needed to manufacture the materials, transport them to site, then install them on site. This interest has favoured the use of timber, which absorbs CO2 during its growth and can be re-planted when cut down for use as a building material.

However, much timber is used as a 'cladding' material to an envelope constructed of quite different materials. The idea of 'cladding' buildings involves increasing the number of layers, and has led to a desire to reduce all the different requirements of construction by making the external walls loadbearing rather than being cladding panels to a structural frame. This interest is linked to a preference for reduced amounts of glazing in many building types, where structural frames were enclosed in highly transparent envelopes. While high levels of glazing encourage increased levels of natural daylight in buildings, they also admit solar gain and provide poor thermal insulation in all climates. The preference for loadbearing construction is in some ways a return to pre-industrial forms of construction. This interest in a 'leaner' higher performing construction is possible with computer controlled manufacturing tools that are linked to drawings and 3D models produced by the design team. Although in practice it is manufacturers who provide the final drawings for CNC machines, this is largely a requirement based on how buildings are procured rather than an imperative of the




Detailed images of a glazing system based on a voronoi pattern

design process. Consequently, designers can produce a full set of drawings for manufacturers to make a much wider range of components than has been the case with mass production. This link of design directly to construction, rather than re-interpreting a design as a set of drawings that in turn 'get built' is forging a much closer link between design and construction. In common with the re-introduction of loadbearing construction, the use of computer controlled mass customisation tools is bringing the design of buildings much closer to the process of constructing them, a privilege enjoyed in the pre-industrial world of construction prior to around 1920. The second essential aspect of environmental concern is of the energy consumed by the building in use. Natural ventilation, thermal mass and associated issues of night-time cooling have become primary tools to reduce energy consumption for heating and cooling buildings. This has resulted in the re-introduction of opening windows and of cross ventilation in buildings.

Material systems

This third edition is aimed as a guide to using material systems in contemporary buildings, with material systems shown as views of 3D models in order to understand how they fit together spatially rather than treat them as 2D sections. This is because traditional vertical and horizontal drawn sections assume most systems are continuous through their length, that they are extruded in a linear direction either side of the section taken. This method of representation also assumes that a drawn section, both vertical and horizontal, is a typical condition. While plan, section and elevation explain the overall scope of the design, junctions of the separate planes represented in these drawings are rarely resolved in these drawings, leaving some coordination issues to be resolved at a later stage. Expressing information as images from a 3D model allows the system's behaviour to be understood from a geometrical point of view of how the components, assemblies or panels are set out.

Traditional detail drawings can show how to describe assemblies in a way which is useful when progressing from design ideas to a design ready for construction, and the material systems shown in this book are set out in more detail in the accompanying books Modern Construction Facades and Modern Construction Roofs. From a design perspective, rather than production of information for tender or for construction, a 3D model and the controlled manipulation of that model in relation to the constraints of the material systems such as glass sizes or bending constraints on panels, is as valid as a 2D section through a building of constant section. Drawings can show the 'kit of parts' required to describe the scope of the building, which is essential to understanding and setting out how much material is required to construct the building. From these drawings, the embodied energy required to construct the building can be calculated.

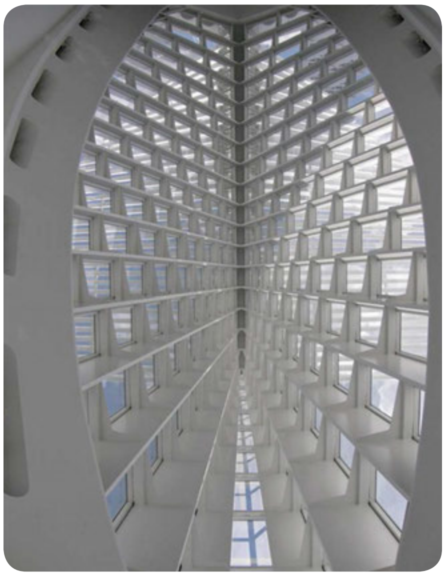
The systems of modern construction set out in this book suggest a gradual move forward to methods of production based on mass customisation techniques that are evolving in manufacturing, as well as showing how current mass produced material systems can be modified and 'diverted' to the end of producing an architecture rooted in the construction techniques that make it possible.

1

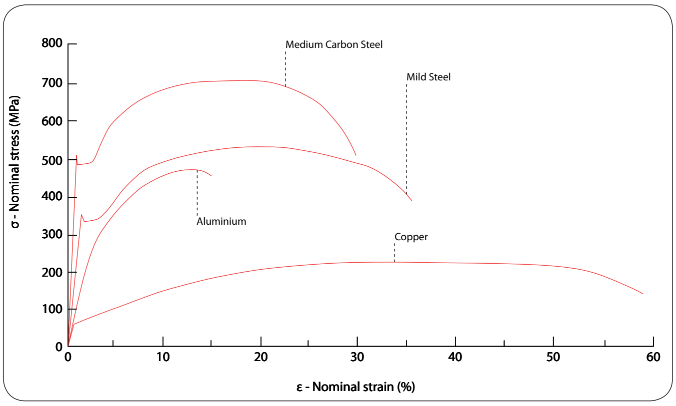
MATERIALS

Milwaukee Museum of Art, U.S.A. Architect: Santiago Calatrava

Milwaukee Museum of Art, U.S.A. Architect: Santiago Calatrava



Milwaukee Museum of Art, U.S.A. Architect: Santiago Calatrava



Metals stress strain diagram

Milwaukee Museum of Art, U.S.A. Architect: Santiago Calatrava

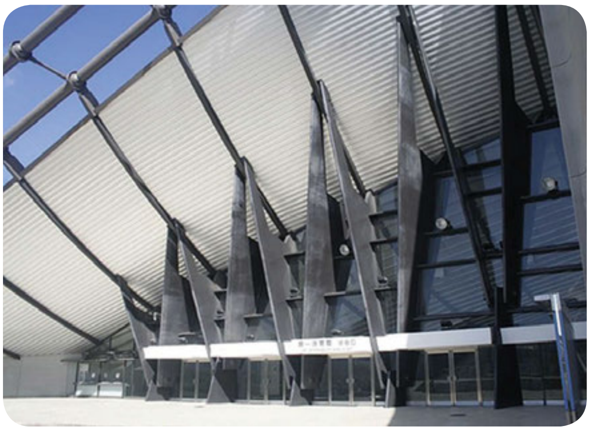
Architectural interest in metals in the early industrial world can be seen in the writings of Jean-Baptiste Rondelet, an admirer of industrial Britain in the early 19th century. His book Traité théorique et pratique de l'art de bâtir discussed architecture from the point of view as comprising a mixture of the visual and the technical rather than the prevailing values of the time of Renaissance architecture, which were primarily of art and symbolism. He also taught stereotomy, that is, the art of cutting stones to form complex shapes such as arches and vaults, which is enjoying a revival with an interest in complex geometry in contemporary architecture. As a construction textbook, the Traité théorique set out many of the components needed for a complete metal construction, such as prefabricated market buildings, showing an approach towards an integrated assembly that follows on from his passion for stereotomy. The metal castings securing the bases of the supporting arches illustrate both the need for the continuity of material needed to fix the arches to their bases as well as the elegance associated with their use. The drawings in Rondelet's books are both a 'kit of parts' showing what components are needed as well as a 3D representation of the assembly of key components. This interest in the physical modelling of junctions rather than in reducing them only to 2D views helps to explain the more complex nature of the construction, whose design approach is embraced rather than simplified. The combination of rolled members, castings and connecting brackets creates a visually striking form of construction that was characteristic of later 19th century construction.

In the 20th century, the Tokyo Olympic Stadium of 1964, designed by Kenzo Tange, comprises steel tension cables in a catenary form, supported by concrete masts at each end. The complete tent-like structure is used to support a metal skin, which would typically be used on a rigid substrate. The metal roof skin is actually a series of metal plates welded together to form a sealed surface. Welded metal roofs have been used in more recent projects for large-scale roofs, but few combine the possibilities of a continuous, welded metal surface with that of a skeletal or tent-like structure that can form a metal cable structure. Even the cable structure is made from short lengths bolted together to form a structure that can support the metal roof plates without an intermediary material. The metal structure and skin is not a 'minimal' structure, but is certainly one where these two components are interdependent. The all-metal roof structure and skin is held in place by a reinforced concrete structure beneath, whose form echoes that of the metal structure rather than contrasting visually with it.

More recently, moving structures such as the sail-like canopy at Milwaukee Museum of Art, designed by Santiago Calatrava, take forward the visually dynamic qualities of metal construction. This canopy is used to provide solar shading, and moves in order to provide different experiences of light. Here a folding structure with a building performing different functions and forming different spaces through moving, is possible because of the relative lightness and flexibility of metal, allowing the possibility of moving parts to be used to form part of the structural frames

Olympic Stadium, Tokyo, Japan.
Architect: Kenzo Tange

Olympic Stadium, Tokyo, Japan.
Architect: Kenzo Tange



Olympic Stadium, Tokyo, Japan.
Architect: Kenzo Tange

Olympic Stadium, Tokyo, Japan.
Architect: Kenzo Tange

of buildings. In the Guggenheim Museum in Bilbao by Frank Gehry, the architectural form of the building is generated as a form of complex geometry, enabled by the possibilities of metal construction, and working with techniques associated with modelling in metal rather than conceiving this innovative form of construction from 2D drawings. In this sense, the buildings described here follow on in the tradition of the Traité théorique of Rondelet, combining the convention of describing elements in 2D while designing in a 3D modelling environment.

The examples described demonstrate the ability of metals to form building enclosures of complex form in a single material where structure and skin are a visible part of the architectural design. In more rectilinear building designs, steel frames can be used which do not necessarily produce a rectangular grid of cladding panels across their surface. Federation Square in Melbourne, Australia, designed by Lab Architecture uses a triangular space frame as a point of departure from which to create a structure which gently departs from this principle, creating junctions which form moment connections rather than the pin joints associated with triangulated frames. This approach allowed a range of glass panels to be added which are still based on a triangular grid. This method of starting with regular forms of construction and working with their geometry is well suited to metal frames, where standard rolled sections are joined with plates or nodes. The technical success of the system lies partly in creating a limited number of node types which can provide a visually rich construction with a small number of node types or bracket sizes. The use of a limited 'kit of parts' can provide a visually rich structure and enclosure that can respond to particular design requirements such as positioning of openings or links with adjacent structures without needing to be aligned to a rectilinear grid.

More recently, designs for metal frames to support cladding systems have begun to use identical polygons which might be twisted or pulled out of plane in their geometry and which produce complex shaped surfaces when joined together. In addition, the 'cold bending' of metal panels to cladding systems can create more complex forms for enclosures from flat sheet or profiled sheet without the need for any special manufacturing. This can combine the benefits of more complex steel frames that are straightforward to construct with metal wall systems usually more associated with rectilinear forms, without changing the way such enclosures are constructed. However, for all these examples of tectonics in metal, the designer is obliged to set out the construction of the structure and enclosure in a more detailed way than that expected for more generic forms of construction, just as Jean-Baptiste Rondelet set out examples from his Traité théorique, completed in 1817.

Federation Square, Melbourne, Australia. Architect: LAB Architecture Studio

The Barcelona Fish, Barcelona, Spain.
Architect: Frank Gehry

IAC Headquarters, New York, U.S.A.
Architect: Frank Gehry

Steel is an iron-based metal alloyed with small amounts of other elements, the most important being carbon. The three main forms of steel used in the building industry are sections, sheets and castings. Steel sections are currently formed using a rolling process. It can be extruded to form complex sections, but this currently has only limited applications due to the high pressure needed to extrude steel. Aluminium is a much softer material, making it easier to extrude. Even when aluminium is alloyed with other materials such as bronze, the extrudable size of sections drops dramatically. Extrusions in steel cannot exceed shapes that fit into a circle approximately 150mm (6") in diameter. This is too small for structural sections, but their smooth appearance makes them suitable for components such as stiffeners in curtain walling (to provide a fin that is visually more refined than an I-section or a tee). Currently, it is still far easier to roll steel sections than to extrude them.

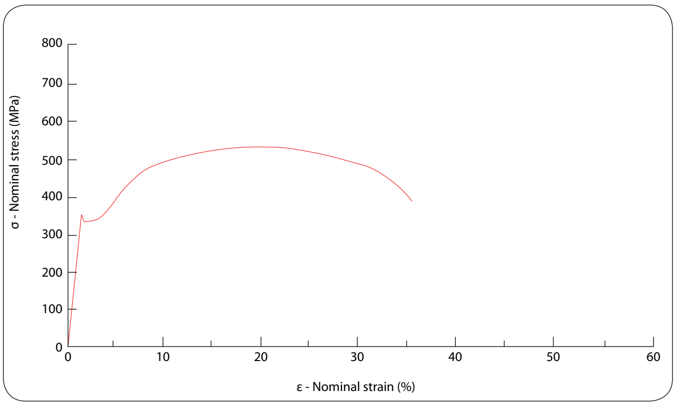
Historically, cast iron and wrought iron were the forerunners of steel. Cast iron, a brittle material with high compressive strength, came into general use as a building material at the end of the 18th century, while wrought iron was developed some 50 years later. Wrought iron is a more ductile material and has greater tensile strength, making it less susceptible to shock damage. (The Eiffel Tower, in Paris, was one of the last large structures to be constructed in wrought iron). By the end of the 19th century, both materials had been superseded by steel. Steel was first produced around 1740, but was not available in large quantities until Bessemer invented his converter in 1856. This device introduced a method of blasting air into the furnace (hence blast furnace) to burn away the impurities that inhibited the extraction of a purer iron. By 1840, standard shapes in wrought iron, mainly rolled flat sections, tees and angles were available which could be fabricated into structural components which are then assembled by riveting them together. By 1880, the rolling of steel I-sections had become widespread, leading the way to this material eventually replacing wrought iron as a material of choice.

Production process of raw material

There are several steps in the manufacture of steel. First, iron is refined from ores containing iron oxide. The iron oxide is heated in a blast furnace until it is molten, using carbon as a reducing agent. The molten material is poured into moulds to produce pig iron. It is then re-heated to remove impurities, including carbon, to make cast iron that has a carbon content of 2.4 per cent to 4 per cent. Steel is produced by reducing the carbon content to approximately 0.2 per cent, with materials such as manganese and silicon added to halt the oxidation process and stabilize the carbon content. It can be poured when molten to make castings or formed into ingots to be rolled into sheets or sections.

Federation Square, Melbourne, Australia. Architect: LAB Architecture Studio

Guggenheim Museum, Bilbao, Spain.
Architect: Frank Gehry



Mild steel stress strain diagram

Guggenheim Museum Bilbao, Spain.
Architect: Frank Gehry

Properties and data

The main properties of structural carbon steels are as follows:

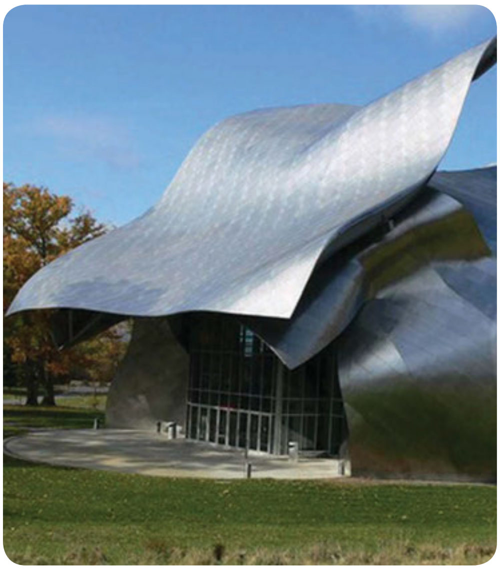
Density: Mild steel = 7840 kg/m^3 (490 lb/ft^3)
Design strength:
Approximate range 275 N/mm^2 to 900 N/mm^2
(5.7×10^6 to 18.8×10^6 lbf/ft^2)
Young's modulus = 210 kN/mm^2 (4.4×10^9 lbf/ft^2)
Coefficient of thermal expansion
= 11×10^{-6} K^{-1} (6.1×10^{-6} $^0F^{-1}$)
Thermal conductivity = 45 W/m°C
(26 BTU/hr.ft.^{0}F)
Specific heat capacity= 480 J/kg°C (0.11 BTU/lb^{0}F)

For comparison with other materials, steels have the following general properties:

- High strength in both tension and compression.
- High stiffness. High rigidity in both tension and compression.
- Its appearance is smooth in sheet form; rougher of texture in rolled sections and castings, even with paint applied.
- Lighter than an equivalent structural member in reinforced concrete.
- High ductility, deforming long before it fails.
- High impact resistance.
- High heat conductor.
- High electrical conductor.
- Thermal expansion approximately half that of aluminium.
- Susceptible to continuous rusting, excluding weathering steels.
- Low fire resistance.

Material selection

Hot rolled structural mild steels are made in three types called 'grades' increasing in design strength from 275N/mm^2 to 400N/mm^2 (5.7×10^6 lbf/ft^2 to 8.3×10^6 lbf/ft^2), varying slightly in different regions of the world. High strength steels can reach design strengths of 800N/mm^2 (17.6×10^6 lbf/ft^2). Since the Young's Modulus is constant for all these types, the strength of material increases but the stiffness remains constant. Steel also increases in cost with higher levels of strength, both in the cost of the raw material and in the working of the material. In addition, as strength increases in the material, welding becomes more difficult and consequently more specialized. In some high strength steels, which undergo heating and quenching during their manufacture, the effects of welding could potentially undo the work of manufacture if sufficient care is not taken. Standard rolled sections are manufactured in the low to medium strength grades but higher strength steels are made mostly in the form of plate, due to lower demand for their use. Consequently, compound shapes



Fisher Center for the Performing Arts, Bard College, Hudson Valley, New York, U.S.A.
Architect: Frank Gehry

Federation Square, Melbourne, Australia. Architect: LAB Architecture Studio

for structural components, such as beams and columns, must be specially fabricated.

Cold worked mild steels are used for much smaller scale structural components such as lightweight structural framing in metal framed housing and low-rise commercial buildings, used mainly in the U.S.A., and drywall partitioning. Cold-formed steel sections are made from structural carbon steel to form sheets or strips approximately 1.5mm (1/16in) thick. Complex sections are formed by folding and pressing, rather than rolling which is the case with hot formed sections.

Working with the material

Sections and sheets can be curved to small radii. Bolting and welding are the most common methods of joining sections, sheets and castings. Steel can also be sawn and drilled. An essential characteristic of steelwork is that it will continue to rust if a surface protection is not provided. When drilling or cutting the material, the newly exposed surface requires protection, which is particularly important if the material has been factory coated prior to drilling and cutting. The economic protection is galvanising, a zinc coating that is corrosion resistant, applied to the steel in a hot dip bath or as a flame spray. Galvanising occurs after fabrication of steel components to cover all the welding and drilling. This process can cause distortion of smaller steel components, so may not suit all types of fabrication. The appearance of galvanising when new is a mottled shiny grey, turning to a dull grey with weathering as the zinc oxidizes. Its visual appearance is often not suitable for exposed structural steelwork or cladding in buildings, where paint coatings are more common. Flame sprayed aluminium can be used as an alternative to galvanising. Paint can be applied by hand on site or in a factory as part of a proprietary finish. Care must be taken to ensure that touching up on site of visible components is done in controlled conditions that ensure the finish both matches and blends into the surrounding coating.

When used as primary structure in a building, steelwork requires fire protection. This can be done by either encasing the material in concrete, by enclosing it in a fire resistant board, or by coating it in intumescent paint. A spray-applied coating that yields a very rough, fibrous surface appearance is often used where the steel frame is concealed behind finish materials.

Coatings

Many factory applied proprietary systems are available for coating steel; the most common types are thick organic coatings and powder coating. PVDF (polyvinylidene di-fluoride, also called PVF2 in Europe), is sometimes used, and is discussed further in the section on aluminium. Organic coatings provide high levels of protection against corrosion but have a distinctive orange peel texture. They are applied to steel coil, from which sheet is cut, during manufacture. These finishes have methods of touching up surfaces that become exposed or are damaged during installation, but colour matching remains an important consideration in successful re-touching.

Recycling

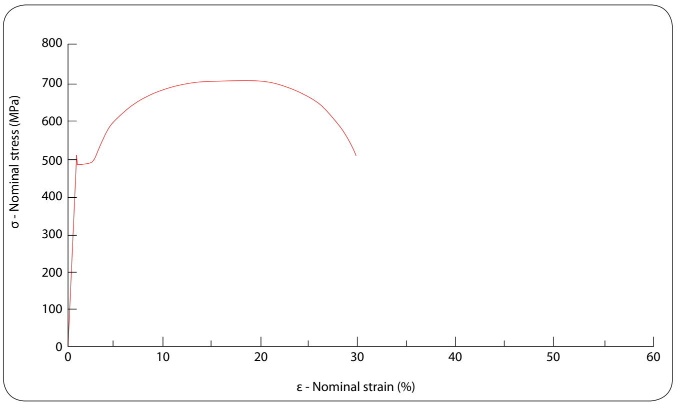
Steel can be recycled at reasonable cost, and requires much less energy than the original production process.

Stainless steel

Stainless steel is an alloy of steel which contains between approximately 11 to 25 per cent chromium, together with nickel in some types, giving it properties that are distinct from carbon steels, the main one being a high resistance to corrosion without the need for an additional coating. Since the material is considerably more expensive than carbon steels, stainless steel is most commonly used in small building components and in cladding panels where durability is a prime concern.

Federation Square, Melbourne, Australia. Architect: LAB Architecture Studio

Dancing House Prague, Czech Republic .
Architect: Frank Gehry



Medium carbon steel stress strain diagram

Properties and data
Density = 7600 to 8100 kg/m^3 (475 to 505 lb/ft^3)
Design strength:
Approximate range 170 N/mm^2 to 1000 N/mm^2
(3.5 x 10^6 to 20.9 x 10^6 lbf/ft^2)
Young's Modulus :
189-210 kN/mm^2
(3.9 x 10^9 to 4.4 x 10^9 lbf/ft^2)
Coefficient of thermal expansion
=13 x 10^{-6} to 17 x 10^{-6} K^{-1}
(7.2 x 10^{-6} to 9.4 x 10^{-6} ^{O}F^{-1})
Thermal conductivity = 16 W/m$^{\circ}$C
(9.3 BTU/hr.ft.^{O}F)
Specific heat capacity= 502 J/kg$^{\circ}$C (0.12 BTU/lb^{O}F)

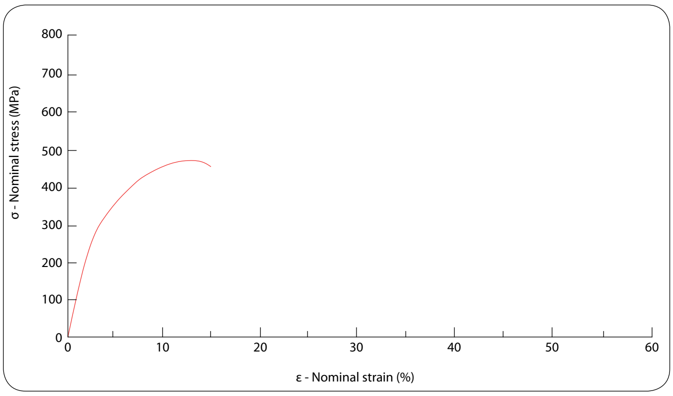
Stainless steel has the following general properties:

- Highly resistant to corrosion and usually requires no further coatings.
- Higher fire resistance than carbon steels.
- A risk of bimetallic corrosion at the junction of stainless steel and carbon steel when they are used together.

Separation at junction is usually required, such as a nylon or neoprene spacer.

Material selection
Although the material develops a thin oxide layer that protects it from further corrosion, different grades of stainless steel are available to suit the severity of exposure from polluted urban to maritime to rural environments. A limited range of standard sections is available and usually in small sizes only. The need for a high degree of fabrication of members can make construction time slower than that for carbon steel applications. For example, plate is folded to form angles and tubes, and hollow sections are formed by bending and seam welding. As with carbon steels, the high strengths types, which have been heat-treated, are more difficult to weld, as the process can undo the heat strengthening. Different finishes are available which are achieved by using a variety of rolling techniques from smooth to textured, in an appearance from matt to polished. In addition, the sheet can be coloured as part of the manufacturing process.

Working with the material
The fabrication of stainless steel follows the traditional pattern of fabrication for carbon steel members except that more use is made of pressing and bending to form suitable shapes. Fabrication of stainless steel should be kept entirely separate from that of carbon steel to ensure that the processes of cutting and grinding do not cause impregnation of carbon steel particles onto the stainless surface, which can lead to rusting. Fabricated elements should seek to eliminate standing seams or edges where water can collect, in order to avoid crevassing corrosion. Stainless steel has high ductility which gives the material excellent resistance to impact loading.



Aluminium stress strain diagram

St Paul's Place car park, Sheffield, U.K. Architect: Allies & Morrison

Aluminium was first produced in 1825, and by the late 19th century a method had been found to mass produce the material by the electrolysis of alumina and cryolite.

Production process of raw material
Aluminium is made from bauxite, which is essentially an hydrated alumina, or aluminium oxide. Mined bauxite is treated chemically to remove impurities and obtain alumina, which is aluminium oxide. This is then reduced to aluminium by electrolysis. Because aluminium has a very high melting point (2450ºC) it cannot be electrolysed on its own, and so it is dissolved in molten cryolite. A high electric current is passed through the alumina-cryolite mixture at around 1000ºC, and the molten aluminium is tapped off. Aluminium alloys are either formed directly, followed by continuous casting, or are cast into solid ingots. The metal is then cast into ingots which form the basis for producing aluminium alloys. Pure aluminium is too soft for structural use and is therefore combined with other metals to form alloys to increase its strength and hardness, though reducing its ductility. Magnesium, silicon and manganese are the most common additives. Aluminium alloys make strong, lightweight structural components. In common with steel, aluminium is a material that can be extruded, rolled and cast into complex shapes: plates, sheets, extrusions and castings.

Properties and data
The main properties of aluminium alloys are as follows:

Density =2700 kg/m^3
(169 lb/ft^3)
Design strength
Heat treated = 255 N/mm^2
(5.3 x 10^6 lbf/ft^2) for extrusions
and 185 N/mm^2 (3.9 x 10^6 lbf/ft^2) for plate
Fully softened= 105 N/mm^2
(2.2 x 10^6 lbf/ft^2) for plate
Young's Modulus = 70 kN/mm^2 (1.5 x 10^9 lbf/ft^2)
Coefficient of thermal expansion
= 23 x 10^{-6} K^{-1} (12.8 x 10^{-6} ^{O}F^{-1})
Thermal conductivity = 200 W/m ^{o}C (116 BTU/hr.ft.^{O}F)
Specific heat capacity = 880 J/kg ^{o}C (0.21 BTU/lb ^{O}F)

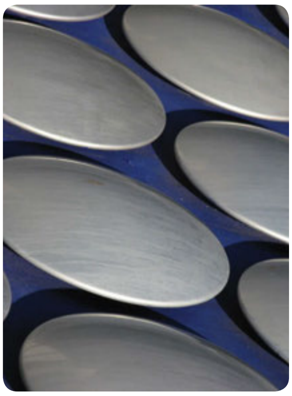
For comparison with other materials, aluminium alloys have the following general properties:

- Lightness, weighing about a third that of steel.
- High tensile strength, similar to that of steel.
- High impact resistance. (compared to steel)
- High corrosion resistance, but aluminium requires protective coating in very polluted or severe atmospheric conditions.
- Coatings are not applied solely for appearance.
- High heat conduction.
- High electrical conduction.
- Poor stiffness.
- Low resistance to soft impact, but absorbs impact energy which localises damage. (Whereas a soft, or low level impact, such as a kick, would not damage a steel panel, it will dent one in aluminium.
- A high impact, such as a car reversing into a panel, would cause a large steel panel to buckle across its entire height and length, but one made of aluminium will again dent only around the impact area).
- Thermal expansion approximately twice that of steel.
- Poor fire resistance.

Material selection
Pure aluminium and its alloys are in two broad groups: the non heat-treated alloys, also called fully softened alloys, whose strength is produced from being cold worked, and the heat-treated alloys whose strength is produced by heat treatment. The non heat-treated types are generally not as strong, but have better corrosive resistance.

Structural use of aluminium alloys is limited by two significant disadvantages: they are more expensive to manufacture than steel and they deform more easily under load. Aluminium alloys are more elastic than steel, restricting their use to components and assemblies where this is not a constraint. Since the Young's Modulus of aluminium is one third that of steel, buckling is an important issue in its structural use. The potential of this material as a full structural material in buildings is beginning to be recognised. The Media Centre at Lord's Cricket Ground, London, England, is a recent notable example because of the full structural use of aluminium in a large-scale building frame.

Working with the material
On exposure to the atmosphere, aluminium forms a protective coating of aluminium oxide. Under adverse conditions, the oxide film can break down locally, but it usually reforms to a greater thickness preventing further attack. Aluminium can be exposed to the weather, in non-polluted environments and away from maritime conditions, without the need for additional treatment provided the surface is maintained. Over time, it loses its initial bright appearance and assumes a dull grey sheen. Aluminium should be cleaned regularly to avoid pits forming in the material surface. However, one



left: Selfridges, Birmingham, U.K. Architect: Future Systems

right: Imperial War Museum North, Manchester, U.K. Architect: Studio Daniel Libeskind

way to avoid this is to anodise or paint the material with a proprietary coating.

Aluminium is susceptible to electrolytic corrosion in contact with certain materials such as copper. Therefore direct contact with copper and copper-rich alloys, such as brass and bronze is avoided and the material should be used in a way that water does not flow onto it from copper. However, water flowing from aluminium to copper or lead is not harmful. There is no corrosive action between aluminium and zinc or zinc coatings and galvanised surfaces. Some timber preservatives contain compounds harmful to aluminium. Untreated timber affects the material to a much lesser extent.

Aluminium can be cut and drilled, riveted, bolted, screwed and glued. The material can also be welded. However, welding is usually done using the fully softened alloys, since this process can undo the work of the heat treatment in the other alloy types. Since the design strength of the fully softened alloys is half that of the heat-treated types, the section sizes used in welded aluminium structures can often be similar to that of comparable steel structures, but with considerably less weight. The design strength of the heat-treated alloys, which is similar to the bottom end of the design strength of steel, can be exploited in extrusions, which require no welding in their manufacture. Extrusions can be used to form complex profiles, such as those needed in window sections or walkway decking, and be much lighter than an equivalent member in steel. The material can also be cast to form complex shapes that are more economic in large quantities than an equivalent fabricated component.

Anodising

Anodising produces a fine translucent film over the surface of aluminium. The anodising process results in the replacement, by electrochemical means, of the metal's naturally formed oxide film by a dense chemically resistant artificial film many times the thickness of its natural equivalent. This film is extremely hard, gives added protection against abrasion, and reduces the adhesion of dirt particles. Anodising is carried out by immersing the aluminium in an electrolyte and applying an electrical current, creating an oxide layer integral with the underlying metal. The anodic film is porous and must be sealed. This is done by immersing the anodised aluminium in boiling water or steam. The anodised coating can be dyed; the sealing then assists its colour-fastness. Anodising should be carried out after welding. The process of welding would otherwise break down the anodising process at heat-affected locations. Broken-down anodising could result in weld impurities that would impair its structural effectiveness.

Aluminium's natural finish, often referred to as mill finish, can be worked to produce a polished, ground or brush-grained finish. Etching gives a matt and non-directional finish with no direct reflections. Anodising generally follows these processes, which increases durability and enhances long-term appearance. Brightening is not suitable for architectural alloys which are only 99.5% aluminium because the brightening is not uniform. Chemical brightening on other alloys dissolves and flattens surface irregularities found in extruded or sheet aluminium surfaces, and produces a mirror finish with a very high reflectivity. It can be anodised without dulling the surface.

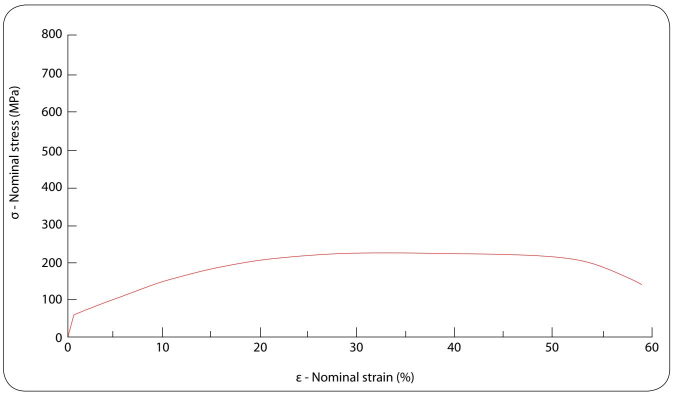
Coatings

Aluminium can be coated in a wide range of colours through the use of proprietary processes. Plastic coatings provide a durable paint surface; polyester powder coating is one of the most common finishes. Plastic coatings are dip-coated, sprayed or electrophoretically deposited underwater. The electrostatically applied finish ensures that an even coat is built-up on the metal. These paints fade and lose their shine with time, though the change is slow and even.

PVDF (polyvinylidene di-fluoride), also called PVF2 in Europe, and powder coatings are most commonly used. PVDF is a spray-applied finish, which is highly resistant to fading in sunlight, making it very suitable for external use where colour stability is an important consideration such as in wall cladding. Powder coating is applied in an electrolytic process that provides a softer, and less expensive coating than PVDF. It is not as resistant to fading in sunlight, but is a harder finish and less expensive, making it suitable for both an economic external finish and excellent for internal use. All these finishes have methods of touching up surfaces that become exposed or are damaged during installation or use, but colour matching remains an important consideration.

Recycling

Aluminium is one of the easiest and cheapest materials to recycle. The conversion of scrap back to high-grade metal requires only about 5% of the energy needed to make the same amount of metal from bauxite.



Copper stress strain diagram

Copper cladding in use

Properties and data

Density :
Copper = 8900 kg/m^3 (556 lb/ft^3)
Zinc = 7000 kg/m^3 (437 lb/ft^3)
Lead = 11,400 kg/m^3 (712 lb/ft^3)

Tensile strength:
Copper = 216–355 N/mm^2
(4.5 x 10^6 to 7.4 x 10^6 lbf/ft^2)
Zinc = 139–216 N/mm^2
(2.9 x 10^6 to 4.5 x 10^6 lbf/ft^2)
Lead = 15–18 N/mm^2
(3.1 x 10^5 to 3.8 x 10^5 lbf/ft^2)

Young's Modulus :
Copper = 112–148 kN/mm^2
(2.4 x 10^9 to 3.1 x 10^9 lbf/ft^2)
Zinc = 68 - 95 kN/mm^2 (pure)
(1.4 x 10^9 to 2.0 x 10^9 lbf/ft^2)
Lead = 13–15 kN/mm^2
(2.7 x 10^8 to 3.1 x 10^8 lbf/ft^2)

Coefficient of thermal expansion :
Copper =17 x 10^{-6} K^{-1}
(9.4 x 10^{-6} ^{0}F^{-1})
Zinc =23 to 40 x 10^{-6} K^{-1}
(12.8 x 10^{-6} to 22.2 x 10^{-6} ^{0}F^{-1})
Lead 29.5 x 10^{-6} K^{-1}
(16.4 x 10^{-6} ^{0}F^{-1})

Thermal conductivity :
Copper: = 368 W/mK
(213 BTU/hr.ft.^{0}F)
Zinc: = 115 W/mK
(67 BTU/hr.ft.^{0}F)
Lead: = 35 W/mK
(20 BTU/hr.ft.^{0}F)

Specific heat :
Copper: = 390 J/kg ^{o}C
(0.093 BTU/lb ^{0}F)
Zinc: = 380 J/kg ^{o}C
(0.090 BTU/lb ^{0}F)
Lead: = 130 J/kg ^{o}C
(0.031 BTU/lb ^{0}F)

Material selection
Apart from steel and aluminium, copper, zinc and lead are the most widely used metals in the building industry. These metals are produced as sheets of up to approximately one metre (3ft 3in) wide sections and castings. All three metals have excellent weather-resisting properties, however, they are susceptible to attack by pollutants such as acids. Their use is restricted to non-structural metals and alloys, because none has the strength or rigidity of steel, or the combination of strength and lightness of aluminium. They are generally used as cladding materials for walls and roofs. Copper is also used extensively for water supply pipework and in electrical wiring.

Working with these materials
Copper is strong in tension, tough and ductile, but is not as malleable as lead. The material has a shiny red/yellow colour when new, slowly developing a protective sulphate layer on its surface when exposed to the atmosphere. This patina has a characteristic green colour which has a fairly consistent colour and texture. Copper is available with a pre-weathered, or pre-patinated finish which is chemically induced. This finish varies slightly from naturally weathered cladding. Well maintained copper cladding which has oxidised atmospherically will last from 30 to 50 years.

There is a variety of copper types available, each of which is suitable for a particular task. For instance, deoxidised copper is suitable for welding, while fire-refined tough-pitch copper, with its tougher resistance to corrosion, is used for cladding. Otherwise, both have similar properties. Copper forms a high proportion of metal in alloys such as bronze, which is primarily a mixture of copper and tin. Brass is primarily a mixture of copper and zinc, and aluminium bronze is primarily a mixture of copper and aluminium. Copper can be cut, drilled, nailed, welded and

Copper cladding in use

Zinc cladding in use

soldered with hand power tools, making it versatile for site-intensive work. When used as cladding, joints between sheets are made by folding the edges together. This method takes advantage of the fact that copper can be bent along an edge fairly easily, but is rigid enough to remain folded.

Zinc sheet for cladding is made from either commercial zinc or from an alloy of zinc with small amounts of copper and titanium added. The properties of the two types are similar, but zinc alloy has better tensile strength and resistance to creep, which is long-term plastic deformation under load. Zinc is a durable material, although it is more brittle than copper. It is manufactured as a white coloured metal, but when exposed to the atmosphere a carbonate is slowly formed which produces a protective coating that is grey-white in colour. The material has a linear thermal expansion that is similar to lead and higher than copper.

Zinc can be cut, drilled, nailed, welded and soldered with hand power tools, making it reasonably versatile for use on site. Its rigidity makes it well suited to standing seam joints. Well maintained zinc cladding can last for between 30 and 50 years. Zinc is liable to attack from copper alloys, so that rainwater running off copper should be avoided. Apart from its use in alloys, zinc is used as a protective coating to steel, applied through a process of galvanising and sherardising

Lead is an extremely durable, ductile and malleable material, making it extremely useful for roof coverings and flashings in traditional roof construction. However, while its relative softness allows lead to be formed into complex shapes, its lack of rigidity means that a supporting material must be provided beneath it. Timber boards are most commonly used for this. Lead has low resistance to creep.

On exposure to the atmosphere, a protective coating of lead carbonate is slowly formed on its surface. This gives weathered lead a dull grey appearance. Lead is a poisonous material, leading to increased awareness of the dangers of water run off from lead cladding reaching the water supply. Lead can be cut, drilled, nailed, welded in a process called leadburning, and soldered with hand power tools. Due to its lack of rigidity, lead sheet is most commonly jointed by dressing it over rounded timber battens or rolls. Where standing seams are used, they often incorporate a steel angle to keep the line of the joint straight and vertical. Lead is alloyed with tin to form solders for jointing and sealing.

Electrolytic action

When different metals are near each other, rainwater running from one to the other can cause corrosion by electrolysis. Run off from copper and zinc will attack cast iron, mild steel, galvanised steel and aluminium. In addition, copper will attack zinc. Lead is much more resilient and does not attack other metals with the exception of aluminium when used in marine environments. When roofs or walls are made from either copper or zinc, typically other metals are not usually used in adjacent components, such as gutters and flashings, where water run off is likely to occur.

Paris Metro station canopy, Paris, France. Architect: Hector Guimard

Paris Metro station canopy, Paris, France.
Architect: Hector Guimard

Paris Metro station canopy, Paris, France.
Architect: Hector Guimard


Bilbao Metro entrance, Bilbao, Spain.
Architect: Foster & Partners

An essential use of glass in buildings is in double glazed units. With the increasing importance of thermal insulation and a reduction in the energy consumed to temper the internal environment of buildings, the use of single glazing with thin supporting frames without thermal breaks, is no longer used in most new buildings except where, for example, the spaces enclosed by the glass are considered to be external and serve only as canopies, or in the outer screens to double facades. In these semi external applications, the visual lightness afforded by lightweight steel supporting structures can still echo the glazed structures of the early 20th century, such as the canopies to Metro stations in Paris by Hector Guimard. These canopies have glass panels which have no support on the outer edges, allowing the supporting metal structure to take precedence. This preference for the expression of the supporting structure at the visual expense of the glass has been a theme in glass tectonics through the 20th century. In the Guimard canopies, covers for lights to illuminate the entrance have a form of their own, with the supporting structure being almost a container for the exquisitely formed lamp covers. The use of glass and metal is finely balanced both technically and visually, though the richness of the forms were only gradually accepted as being of architectural merit.

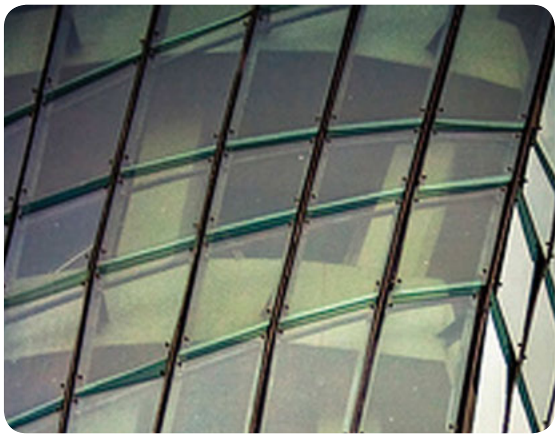
Glass is manufactured in sheets of float glass approximately 6000mm x 3000mm, which is typically much larger than can be used as single sheets in buildings. Some glass manufacturers are able to temper and laminate glass at this size, providing more opportunities for designers to use large glazed panels in facades. However, since most glazing is made in double glazed units, glass panels do not often achieve these sizes, primarily due to issues of deflection under wind load and the dead weight of the glass. A 3000mm wide double glazed unit, storey height, weighs around 650kg, making it difficult to lift into place using conventional lifting systems for glazed units and even more difficult to consider moving it around by hand. Double glazed units of half their size can be difficult to manhandle on site. In addition to the weight of glass, its size is an important consideration when designing with the material. The six metre by three metre sheets, called 'jumbo' sheets, are required to be cut economically to avoid waste. This makes glass economic for the 1500mm wide panels preferred in office buildings, but does not restrict their cutting to rectilinear panels. Triangular panels can also be economic if cut without significant waste, as can other shapes which fit the jumbo sheet format.

In wall construction, where glass is used in most quantity in most buildings, the material is fixed either along its edges or at points. The use of edge restraint results in a frame behind all glass edges, but point fixed glazing allows the material to become visually dominant, allowing it to be seen almost as a continuous plane of glass rather than as an infilling material. The glazed screen in the Dancing House by Frank Gehry in Prague, completed in 1996. This contrasts with the use of glass at Federation Square by Lab Architecture, completed in 2003, where the supporting frames dominate as the language


187 - 195 Oxford Street, London, U.K. Architect: Future Systems


Swiss Re Tower, London, U.K. Architect: Foster & Partners


Dancing House Prague, Czech Republic.
Architect: Frank Gehry


Dancing House Prague, Czech Republic.
Architect: Frank Gehry

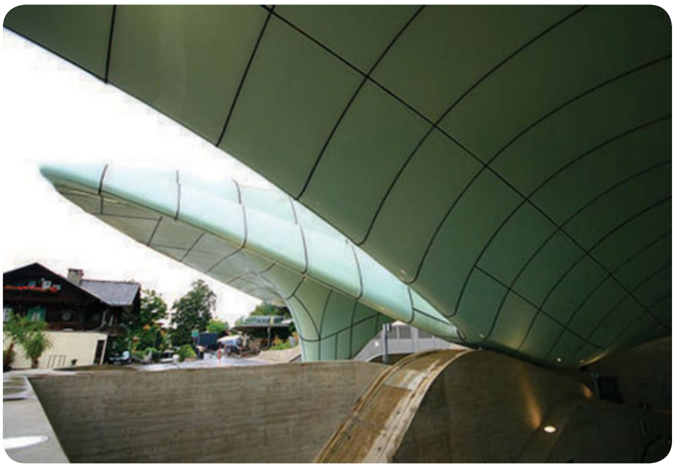
of the tectonic, with the glass as an infill material. An advantage of the framed approach is economy, as the double glazed units can be fitted directly to the supporting frame. Bolt fixed glazing requires the glass to be drilled before any tempering is done, making it expensive to use, though recent examples use bolt fixings that are bonded to one face of the glass, or drilled through only one sheet of the double glazed unit. An alternative approach is to clamp the glass by passing plates through the joints between the units. Consequently, the design and position of the clamps becomes a primary issue in the design of the system as the visual impact of a surface covered with small clamps creates a kind of 'point cloud' of fixings across the surface of the glass wall or roof.

The curving of glass has undergone some development, at least in the quality of production, in recent years. Specialist companies around Europe now offer single curved glass panels in both tempered and laminated glass. Some companies around the world will now provide double curved panels, as used at the Nordpark Cable Railway in Innsbruck, Austria, which form a durable and reflective surface finish for canopy enclosures. The ability of glass to be curved, coated and tempered is making it more of a sculptural material again, following in the tradition of the Guimard Metro entrances.

The use of glass in double glazed units allows the encapsulated inner faces of the glass to have coatings applied to them to reduce their U-value and to reduce solar gain. This makes double glazed units increasingly energy efficient, and the introduction of argon gas into the void between the glass panels further increases their thermal performance. When used in curtain walling, the framing is typically much poorer in thermal performance, bringing the U-value from a typical 1.1 W/m2K up to a typical 2.0W/m2K, depending on the framing type. The thermal break in curtain wall systems is a structural component at present, so finding a much higher performing thermal break is not without its difficulties. In very cold climates, triple glazed units are being introduced, though there is still a limited condensation risk at the edges of the unit where the perimeter spacer conducts greater amounts of heat energy. A development over the past 10 years has been in the introduction of so-called 'super neutral' glasses in double glazed units which have high solar control performance combined with higher levels of transparency than was formerly the case with so-called 'body tinted' glasses. Super neutral glasses have a colour which is visually not as strong as the older generation of body tinted types, though these are still available. Super neutrals allow more daylight transmission than their forerunners, but in locations where there is considerable exposure to the effects of the sun an additional outer screen of solar shading panels might be used.

A recent development in glass design has been the introduction of all-glass structures, where glass components are connected together by silicone bonds. The silicone serves as both adhesive and sealant, providing weathertight enclosures. The scale of use to date has been modest, with single storey conservatories,

Federation Square, Melbourne, Australia.
Architect: LAB Architecture Studio



Nordpark Cable Railway, Innsbruck, Austria. Architect: Zaha Hadid Architects

walkways, canopies and glass floors as the primary examples of their use. Most applications have additional mechanical fixings to overcome concerns about the long term durability of all-glass structures, but this varies from project to project. An alternative to the all-glass structure is the cladding of conventional structures or walls in opaque rainscreens. This method uses screen printed glass which is typically silicone bonded to a backing frame, then hooked on, or fixed back to, a carrier frame behind. This use of glass as an external rainscreen allows the void between the glass and the external face of the backing wall to have lighting, creating a glow to an otherwise opaque or utilitarian facade, with the benefit of creating some lighting for safety of users around the building.

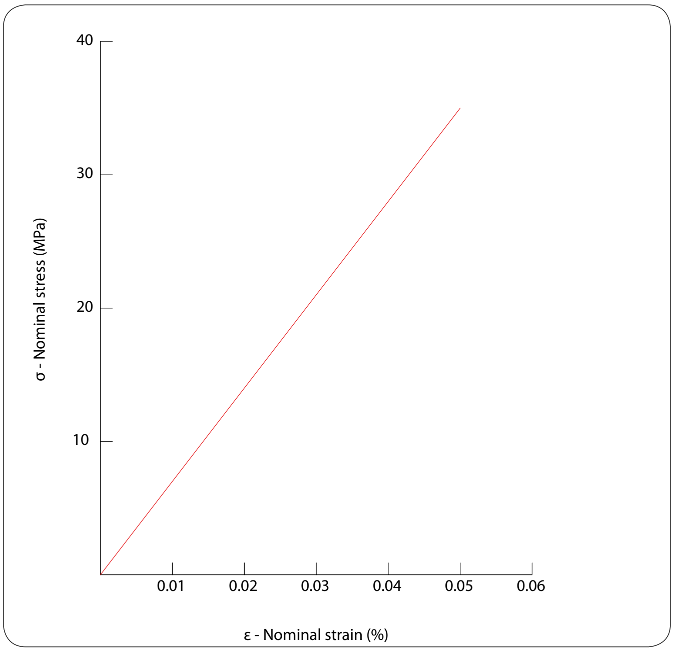
One of the main changes in the use of glass in facades and roofs is a gradual move away from entirely rectilinear glass panels to those that deviate slightly from it. These can range from parallelogram shapes to triangular to diamond patterns in glazed facades, but all are based on the need for repeatability of glass unit size in order to make the glass economic to manufacture. In addition, glazed walls are required to move in relation to their supporting structure, and must be able to move from one panel to the next. This further encourages the panels to be of the same size in order to ensure that the movements have a consistent 'behaviour' of movement across the extent of the walls. Some projects, particularly for glazed roofs, have used a large number of glass panel sizes in order to suit the structural geometry of the roof form, but these are typically quantified in detail by the design team in order to control cost.

A recent alternative to the curving of glass as part of the manufacturing process has been to 'cold bend' glass sheets on site, typically as part of a stick (site assembly based) glazing system. The amounts to which the glass can be pushed at the corners to take up a curved form across its surface is limited, but curves in glazed walls and roofs are often modest, making the idea of cold bending more attractive to contractors.

Production process of raw material

The manufacture of float glass is the first stage of production. Float glass is made by pouring molten glass onto a bath of molten tin. The glass floats on top and is drawn off as it solidifies. It is available in thicknesses ranging from 2mm to 25mm (1/8in to 1in).

Most float glass has a green tint caused by small amounts of iron oxide in the glass. Adding different oxides to the mix during the manufacturing stage can alter the tint of the glass.



Glass stress strain diagram

Oriente Station Lisbon, Portugal.
Architect: Santiago Calatrava

The City of Arts and Sciences in Valencia, Spain.
Architect: Santiago Calatrava

City of Arts and Sciences, Valencia, Spain.
Architect: Santiago Calatrava

Properties and data
Density: Float glass = 2500 kg/m^3 (156 lb/ft^3)
Tensile strength: Float glass = 45 N/mm^2 (9.4×10^5 lbf/ft^2)
Compressive strength:
Float glass = 130–250 N/mm^2 (2.7×10^6 to 5.2×10^6 lbf/ft^2)
Young's Modulus:
Float glass = 70 kN/mm^2 (1.4×10^9 lbf/ft^2)
Coefficient of thermal expansion = 9×10^{-6} K^{-1} (5×10^{-6} F^{-1})
Thermal conductivity = 1.1 W/m°C (0.64 BTU/hr.ft.°F)
Specific heat capacity = 840 J/kg°C (0.20 BTU/lb °F)

Approximate and easily available maximum glass sheet sizes
1) Float glass
Maximum size 3180 x 6000mm (125in x 235in) for thicknesses from 2mm to over 25mm
2) Clear toughened glass
Maximum size 4200 x 2000mm (165in x 80in) for thicknesses from 6mm to12mm
3) Laminated glass
Maximum size 3180 x 4200mm (125in x 165in) for thicknesses from 4.4mm to 9.8mm (3/16in x 3/8in)
4) Rough cast wired glass
Maximum size 3700 x 1840mm (145in x 72in) for thickness 7mm (1/4in)
5) Polished wired glass
Maximum size 3300 x 1830mm (130in x 72in), thickness 6mm (1/4in)
6) Body tinted float glass
Maximum size 2540 x 4600mm (100in x 180in) for thicknesses from 6mm to12mm
Glass block sizes for external walls:
146 x 146mm (nominal 6in x 6in)
197 x 197mm (nominal 8in x 8in)
197 x 95mm (nominal 8in x 4in)
Typical thickness 98mm (nominal 4in)
Glass block sizes for internal partitions:
120 x 120 x 40mm (nominal 6 x 6 x 1 3/4in)
and 200 x 200 x 50mm (nominal 8 x 8 x 2in).

The characteristics common to different glass types are:
- Variable tensile strength.
- It is prone to fracture resulting from tiny cracks or imperfections.
- Variable impact resistance.
- Non-corrosive.
- Non-combustible.
- High heat conduction.
- Low thermal expansion.

Material selection
Heat soaked glass is made by re-heating float glass then cooling it quickly, which puts the surface of the glass into compression and removes impurities such as nickel sulphide. When broken, fully toughened glass disintegrates into tiny, comparatively harmless, pieces. Its strength, measured in terms of impact resistance, is up to five times that of float glass. The toughening process can produce minor distortions in the glass, usually caused by roller marks. Heat soaked glass is a partially toughened glass for use where full toughening is not required or as part of a laminated glass construction.

Laminated glass is made by bonding two or more sheets of glass together with a film of plastic in between, called the interlayer. The interlayer can be clear or translucent, and is available in a wide range of colours to create effects of colour in the glass that are translucent in a way which is different from the screen printing of glass. When broken, laminated glass stays together in a single piece due to this bonding between the layers. This makes it very useful for glazed roofs and for glazed screens which are set forward of glazed facades. However, after the initial impact, laminated glass will eventually fall away as dangerous fragments of glass, so it is required to be replaced as soon as possible, with

Metropolitan Cathedral, Brasilia, Brazil.
Architect: Oscar Niemeyer

Oscar Niemeyer Museum, Curitiba, Brazil. Architect: Oscar Niemeyer

Nordpark Cable Railway, Innsbruck, Austria.
Architect: Zaha Hadid Architects

the floor area beneath the broken panels typically being secured to avoid the risk of injury to those below. Combining several laminates together in one sheet can make anti-vandal and even bullet resistant glass.

Wired glass is made by sandwiching a steel wire mesh between two layers of glass, which are then rolled flat. The wire holds the glass together for a period of time during a fire and so prevents the passage of smoke from one side to the other. The roughcast product can be polished to provide a more transparent finish. Wired glasses cannot be toughened and are not regarded as safety products.

Fire resistant glass is formed by glass sandwich panels containing an intumescent layer. In a fire the layer of gel, or salts, reacts to the rise in temperature to provide a degree of insulation against radiant heat.

Variable or switchable transmission glass is a new form of treated glass. Though expensive, it aims to reduce internal heat loss from inside as well as to reduce solar gain. It is able to change its own thermal and light transmission performance by means of an electrical signal. In many applications, it turns from transparent to an opaque white when an electric signal is introduced. Applications include glazed partitions in office buildings.

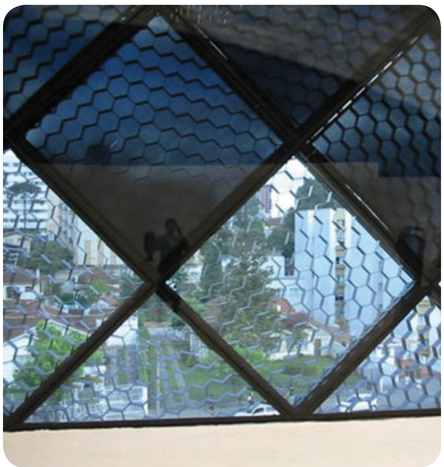
Glass blocks can be solid or hollow. Solid blocks are used as paving for floors. The hollow type is used for walls and consists of two half-bricks fused together to give a smooth appearance on both faces.

Glass can be mounted in double- and triple-glazed units to provide greater thermal insulation and sound insulation than is achieved by an equivalent single sheet of glass. An insulated unit can be a mix of float, laminated or other glasses. To improve thermal performance, the air gap between the layers can be evacuated to create a vacuum or be replaced with a low conductivity gas such as argon. The maximum size of double glazed units is determined by the maximum sizes of glass types used. However, the size of unit is usually determined by windloading rather than maximum glass sizes.

Working with the material

Float, toughened and laminated glass can be curved. Flat glass is heated and moulded to shape in either one or two directions. Float glass can be cut, drilled, screwed and glued. It can also be bolted using proprietary systems. Toughened glass cannot be

Oscar Niemeyer Museum, Curitiba, Brazil. Architect: Oscar Niemeyer



Oscar Niemeyer Museum, Curitiba, Brazil.
Architect: Oscar Niemeyer

Lyon-Satolas TGV Station, Lyon, France. Architect: Santiago Calatrava

BCE Place, Allen Lambert Galleria and Heritage Square, Toronto, Canada
Architect: Santiago Calatrava

cut, drilled or surface worked after manufacture but laminated glass can be drilled with specialist equipment.

Surface and body treatments

Float, toughened and laminated glass can be further treated to allow varying levels of light transmission and thermal insulation. Sometimes this is done during the manufacturing process. These treatments are body tinting, screen-printing, sand blasting and acid etching, coatings, including low-E and fritting, and curving.

Body tinted glass is produced by small additions of metal oxides to the glass, reducing solar gain. A limited range of tints is available, including shades of green, grey, bronze and blue.

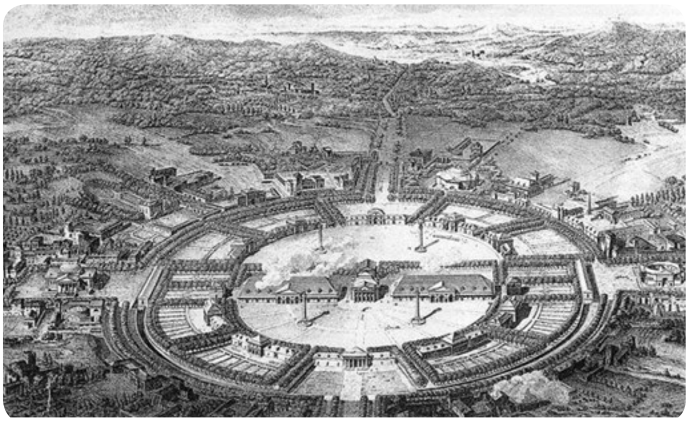
Fritted glass is made by printing ceramic designs onto float glass, which is then toughened. This process involves fusing coloured frit (powdered glass), through a stencil onto the surface of the glass, providing a permanent durable finish. This treatment can be used to help reduce solar gain. Surface printing with a high level of detail can be achieved by screen-printed dots, lines or meshes.

Sand blasting and acid etching are surface treatments which produce a uniform, matt translucent finish. The microscopically pitted surface has a tendency to retain dirt and grease, making it difficult to clean.

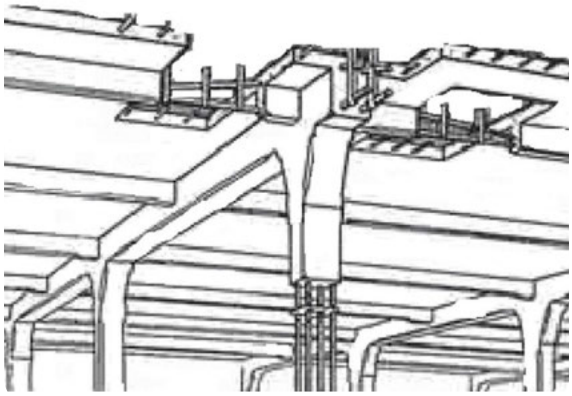
A low-emissivity coating (low-E) is applied to glass to improve its thermal insulation. The coating is a microscopically thin layer of metal which allows maximum daylight and short-wave heat to enter the building but reduces heat loss by reflecting long wave radiation trying to escape at night. The coating is hardly visible.

Recycling

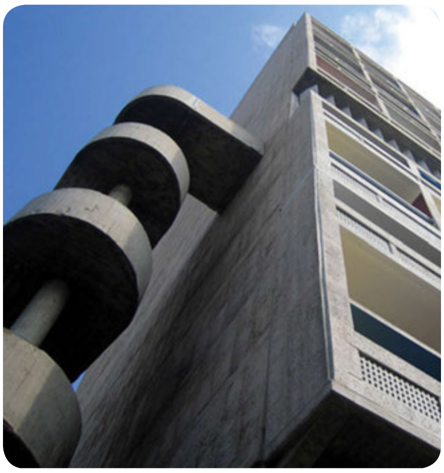
Glass is one of the easiest materials to recycle and is economically viable. Enormous energy savings in glass manufacture can be made by recycling the material.



Claude Nicolas Ledoux: the Ville de Chaux, France



François Hennebique



Unité d'Habitation, Marseille, France. Architect: Le Corbusier

De la Warr Pavilion, Bexhill, U.K. Architect: Erich Mendelsohn and Serge Chermayeff

Concrete had been used for over 2000 years before advances were made during the 19th century with the development of reinforced concrete, a technique that involved incorporating metal rods to compensate for the inherent weakness of the material in tension. François Hennebique constructed in 1892 what is thought to be the first building with a reinforced concrete frame. Ernest Ransome patented a similar system in the US in 1895. By the beginning of the 20th century, in Europe and in North America, iron rods and wires were being used as reinforcement in patented floor systems and structural frames. Modern reinforced concrete is essentially a development of these systems.

An essential quality of concrete is that it is a moulded material, capable of creating large-scale monolithic forms without joints in the material. This essential quality was hinted at much earlier, the work of Claude Nicolas Ledoux in the late 18th century demonstrates an intent in architectural expression through abstracted forms that represent 'functions' of the building or the functions of the principal uses of the building. His book Architecture considérée sous le rapport de l'art, des moeurs et de la législation sets out a vision of the architect as providing a visible structure of a society where status is accorded to 'functions' in society rather than power or wealth. The Water Inspector's House expresses the function of its occupier, with river water passing through the building. The form shown in the drawings is monolithic, with little expression of the material used. There is no visible detailing; the monolithic expression of the building forms seem to relate more to military installations of the time than to the language of public buildings. The window openings are small and seem only to emphasise the visually massive quality of the walls. While the material used for the buildings is not clear from the drawings, stone-faced loadbearing masonry would probably have been used as the material system of the time. However, the monolithic forms are very much in tune with concrete; large flat areas with no registration of joints or traces of the way the building would be constructed. It looks as if no evidence of the construction method should be visible in order not to detract from the architectural messages in the form of the building concerned with expressing the intended use of the building. Another drawing shows a design for a cemetery with a shell structure in the centre of an unspecified construction. This could have been achieved 150 years later in concrete, as seen in the work of Eero Saarinen and Santiago Calatrava. Ledoux built on examples of his vision at the Ville de Chaux using primary geometric forms with columns and rusticated stonework. The idea of the architect as giving visible form to the function of society in monolithic architectural form was later taken up by Le Corbusier, as seen in his design for the chapel at Ronchamp.

The evolution of concrete as a building material was the result of a 'rediscovery' of the material primarily as a mortar in engineering projects, but to its eventual use as a structural material used with first arches and then for floors, columns and then as a full structural frame. Joseph Monier's system of using steel reinforcement in a systematic manner, first seen in 1867, was a development of earlier mixes of metal and concrete that

The Centennial Hall, Wroclaw, Poland. Architect: Max Berg

The Centennial Hall, Wroclaw, Poland.
Architect: Max Berg

The Pantheon, Rome, Italy.

The Niterói Contemporary Art Museum, Brazil.
Architect: Oscar Niemeyer

themselves probably evolved from the metal rods and brackets used as tension members in timber and masonry structures that go back to at least the reinforced metal hammer beam roof of the Palace of Westminster Hall in London, built in the late 14th century. Francois Hennebique's reinforced concrete system developed this concept into full reinforced concrete with a system patented in 1892. The nature of reinforced concrete is such that its method of construction is not visible, except for the marks left by the formwork which can be either expressed or concealed; but the formwork is removed, with the boards or sheets being used only once or twice before being discarded after use. Hennebique's system, now so familiar to us, uses a web of steel reinforcement which is never visible but which has a high degree of elaboration and visual character prior to it being concealed within concrete. The benefit of concrete as having a high level of fire protection has added to the popularity of this material. However, concrete was still used as a substitute for masonry and timber construction, with its rectilinear forms.

An example of the use of concrete as a material in its own right, rather than imitating the language of an earlier technology is the Centennial Hall in Wroclaw, designed by Max Berg and completed in 1913. The building has a roof that begins to exploit the sculptural possibilities of concrete: the architect was influenced by, among others, the unbuilt projects of Ledoux. The base structure that forms part of the ring beam for the dome above is curved in three dimensions, and shows the possibilities of construction which were followed up in later concrete shell structures. The dome is formed with inclined sculptural ribs on which are set vertical members, which in turn support horizontal decks that provide both horizontal ribs to stiffen the inclined members as well as serving as ring beams for lateral stability. This structure seems to support vertical windows to withstand the rain and snow of the harsh winters. This structure begins to exploit the possibilities of structure of enclosing spaces without the rectilinear imperatives of masonry and timber construction where walls, structure and enclosure are made from concrete as a single material. A steel frame would require infill of the lower arched structure and of the roof decks circling the dome in a different material, which results in a loss of clarity of the architectural idea of sculpting structural forms; ideas which would later be developed by Santiago Calatrava.

In about the same year as the Centennial Hall in Wroclaw was the Dom-ino concept of structure by Le Corbusier. The idea is essentially a reinforced concrete structure of flat slab supported by columns, a method that was not in general use until the 1990s when reinforcing methods made economic the junction of slab and column. Unlike Le Corbusier's later celebrated concrete structure of the chapel at Ronchamp, the external walls are formed from another material, which would typically be a combination of concrete and glass. The diagram of the Dom-ino structure is clear, but the bands of glazing, running either vertically or horizontally, with an infill of rendered blockwork are independent of the system. Le Corbusier's idea of a structural grid with constructed objects set within it and which contrast with the grid, seems to connect very strongly with the Dom-ino concept. The gesture and grid contrast of forms is still

Notre Dame du Haut Ronchamp Chapel
France. Architect: Le Corbusier

The Guggenheim Museum, New York, U.S.A.
Architect: Frank Lloyd Wright

The Guggenheim Museum, New York, USA.
Architect: Frank Lloyd Wright

visible at Ronchamp in three of the external walls with an overall form described by the floor plane.

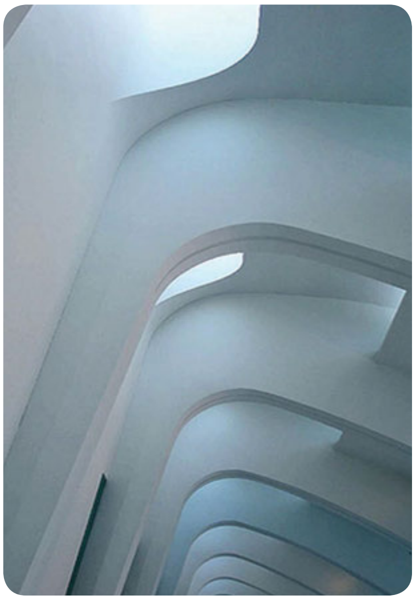
The Guggenheim Museum in New York, completed in 1959 and designed by Frank Lloyd Wright, exploits the cast nature of concrete to create a single spatial form of external walls and floors and follows in the tradition of Ledoux of highly modelled form that creates a clear visual impression of the idea without the visual language of a visible building assembly. An example of a roof based structure where the sculptural abilities of concrete are used is the Xochimilco Restaurant in Mexico City by Felix Candela. This form, based on hyperbolic paraboloids, was formed using straight lengths of timber board for the formwork, allowing a complex form to be created with very simple formwork that required no specialist carpentry skills, since the formwork was not required to be curved. The concept of the concrete shell was developed in the TWA Terminal by Eero Saarinen. In this building the sculptural possibilities of concrete are extended to internal floors, staircases and partition walls, with internal fittings of information desks and counters being designed as miniature building forms in their own right. The building could have been formed using inflatable formwork; its intersecting vaults would have lent themselves to inflatable structures. In many ways the constructed building is itself almost a virtual form of an inflatable building, the concrete describing the forms which could be achieved by plastics and fabrics, and can be seen as a 'frozen' idea of invention in building construction yet to come.

The work of Santiago Calatrava takes a different turn to that of Eero Saarinen. Where the TWA Terminal uses a series of intersecting vaults that are formed as concrete shells, projects such as the Science Park at Valencia are formed as framed and arched structures from a series of sculpted ribs. Rather than the vaulted aesthetic of a single material system of TWA, the Valencia building uses glass as an enclosing material which avoids the need to add layers to an equivalent concrete shell. The use of bolt fixed glazing with steel supporting ribs linked back to the concrete ribbed structure creates an approach of mixing materials where the concrete frame and the glass enclosure are part of a single idea of using animal skeletons as a metaphor for the design. Calatrava's interest in anthropology led him to consider the relationship of bone and muscle to use two materials in an interdependent way rather than the more straightforward 'layered' approach of traditional construction. This approach can also be seen in Calatrava's bridge structures, where steel is used as a material separate from the reinforcement linking concrete elements rather than being only within the concrete as reinforcement. In the bridges, the tension qualities of steel reinforcement are brought out of the concrete as steel components in their own right. Of course, the concrete is still reinforced, but steel is also used as a component with other functions rather than being only buried in the concrete. Calatrava's interest in animal skeletons and the lessons that can be drawn from them for use in building design can be seen in his proposal for the Cathedral in New York where the sculptural possibilities of concrete, together with their ability to be made into large scale components, is clearly visible in the design. These ideas have found their way into Calatrava's single designs for glazed roofs such as the Milwaukee Art Museum. The Milwaukee additions form an extension of an earlier project by Eero Saarinen. Where Saarinen's project is essentially rectilinear, with identical sculptural elements used in bays to create what is essentially an extruded structure, Calatrava uses a similar discipline of geometry to create more complex forms, but with his characteristic interest in bringing daylight from roof lights and creating varying effects of daylight.

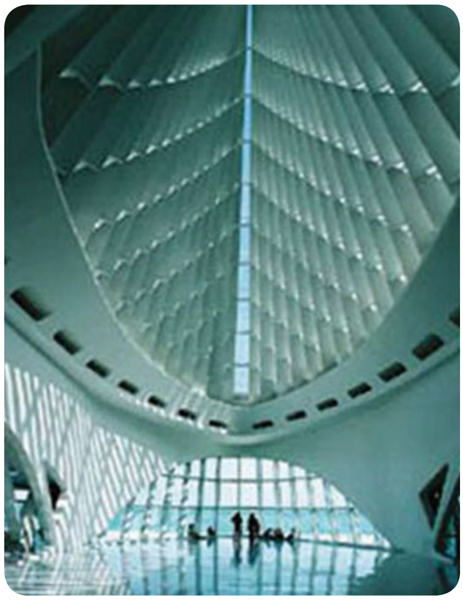
Properties and data

The main properties of concrete are as follows:
Density:
Concrete with dense aggregate:
2200 to 2600 kg/m^3 (137 to 162 lb/ft^3)
Concrete with lightweight aggregate:
320 to 2000 kg/m^3 (20 to 125 lb/ft^3)

TWA Terminal, JFK Airport, New York. U.S.A.
Architect: Eero Saarinen



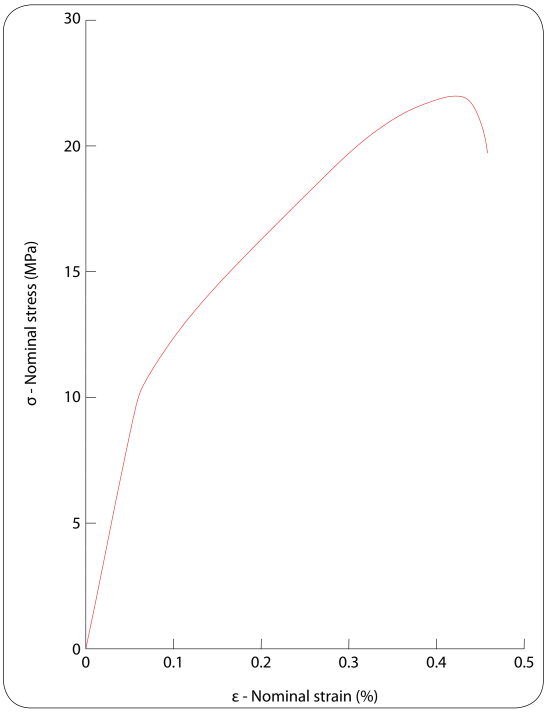
Milwaukee Museum of Art, U.S.A.
Architect: Santiago Calatrava



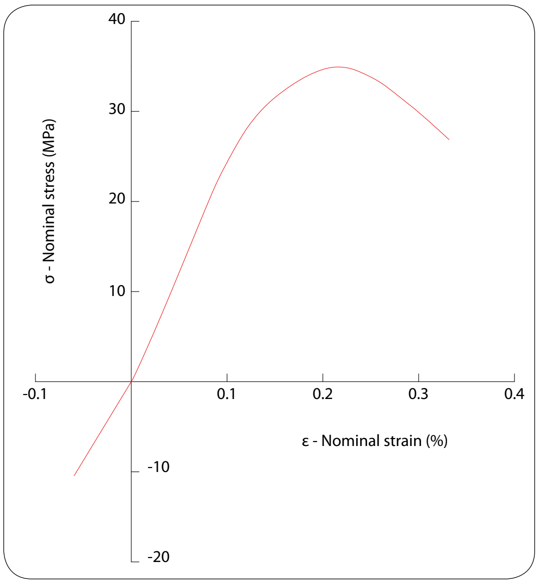
Milwaukee Museum of Art, U.S.A.
Architect: Santiago Calatrava

Design strength = 35 N/mm^2 (7.3 x 10^5 lbf/ft^2)
Young's Modulus = 15 to 30 kN/mm^2 (3.1 x 10^8 to 6.2 x 10^8 lbf/ft^2)
Coefficient of thermal expansion =12.0 x 10^{-6} K^{-1} to 7.0 x 10^{-6} K^{-1}(6.7 x 10^{-6} to 3.9 x 10^{-6} F^{-1}) reducing with age.
Thermal conductivity:
Concrete with dense aggregate = 1.0 - 1.8 W/m^{o}C
(0.58 to 1.04 BTU/hr.ft.^{O}F)
Concrete with lightweight aggregate = 0.4 - 0.7 W/m^{o}C
(0.23 to 0.4 BTU/hr.ft.^{O}F)
Specific heat = 840 J/kg^{o}C (0.20 BTU/lb ^{O}F)

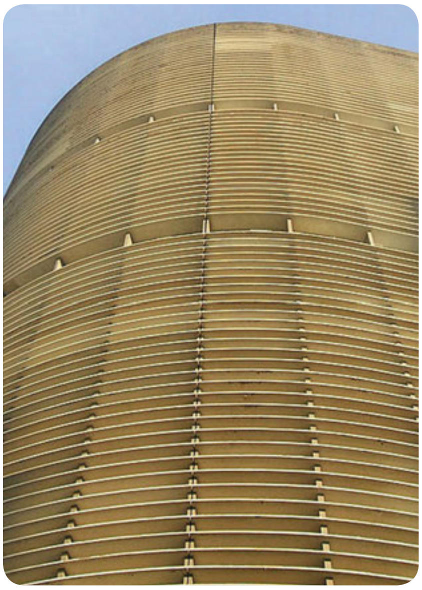
Concrete has the following properties:
- Easily moulded.
- High strength in compression.
- High acoustic insulation for both airborne and structure-borne sound.
- High fire resistance, but appropriate cover to steel reinforcement is needed.
- Most shrinkage of the material occurs, as creep, during the first year after casting.
- Moisture movement occurs but is less significant than timber.
- Slightly permeable to water.
- It will not set properly if the air temperature approaches freezing point. If the air temperature is too high, it will set too quickly, causing cracking.



GRC stress strain diagram



Concrete stress strain diagram



Copan Building,, São Paulo, Brazil.
Architect: Oscar Niemeyer

Copan Building,, São Paulo, Brazil.
Architect: Oscar Niemeyer

Xochimilco Restaurant, Mexico City.
Architect: Felix Candela

Material selection

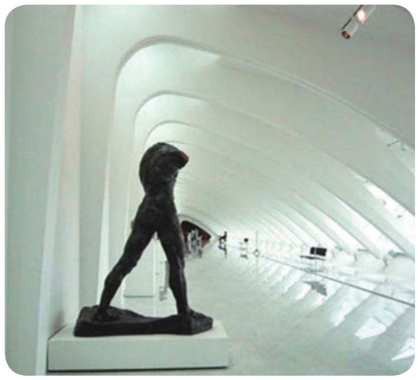
Concrete is a dense material, composed of cement and aggregate mixed with water. It sets to form a hard, brittle material, strong in compression but weak in tension. Portland cement is the most widely used binding agent for concrete and consists of lime and clay mixed together at high temperature, which is then crushed to form a fine powder.

The type and relative proportions of cement and aggregate will vary according to use and desired appearance. The mix should make economic use of the cement. Varying the composition of the constituents produces different strengths of concrete. The most important factors are the water to cement ratio and the proportion of cement to aggregate. A typical mix is the 1:2:4 (cement: fine aggregate: coarse aggregate). The amount of water used in the mix affects both workability and strength. Less water increases strength but reduces the workability, making it more difficult for the concrete to flow around the reinforcement when it is being poured in place. The reduced workability is improved by using additives, such as plasticisers, to the mix. The coarse aggregates, consisting of small stones, form most of the mass, while spaces between these stones are filled by fine aggregate and cement which bind the mixture together. It is important when pouring concrete, that the mixture is properly vibrated to ensure that the coarse aggregate is fully surrounded by the finer material.

Concrete shrinks as it dries, and can take more than a year to reach its final size, though it continues to shrink indefinitely by tiny amounts. The rate of shrinkage is considerable in the period immediately following the pouring, but slows down by the end of the first year. After approximately 28 days, concrete approaches its design strength. It is important that the mixture should not dry out too quickly to enable the chemical reactions between the constituents to take place. Controlling the drying process is known as 'curing'. Having dried out, concrete subsequently absorbs water, but any expansion is always much less than the original shrinkage during the curing process. Plasticisers can be used to vary the rate of drying, which reduces construction time. Plasticisers also increase the workability of the wet concrete.

In reinforced concrete, steel and concrete are combined to take advantage of the compressive strength of concrete and the tensile strength of the steel used. Two types are used; mild steel reinforcement is used to form complex elements and has a yield-strength of around 250N/mm^2, and high yield reinforcement is used elsewhere with a yield-strength of around 460N/mm^2. As the concrete sets it shrinks, gripping the steel bars thus producing a monolithic structural material for use as frames, walls and floors. These can be cast-in-place at the site, or off-site as precast elements. With either method, the cost of formwork or mould can represent up to half of the cost, and therefore the efficient use and re-use of formwork is essential.

Opera House, Valencia, Spain. Architect: Santiago Calatrava.



Milwaukee Museum of Art, U.S.A.
Architect: Santiago Calatrava

Concert Hall of Santa Cruz de Tenerife, Spain.
Architect: Santiago Calatrava.

Stadelhofen Station, Zurich, Switzerland.
Architect: Santiago Calatrava

Cast-in-place reinforced concrete is usually delivered to site ready mixed and is poured either by pumping or by crane bucket. Cast-in-place reinforced concrete is made by setting steel reinforcing rods, often in the form of a cage, between formwork, made from plywood, steel or timber boards. Wet concrete is poured and compacted. The reinforcement must have an appropriate cover of concrete to protect it in the event of fire. The cover also protects the steel from corrosion.

A series of bolts holds the sides of the formwork apart and shoring on the outside of the formwork supports the weight of the wet concrete. The formwork is removed, or struck, after 3 to 4 days and the holes left behind are filled with grout, which is a mixture of cement and water. Since the holes remain very apparent, they are arranged at regular centres in order to enhance their appearance.

The technique of manufacturing precast concrete, developed in the 1950s, has the advantage of a reduced construction time as no curing, and much reduced formwork, is needed on site. Concrete is cast in moulds in a factory, and then delivered to site. Precast techniques have two main advantages over cast-in-place construction. The first is that quality can be easier to control in a workshop, and the second is that precast elements can be assembled rapidly on site. Cast-in-place concrete needs time to gain strength before it can support another element and this slows down construction dramatically.

Precast concrete is usually more expensive than cast-in-place due to additional transport costs. To be economic, and comparable in cost with cast-in-place construction, the number of different components should be kept to a minimum because fewer moulds, prototypes and trial panels would be used. On larger projects, it may be cost-effective to manufacture precast components on site in a temporary facility. This avoids the need to transport components, though such conditions may not be ideal for high quality work. Precast concrete systems are manufactured as proprietary systems for both structural frames and wall cladding panels. There is a significant move towards re-using the formwork from one application to the next.

Components are cast in moulds which are made from glass reinforced polyester, steel or concrete. Accurate manufacture is difficult with plywood and timber due to the thermal movement of these materials, making the mould sizes unreliable. Panels are cast either face-up or face-down. In face-down casting the inside surface of the mould forms the component finish. In face-up casting the surface of the mould forms the back of the component so that structural ribs can be formed, leaving the panel face flat. An alternative method, which avoids complex formwork, is tilt up construction. This is a partially precast method where a wall is cast flat on the ground at the site, directly adjacent to the floor slab. Once it has cured sufficiently, it is then lifted up into the vertical position and bolted directly in place.

Phaeno Centre, Wolfsburg, Germany.
Architect: Zaha Hadid Architects.

Phaeno Centre, Wolfsburg, Germany. Architect: Zaha Hadid Architects.

Prestressed concrete is a precasting technique that is typically used in floor structures. It allows increased clear spans to be used with thinner slabs resulting in lighter structures. The reduced cracking and reduced deflections in this technique are a distinct advantage over normal reinforced concrete. In common with other precasting techniques, this rapid construction method allows construction times to be reduced.

In prestressing, high strength steel wires, rods or cables are passed through a small diameter tube set into a precast component, typically a beam or a tee-section used as a structural deck. The wires, set in the bottom half of the beam, are tensioned at the ends, resulting in the beam or tee arching up in a slight camber. The tubes are then filled with grout. When the prestressed component is set in place, the imposed loads flatten the pre-camber and reduce the deflection experienced by the component.

When an ordinary reinforced concrete beam is loaded, compression is created in the top half of the beam and tension in the bottom part. The compressive stresses in the concrete created by the tension wires must be overcome before the beam bends. However, when a prestressed beam or similar component is loaded, the concrete is in compression throughout its depth, allowing it to be shallower in depth than a reinforced concrete equivalent. Prestressed concrete is more suitable for large spans than ordinary reinforced concrete because components can be shallower and as a consequence be lighter, reducing the dead load. Prestressing increases resistance to shear forces compared to a reinforced concrete beam, making it possible to achieve a more slender section than using cast-in-place techniques.

Where these components are too large to be prestressed, or where the construction method dictates that they are to be built on site, the technique of post-tensioning can provide a similar method of reducing the depth of beams, decks or related assemblies such as masonry arches. Although this technique is used mainly in bridge-building, post tensioning allows individual large-scale components, such as frames and floors, to use prestressing techniques with a site-based construction method. Post tensioning is more suited to large assemblies such as arches and long-span floor decks than to smaller-scale assemblies where the time needed on site to effect the tensioning would slow down the speed of construction.

Lightweight concrete is used primarily for toppings in profiled steel/concrete composite construction. It is also used for non-loadbearing components such as precast wall panels. It is not used for high strength applications, but is suitable for most structural applications where weight is an important consideration. The material is typically made from crushed pumice or clinker, giving it better properties of heat and sound insulation than cladding panels made from other materials.

Ferro-cement is a concrete-based material which is typically used to make yacht hulls. This material is beginning to be used as a structural material in buildings, and is suited to complex shapes with a high quality smooth finish. A recent example is the curved roof trusses of the Menil Museum in Houston,

Precast concrete components being made with steel moulds in a factory setting.

Texas, U.S.A Ferro-cement consists of a cement mortar-based mix with a high degree of steel reinforcement. It has good tensile strength in thin sections. Complex shapes can be formed by applying the wet mix onto a steel mesh by hand without the need for formwork.

Working with the material

Concrete is compacted by vibration when poured in order to remove air voids in the mix and to achieve an even distribution of the material in the formwork. Too little compaction of the wet material can result in air pockets being left in the mix, weakening the concrete. Too much compaction brings the fine aggregate to the surface, making the surface crumbly, and causing surface staining. A vibrating instrument, inserted into the wet concrete, is used to ensure an even consistency. The reinforcement is given an adequate cover of concrete to protect it in the event of fire. The cover also reduces the possibility of water reaching the steel which can cause it to rust. In the manufacture of precast components the mould is typically compacted, either by placing it on a vibrating table or by applying a surface mounted vibrator.

Finishes

Concrete adopts the texture of the formwork. Steel formwork leaves a smooth appearance while softwood boards leave an imprint ranging from fairly smooth plywood to rougher finishes of planks. Boarded formwork produces a pattern of joints across the concrete face. Other finishes include tamping, where a board is moved in a tapping action across the surface of the concrete to form a directional texture; trowelling, where concrete is smoothed with a hand tool; and power floating, where a poured slab is smoothed with a machine to provide a finish that avoids the need for an additional layer of smooth screed.

The fine aggregate and cement determine the colour of the concrete. Changing the attributes of the fine aggregate has a dramatic effect on the appearance of the concrete, whereas large aggregate has little effect unless retardants are used and the large aggregate is exposed. Colour additives can also be added to the mix. Unfortunately, slight variations in the proportions of additives have a dramatic impact on the appearance of the concrete, making it hard to achieve consistent coloration between batches.

Paint provides a thin decorative layer, but is prone to flaking and requires re-coating at regular intervals. Colour stains are an alternative as they are absorbed by the top surface of the concrete forming a permanent coloured finish. Sand blasting and acid etching, processes more commonly associated with glass, can also be used. Bush hammering the material exposes the large aggregate and provides a rough texture to the surface. Conversely, polishing provides a smooth shiny surface. However, both of these surface treatments are very labour intensive. Unpolished concrete has a dusty surface and it may be appropriate to seal the surface.

Recycling

Concrete can be recycled by crushing the material and using it as an aggregate in new concrete. Although the use of recycled concrete is new, it has been successfully used in new reinforced concrete structures.

Corpus Christi, Cambridge, U.K.

Bristol Cathedral, Bristol, U.K.

Oriel College, Oxford, U.K.

St George's Chapel, Windsor Castle, Windsor, U.K.

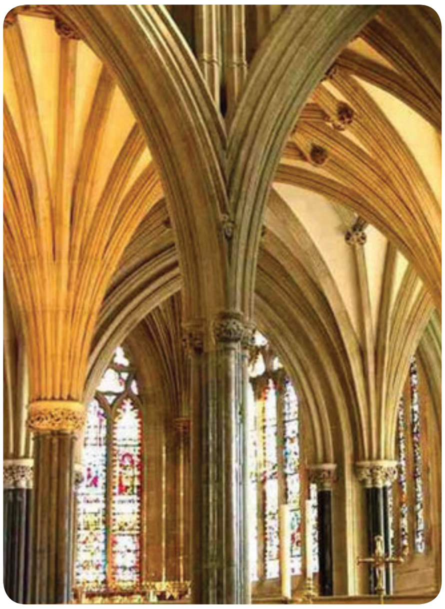
The pre-industrial use of masonry was as a loadbearing material that integrated structure and facade into a single construction that was capable of taking up complex geometric forms, such as those used in castles and later in medieval houses across Europe. In addition to their ability to form complex shapes in plan, masonry has the ability to corbel outwards or inwards from the vertical plane of the wall through their height to create a more complex section than that of vertically set walls. A 20th century example of this principle was used in Antonio Gaudi's work on the Sagrada Familia in Barcelona. This use was in parallel to the emerging use of cavity walls at the time for houses built in England.

In cavity wall construction, the loadbearing wall is divided into two separate halves, and linked structurally to form a diaphragm wall; a construction that uses less material to achieve the same purpose. A disadvantage is the need to extend floor plates through in order to make the wall perform structurally as a diaphragm wall, which results in a thermal bridge that can cause high levels of heat loss (or heat gain in hot climates) and associated condensation risk. Consequently, the outer leaf of the cavity wall became isolated from the construction behind, except at fixing or restraining points as is the case with stone cladding. The resultant use of cavity walls as an outer protective screen has robbed it of any real significance in the construction.

The use of masonry in Gothic cathedrals as loadbearing structure and enclosure continued on, almost uninterrupted, in built examples across England. The college buildings of the universities of Oxford and Cambridge contained Gothic elements of construction through the Renaissance, with a gradual re-introduction of Gothic language emerging in follies to English country houses built during the 17th and 18th centuries. The Gothic revival of the 19th century, which associated the architecture and its associated forms of construction with renewed spiritual values, introduced the use of iron into forms previously constructed entirely in masonry. Buildings such as the Oxford Museum in England combined medieval methods of loadbearing masonry construction and their re-interpretation as glazed vaults of iron ribs into a single building. The ability to mix different loadbearing structures gives a structural continuity between building elements and also between building forms, as seen in the city centre of Oxford, where there is a continuity of constructional language from door to wall to building to city block to street.

The move from masonry used in loadbearing structures to its use almost entirely as non-loadbearing cladding came in the early 20th Century with the introduction of steel and concrete frames, initially intended for taller buildings but soon becoming the standard method of construction for all but small residential buildings, with the outer walls becoming non-loadbearing and

St John's College, Cambridge, U.K.



Wells Cathedral, Wells, U.K.

Bristol Cathedral, Bristol, U.K.

Westminster Abbey, London, U.K.

roofs using the full extent of the structural frame for support.
A trend in the past 30 years has been the introduction of thermal insulation into masonry construction as well as a layer of weatherproofing when a cavity is introduced. This has resulted in much masonry construction becoming an outer rainscreen, either as cladding panels of stone, or as the outer skin of a cavity wall. In some cases, loadbearing walls have had the insulation set in the centre of the wall, with the two halves of the construction linked by stainless steel ties to provide structural continuity through the full thickness of the loadbearing wall. The Glyndebourne Opera House in England, designed by Michael Hopkins and completed in 1994, has no thermal insulation but is fully loadbearing. Loadbearing brickwork is used to form the external wall and gallery for the opera house auditorium. Lime-based mortar was used to avoid the cement-based mortar associated with high strength, but the need for vertical movement joints at typically 7.5 metre centres. These joints have the effect of dividing an external wall into separate bays, making a single monolithic wall almost impossible to achieve. Because of the loadbearing strength of lime mortar being approximately half that of cement-based mortar that would have been required for this project, the walls were thicker but, at one and a half bricks thick, are no wider than an equivalent cavity wall, but with piers which are two bricks thick. The avoidance of movement joints assured the monolithic appearance and structural efficiency of this structure.

In other applications of loadbearing masonry, the positioning of the thermal insulation in the centre of the wall allows the benefits of thermal mass to be used within the building as well as a weathering surface on the outside, along with the possibility of the masonry being exposed within the building.

The use of loadbearing masonry has found limited applications due to the perceived disadvantages of setting thermal insulation on the inside face of the wall, reducing its thermal mass. Consequently, masonry is used mainly as cladding to a backing wall which is typically insulated on its outside face in order to benefit from the thermal mass of the wall within the building, with the additional advantage of being able to fix interior items such as shelving to the inside face of the wall. A disadvantage of the use of masonry is its lack of relationship with the real building immediately behind the outer skin. As an outer veneer, its relationship to the structure and enclosure of the building is largely a matter of individual aesthetic choice. Since cladding panels can be large in size, up to around 700mm x 1400mm for granites and stronger sandstones, the relationship with historical context is severely limited.

The contemporary use of loadbearing construction provides an opportunity to provide thermal mass in facades as well as in that provided by adjacent floor construction. When informed by structural requirements linked to either a historical typological

Trinity College, Cambridge, U.K.

Magdalen College, Oxford, U.K.

Market Cross, Chichester, U.K.

George Hotel and Pilgrim's Inn, Glastonbury, U.K.

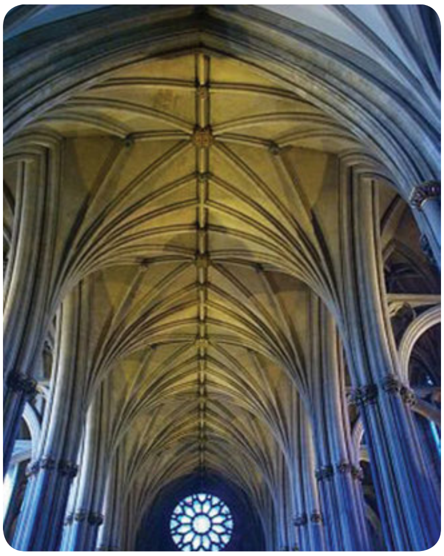
model, or spatial sequence, the material system suggests ways of enclosing space that creates an architectural expression specific to the requirements of the building. In the case of masonry, which forms the historic fabric of English towns and cities. This use of masonry would provide a continuity with the past but would be able to have a more dynamic and progressive relationship with historic fabric as is achieved in the buildings of Antonio Gaudi in Barcelona. Loadbearing brickwork was used in larger scale buildings by Louis Kahn in the Indian Institute of Management of1962, and where the brickwork is used as 'cladding' Kahn expressed its sense of separation without reducing its quality of visual massiveness. Kahn in part achieved this by putting 'buildings within buildings' which might be a way forward for loadbearing masonry construction by creating buffer zones in buildings which do not require thermal insulation, such as winter gardens, circulation areas or outer spaces that provide a thermal buffer.

Material systems based on masonry construction often work well with those in timber, as in English medieval guildhalls and inns. Lightweight timber structures are often set on top of masonry structures, while more ambitious structures such as the George Inn at Glastonbury seem to imitate the framing of timber in stone – the refinement of timber finding its way into loadbearing masonry wall design. In some buildings such as the Guildhall at Cirencester and college buildings at Oxford and Cambridge, stone is used for window mullions, with glass being set into a narrow lead frame that avoids the use of timber altogether. The invention in masonry at this time can be seen in buildings such as the Market Cross at Chichester and the Poultry Cross at Salisbury, where techniques of buttressing from cathedrals have been used at a more modest scale for secular use.

Loadbearing masonry has the ability to make complex shapes for structures and enclosures, but the position of thermal insulation within the construction is difficult to achieve. An equivalent framed structure in reinforced concrete or steel, with masonry cladding fixed to it, is typically much easier to form but the masonry skin is reduced to an essentially decorative role. A future direction for masonry may be as a mixture of precast concrete masonry-like forms that can be both structural and integrate thermal insulation within the depth of the material. If precast concrete techniques for making vertically stacked units are made at a smaller size than is usually the case, then they could be used to make loadbearing structures from these small units. This would bring the historic advantages of masonry construction back into mainstream construction. Concrete can be formed into small masonry units that can be lifted with modest equipment. The ability of masonry to corbel in

Trinity College, Cambridge, U.K.

New College Chapel, Oxford, U.K.



Bristol Cathedral, Bristol, U.K.

Divinity School, Oxford, U.K.

Christ College, Oxford, U.K.

and out of the vertical plane without the need for formwork is a characteristic that has had limited use in the design of external walls, but is experiencing a modest revival with brick walls of complex geometry or curved surface.

Material selection

The principles of using materials are common to stone, brick and block. The relationship between the masonry unit and the mortar is of particular importance.

Mortars for loadbearing masonry and cladding panels use the same materials and follow the same principles in stone, brick and concrete blockwork. The compatibility of masonry and mortar is an essential factor. It is usual to use the weakest mortar that will adequately sustain the load, because increasing strength can result in too much rigidity which would cause cracking.

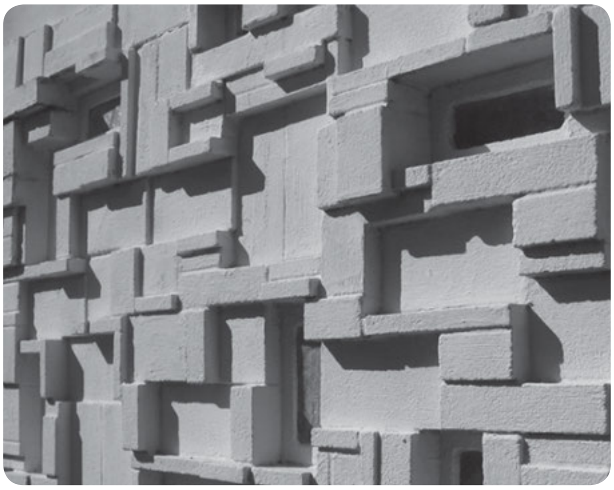
The strength is varied by altering the proportions of the binders cement and lime. Stronger mixes have more cement, while lime provides flexibility which allows the brickwork to move without cracking. Different mixes of mortar are used depending on whether the masonry is used as cladding or as loadbearing masonry. Mortar mixes have to achieve a balance between strength and flexibility. The comparatively low permeability of lime gives greater resistance to rain penetration. Lime also makes a mortar lighter in colour than a cement-based mix. Mortar mixes are a balance between the needs of loads, structural movement, water permeability and preferred colour.

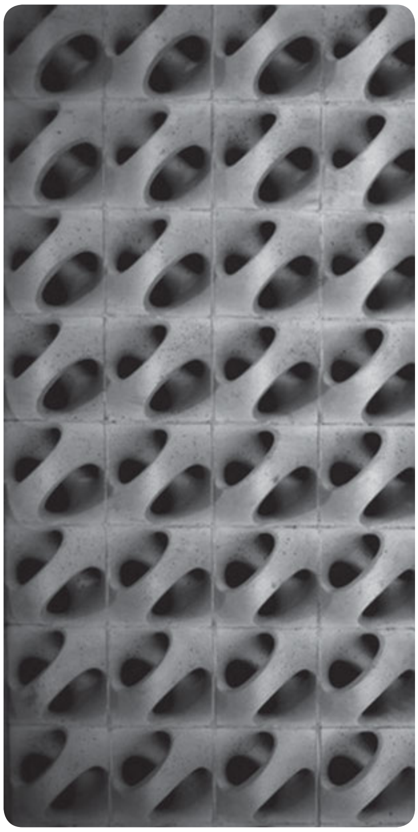
In terms of appearance, it must be noted that the mortar accounts for between 10 and 20 per cent of the masonry, and consequently makes an important contribution to the colour of the surface. The colour of the mortar can be controlled by using pigment additives. In addition, the way that the joint is made has an important effect on the flatness or amount of shadow perceived.

In stonework, crushed stone is often added to the mortar mix as fines instead of sand so that the joints match the stone as closely as possible. The mix depends on the type of stone and its intended use. As a result the mortar is the best compromise between load, structural movement, water permeability and preferred colour. Mortar joints can also be reinforced with steel mesh.

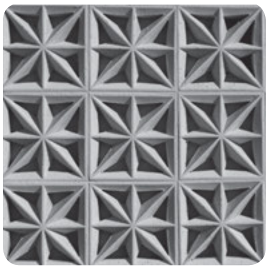
Recycling

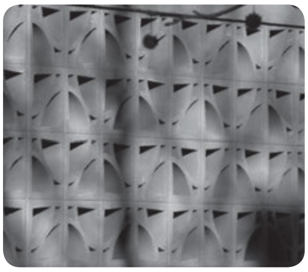
Natural stone can be recycled if the mortar is soft enough to be removed, particularly if a lime putty mortar has been used. Otherwise, stone and brick are used for structural fill.





Built examples of concrete block





Masonry block

Masonry blocks are made from concrete in a range of sizes and strengths. Some types are designed to withstand large compressive forces and are therefore made with a high-density concrete. They can withstand forces of up to around 20N/mm^2 (4.2 x 10^5 lbf/ft^2). Other types are designed to provide limited amounts of thermal insulation and are made with aerated concrete or with insulation bonded to one side. Most types of block are manufactured to course with brick but the size of the block will depend on its weight, since the block must be lifted by hand. Various thicknesses of block are available for different applications.

Material Types

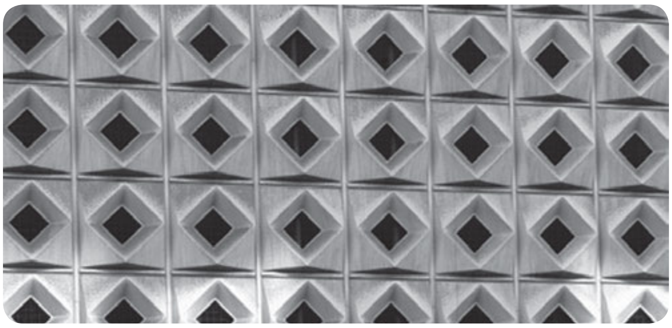
Types used are dense aggregate blocks, light aggregate blocks and aerated blocks. Blocks with dense aggregates are more commonly used for loadbearing walls. Those with lightweight aggregates and aerated mixes are used for non-loadbearing walls and partitions. All these types are made in solid, cellular and hollow form. Cellular types allow the voids to be filled with concrete and reinforcement to improve structural performance. The main advantage of block is its low cost and the speed with which walls can be built. Although some blocks, called fairfaced blocks are made as a facing material, it is more usual to conceal blocks, or face them with another material such as render.

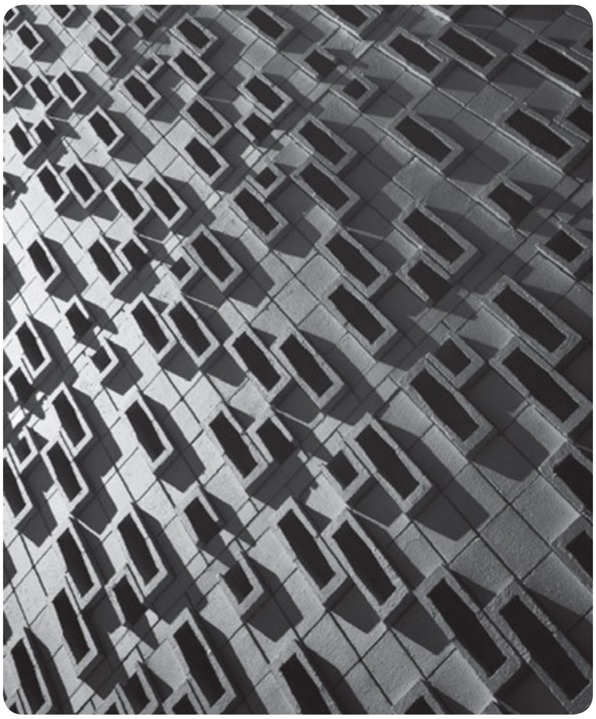
Working with the material

Block can be easily cut and drilled. Metal fixings in the form of brackets and dowels are used for walls where the blockwork does not provide sufficient stability. These fixings are used extensively in blockwork cladding which is supported by a structural frame.

Sizes

Common metric block size:
Length 390mm x Height 190mm (15.5/8in x 7.5/8in)
Overall dimensions
(Length 400mm x Height 200mm with 10mm joint) (16in x 8in with 3/8in joint)
A range of thicknesses is made.
Common U.K. block size to course with U.K. brickwork:
Length 440mm x Height 215mm (Length 450mm x Height 225mm with 10mm joint)





Blockwork has the following general properties:

- Heavy.
- High compressive strength.
- Very low tensile strength.
- High resistance to weathering
- High impact resistance.
- High fire resistance.
- Susceptible to thermal and moisture movement.
- Not waterproof.
- Low seismic resistance.
- Easy to cut to size.

Properties and data
The main properties of masonry blockwork are as follows:

Density:
Dense aggregates = over 1500 kg/m^3 (94 lb/ft^3)
Lightweight aggregates =1000 to 1500 kg/m^3 (62 to 94 lb/ft^3)
Aerated = 500 to 1500 kg/m^3 (31 to 94 lb/ft^3)

Compressive strength
Dense concrete blockwork = 10 N/mm^2 to 20 N/mm^2
(209 x 10^3 to 418 x 10^3 lbf/ft^2)
Aerated concrete blockwork = 3.5 N/mm^2 to 7.0 N/mm^2
(73 x 10^3 to 146 x 10^3 lbf/ft^2)

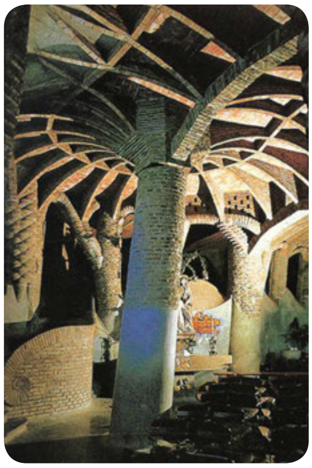
Young's Modulus :
Dense concrete blockwork = 5.0 N/mm^2 to 25.0 N/mm^2
(104 x 10^3 to 522 x 10^3 lbf/ft^2)
Aerated concrete blockwork = 2.0 N/mm^2 to 8.0 N/mm^2
(42 x 10^3 to 167 x 10^3 lbf/ft^2)

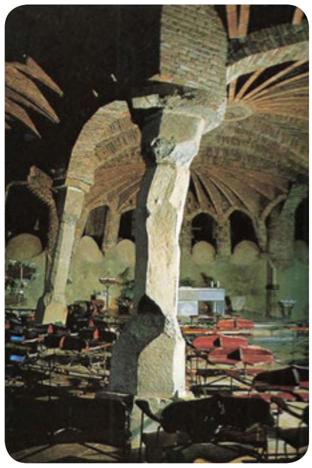
Coefficient of Thermal Expansion:
Dense concrete blockwork = 6 x10^{-6} to 12 x10^{-6} K^{-1}
(3.4 x 10^{-6} to 6.8 x 10^{-6} ^{O}F^{-1}) at 5% moisture content
Aerated concrete blockwork = 8 x 10^{-6} K^{-1} (4.5 x 10^{-6} ^{O}F^{-1}) at 5% moisture content

Thermal conductivity:
Dense concrete blockwork = 1.2 W/m^{o}C (0.69 BTU/hr.ft.^{O}F)
Aerated concrete blockwork= 0.3 W/m^{o}C (0.17 BTU/hr.ft.^{O}F)

Specific heat capacity= 840 J/kg^{o}C (0.2 BTU/lb ^{O}F)
for dense concrete blockwork

Parc Guell, Barcelona, Spain. Architect: Antonio Gaudi





Colonia Güell, Barcelona, Spain. Architect: Antonio Gaudi

Production process of raw material

Stone is cut or hewn from large blocks which have been cut, blasted or split from the bedrock. Being a natural material, the appearance and durability of stone, even from the same block, can vary enormously. To control quality, it is sometimes best to select cut stone at the quarry. Since no two cuts produce the same appearance, when defining the required quality it is advisable to define a limited band between the most veined and least veined stone acceptable. As stone is a naturally occurring material, the properties are not as controlled as man-made materials such as steel. Stone from a particular quarry is usually tested before sale in order that its physical and mechanical properties are known. When stone is used in structural applications, the material undergoes rigorous testing to determine its performance in the intended application.

Natural stone has the following properties common to most types:

- Durable
- A heavy material, weighing as much as reinforced concrete.
- High compressive strength.
- Low tensile strength.
- Finish can be adversely affected by weathering due to exfoliation as a result of a freeze/thaw cycle, pollution, salts, etc.
- Low moisture movement.
- Brittle, but high impact resistance improving with thickness.
- High fire resistance.
- Low seismic resistance

Material selection

Natural stone is a brittle material that is strong in compression but is weak in tension. It is used mostly for wall facings and pavings, although the high unit cost means that it is rarely used in a traditional loadbearing capacity. Most stone has the strength and durability of block and brickwork. The most widely used types are granite, limestone, sandstone, marble and slate. Igneous rocks, such as granite, are formed directly from molten magma. Sedimentary rocks, such as limestone and sandstone, are made up from the eroded elements of earlier rocks laid down in beds near the earth's surface, and are often composed of loose material bound together by cement-like materials. Metamorphic rocks, such as slate and marble, are igneous or sedimentary rocks which have undergone a chemical transformation due to high temperature and pressure.

Granite, within the building industry, refers to coarse-grained igneous rocks. It has a wide range of colours, and is extremely hardwearing. Most granites are grey or pink, with mixtures of white/grey and pink/grey depending upon their geographical source.

Limestone is made up from rock material bound together by calcium carbonate, in the form of the mineral calcite. Many limestones contain a proportion of the mineral dolomite. The colour is generally light, ranging from near white through to brown and grey. Chemical impurities can cause a darkening of the colour. Limestones vary in texture and can range from a sand-textured and coarse material to one that is so fine-grained as to lack visible particles. Limestones such as Portland Stone (Indiana Limestone in the US) are strong and durable.

Most sandstones consist mainly of quartz grains cemented together by mineral solutions. Calcareous, dolomitic, ferruginous and siliceous cements are common. Small amounts of other minerals, often iron compounds, give the stone its colour. Sandstones vary in colour from dull crimson to pink or green/brown mixtures to blue/grey. Sandstones vary enormously in durability from soft, easy to work types with low strength and high porosity, to relatively durable

Sagrada Familia, Barcelona, Spain.
Architect: Antonio Gaudi

Casa Batllo, Barcelona, Spain. Architect: Antonio Gaudi

Casa Batllo, Barcelona, Spain.
Architect: Antonio Gaudi

types with strengths approaching those of granites, with lower porosity.

Marble is a metamorphic rock formed by the recrystallisation of limestone or dolomite through a combination of heat and pressure. The crystalline structure is seen in a fractured surface, which gives it a sparkling appearance. During metamorphism, impurities in the original limestone, such as different minerals, are incorporated into the rock and appear as bands or as discrete inclusions scattered through the calcite mix. No true marble shows fossils. Veined marbles are the result of minerals deposited from solutions penetrating cracks and fissures. Some marbles contain fragments of earlier crushed rocks. A wide range of colours and textures may be found. The presence of iron gives rise to shades of yellow, brown and red as a result of oxidation.

Slate is a crystalline rock produced by dynamic metamorphism of clays and shales, causing it to be orientated along a single grain or 'slaty cleavage' which allows the rock to be split into sheets. It is used mainly for roof slates and for durable surface finishes such as floors. The colour of slate varies from grey to green to black to red.

Working with the material
Stone is shaped either by cutting or sculpting, which is a slow and difficult process. Metal fixings in the form of brackets and dowels are used where the mortar joints do not provide sufficient stability for lintels and copings. These fixings are used extensively in stone cladding panels where the material is supported by a structural frame.

Stone has a very different appearance when polished, though not all types benefit from the process. Depending upon type and application, stone can be finished to different levels of sheen from a reflective polished finish to a matt honed finish. Polishing does not change the structure or weathering of stone and is typically applied where stone is used as a flooring material. Additional finishes include etching and needle gunning, but stone used externally usually has no additional treatment after being cut to size.

Reconstituted stone
Reconstituted stone, also referred to as cast or 'reconstructed' stone, is made from cement and crushed stone that is cast in a mould. It is used either as a structural material or as a facing to a concrete component. Steel reinforcement is used if the casting has a structural function.

Reconstituted stone has the following properties:

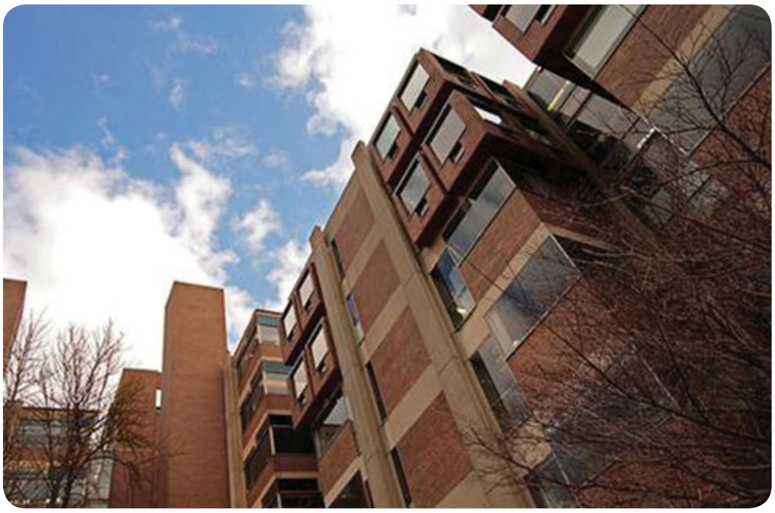
- Very durable.
- A heavy material, weighing as much as reinforced concrete.
- High tensile and compressive strength.
- High impact resistance.
- High fire resistance.
- Susceptible to shrinkage like concrete.

Properties and data
The main properties of stone are as follows:

Density:
Natural stone: 2200 to 3000 kg/m^3 (137 to 187 lb/ft^3) wet
Cast stone: 2100 kg/m^3 (131 lb/ft^3)
Characteristic compressive strength:
Granite = 30 - 75 N/mm^2 (6.3 x 10^5 to 1.5 x 10^6 lbf/ft^2)
Sandstone = 10 - 30 N/mm^2 (2.1 x 10^5 to 6.3 x 10^5 lbf/ft^2)
Young's Modulus = 6.9 N/mm^2 to 21N/mm^2
(144 x 10^6 to 439 x 10^6 lbf/ft^2)
Coefficient of Thermal Expansion = 7.9 x 10^{-6} K^{-1} (4.4 x 10^{-6} $^{o}F^{-1}$)
Thermal conductivity: = 1.7- 4.0 W/m°C (0.98 - 2.3 BTU/hr.ft. ^{o}F)
Specific heat capacity= 840 J/kg°C (0.19 BTU/lb ^{o}F)



Above and below. Richards Medical Centre, University of Pennsylvania, U.S.A. Architect; Louis Kahn



Production process of raw material

Bricks are made by cutting or moulding clay. They are then baked in a kiln to form a hard, brittle unit. A very wide range of colours and textures is available, from the precisely dimensioned, evenly coloured types which are wire cut from a clay extrusion to the less regular handmade bricks which are individually formed in moulds. Extruded wirecut bricks are sometimes made with holes running through them to reduce their weight or to allow reinforcing rods to link them together. Hand-made bricks often have an uneven appearance which provides a rich visual texture as a completed wall.

Most bricks in the U.K. are made in a single standard size: 215mm long x 102.5mm wide x 65mm high, (7 5/8" l. x 3 5/8" w. x 2 3/8" h.) though metric size bricks are also available. When constructing brickwork a 10mm joint is used throughout, resulting in vertical courses 75mm high and 225mm long. Two bricks laid side by side with a 10mm joint are equal to a brick length. The modular nature and size of bricks makes brickwork a very flexible medium. The weight and size of one brick allow it to be lifted with one hand. The modular nature of brickwork imposes a strict discipline on the detailing of openings and corners if expensive specially shaped bricks, called 'specials' are to be avoided. Bricks are economically and easily transported in large or small quantities.

Brickwork has the following general properties:

- A heavy and durable material.
- High compressive strength.
- Very low tensile strength.
- High resistance to weathering.
- High thermal mass.
- High acoustic mass.
- High impact resistance.
- High fire resistance.
- Susceptible to thermal and moisture movement.
- Low seismic resistance

Material selection

The most widely used types are common, facing, engineering and calcium silicate bricks. Common bricks are the weakest type, while engineering bricks are the strongest. Facing bricks are usually used on the external face, while cheaper bricks can be used within the wall. Engineering bricks are used for their high strength and are almost impervious to water, and so are often being used below ground in addition to structural applications

Above and below. Indian Institue of Management, Ahmedabad, India. Architect: Louis Kahn

Above and below. Phillips Exeter Academy Library, New Hampshire, U.S.A Architect; Louis Kahn

where brick is used as a primary loadbearing element. Calcium silicate bricks are made from a mixture of sand and lime which are compressed under steam pressure in a mould. They are low to medium strength, and their water absorption is comparable to that of clay bricks. They are mainly used in internal walls where their light appearance can be exploited. Brickwork is strong in compression, but is not used to resist tensile forces.

Working with the material

Brick can be easily cut and drilled. Metal fixings, in the form of brackets and dowels, are used for walls where the brickwork would not be sufficiently stable by itself. These fixings are used extensively in brick cladding which is supported by a structural frame. Bricks are made in a vast range of colours from reds to blues. Colour is defined by the type of clay, combined with the way it is fired and any pigments which may be added. Calcium silicate bricks are white.

As new brickwork and mortar dries out after rain, traces of salt deposits are sometimes left on the surface. These appear in the form of white stains known as efflorescence. It can be easily removed with a brush and water. Where moisture continues to penetrate the brickwork this efflorescence will continue to manifest itself.

Properties and data

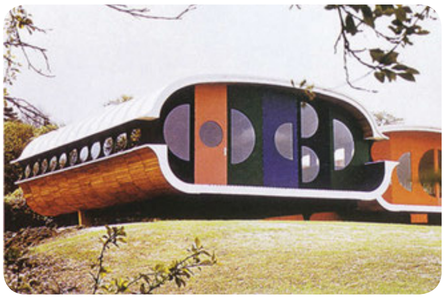
The main properties of brick are as follows:

Density:
Average brickwork = 1900 - 2100 kg/m^3
(118 to 131 lb/ft^3)
Design strength = 5.0 N/mm^2 to 25.0 N/mm^2
(1.0 x 10^5 to 5.2 x 10^5 lbf/ft^2)
Coefficient of Thermal Expansion
= 5.0 x 10^{-6} K^{-1} to 8.0 x 10^{-6} K^{-1}
(2.8 x 10^{-6} to 4.5 x 10^{-6} $^OF^{-1}$)
Thermal conductivity: = 1.3 W/m^{o}C at
5% moisture content (0.75 BTU/hr.ft.^{O}F)
Specific heat capacity= 800 J/kg^{o}C (0.19 BTU/lb ^{O}F)

Kunsthaus, Graz, Austria. Architect: Spacelab Cook-Fournier

Mound Stand, Lords Cricket Gound, London, U.K.
Architect: Hopkins and Partners

Verner Panton Chair



Monsanto House of the Future, Disneyland, Californa, U.S.A.

The use of plastics is very much a part of recent history from 1945. Plastics were given an impetus for development during the Second World War and found wider industrially-based uses in building construction from the 1950s onwards. The Monsanto House of 1957 was developed by an American housing company with the Massachusetts Institute of Technology (MIT). The aim of the project was to create an all-plastic house that also used much more plastic in its interior fittings, which were already being used extensively in more traditional construction, from vapour barriers to plastic plumbing and electrics. The design of the Monsanto House extended the idea of the consumer product to the building itself by making the house from a series of plastic 'pods' formed from wall and roof panels of repeated module. The visual effect of the repetition of the facade panel was reduced by setting them around a single core, giving them a visual complexity where each room is seen as a separate volume. Each room was naturally cross ventilated, though the use of air conditioning was suggested as a benefit in the time before the environmental effects of energy consumption became a primary design consideration. Windows were glazed however, and were not curved, unless the opaque plastic panels, giving the visual effect of glazed 'slices' through a complex single volume. A primary benefit of the house was possibly its ability to move location as the family moved from place to place, which perhaps was as appealing as its form with its suggestion of lightness, almost appearing to 'hover' in its suburban garden context.

Later during the 1960s, the Archigram Group in the U.K. explored this temporary or mobile nature of construction, with its ability to create, at least potentially, the Instant City or Walking City. An additional appeal of this architecture is its ability to form an addition to an existing built context along with its ability to create a complete built environment. In parallel with the work of Archigram, the ecology movement was emerging at this time as a result of concern for the natural environment, and our impact on it, gradually rising in the public consciousness. An interest in a return to 'low' energy technology began to emerge at this time, with events such as the image of the earth being seen from the moon for the first time in 1969, allowing us to see our world from outside its boundaries. The revived interest in the flying machines of Leonardo de Vinci at the time can also be seen as a kind of hope for the future: low energy machines that might have a real technical performance. The possibilities of low energy flight, and their parallel in architecture was the flying machine of Clement Adler in France, who developed the idea of flying machines, following examples from nature such as the bat, rather than the flat, fabricated components used much more successfully by the Wright Brothers. Many of these principles would eventually find an echo in the 'tent' structures of Frei Otto, but were used to great effect in the airships proposed by Archigram. The work of the Archigram Group themselves appeared to come to life for the first time at the big scale in the designs of non-Archigram architects Richard Rogers and Renzo Piano. Plastics were used to form the escalators in the Centre Pompidou in Paris of 1977, which would have been

Schlumberger Cambridge Research Centre, Cambridge, U.K.
Architect: Hopkins and Partners

Media Centre, Lords Cricket Gound, London, U.K.
Architect: Future Systems

Olympiapark, Munich, Germany.
Architect: Frei Otto

Above. Olympiapark, Munich, Germany.
Architect: Frei Otto

Eole flying machine, Clement Ader

both heavy and difficult to fabricate in glass. Plastics were not used elsewhere in the building, where glass and metal panels are used for their greater life span. The use of sheet material in the designs of Archigram in airships and tent structures was reflected by the use of plastics in the Munich Stadium canopy of 1972 and the tent structures of Michel Hopkins in the Cambridge Schlumberger building and the Mound Stand at Lords Cricket Ground in London, both built during the late 1980s. Peter Cook of Archigram built his first large scale building that reflected some of the values of Archigram in the Kunsthaus in Graz, Austria, completed in 2003. Acrylic rainscreen panels were curved to create a non rectilinear form that creates a translucent outer skin.

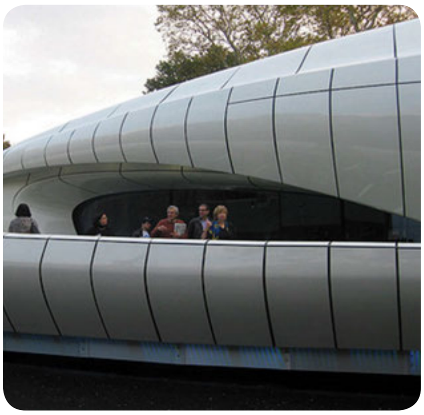
The ability to cut plastic based fabrics into different forms has been exploited in the Natural Ellipse building by Masaki Endoh and Masahiro Ikeda in Tokyo. There the transparent nature of the building is exploited to create a complex geometric building skin from a flat material. Solid plastic panels in the tectonic tradition of the Monsanto House can be found in the travelling pavilion for Chanel by Zaha Hadid. Here, the geometry is complex, with different sized panels formed from a set of relatively economic moulds, the shapes of which could be generated from models generated in 3D modelling computer software rather than by hand. This digital approach is gradually making its presence felt in construction with the ability to transfer 3D digital model files directly to manufacturing machines.

Recent examples are limited to modest scale architectural compositions, but those imagined in the design work of artist Roger Dean in the 1970s were far more ambitious, which were either conceived as sprayed concrete onto a plastic formwork, or could have been made entirely in concrete. The complex geometry of Zaha Hadid's project for Chanel was suggested at a much larger scale in the Jade Sea painting by Dean of 1976. In Dean's work the architecture is continuous with the forms of nature, which would suit a range of materials, but plastics suit the transition from complex mould to complex weathertight form which is difficult to achieve with other materials.

A possible development for plastics is that of the use of common components for walls and fixtures and fittings, so that the interchange of cladding for elements of curved wall could be used in associated fitted furniture in a complete system capable of replacement through the life of the building. The life span of building components in contemporary buildings varies from 10 years for fittings, to 25 years for windows and doors to 50-100 years for the structure. The overall life span of building elements might vary more by allowing more replacement and interchangability of components within a building rather than its complete replacement by a new assembly, or new facade, for example. This would ensure that components are used for longer than is the case in current building construction.

Above and right. Natural Ellipse Building, Tokyo, Japan. Architect: Masaki Endoh and Ikeda Masahiro

Allianz Arena, Munich, Germany. Architect; Herzog + de Meuron



Chanel Contemporary Art Container, Mobile. Architect: Zaha Hadid Architects

Issues of the interchangability of components are tied to the issue of scale, and design appropriate to a given scale. Where small structural components such as ties or struts are designed quite differently to building beams, due to much higher forces experienced by large scale building components, the difference in approach to their design is shrinking with the need to provide greater visual expression in large scale constructions. At the scale of transportation, the design of MIT's vehicles based on a more architectural approach suggests a range of components that could be developed in plastic, from the semi-structural seats to the enclosure of the vehicles.

Production process of raw material

'Plastics' are resinous polymer-based materials divided into two groups. These are thermoplastics, which melt at high temperature, and thermosetting plastics, which set hard and do not melt on further reheating. They are used mainly in cladding systems but composites are beginning to be used as fully structural materials in relatively modest applications such as footbridges. The most commonly used types, under the generic names used in the building industry rather than their polymer-based names, are as follows:

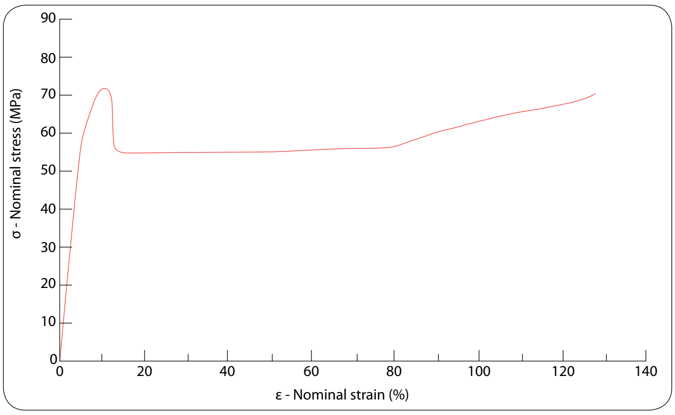
- Polycarbonate
- Acrylic sheet
- PVC-U

Composites comprise two or more materials combined together where the properties of each constituent can complement the others. Although reinforced concrete, plywood and other more traditional materials are sometimes referred to as composites, the term is generally used in the building industry to refer to polymer-based composites. These materials have a polymer resin reinforced with thin fibres, usually glass fibres or carbon fibres. Glass-fibre-reinforced polyester (GRP) was first used during the Second World War for radar covers and was later applied in a GRP boat for the US Navy in 1947. Carbon-fibre was developed by the Royal Aircraft Establishment in Farnborough, England, during the 1960s and was applied in composites for use in compressor blades in jet engines later in that decade. Carbon-fibre-reinforced polymer is much stronger and stiffer than GRP but remains extremely expensive in relation to most metals or other plastics and has yet to find a significant use in building construction.

Polycarbonate is used in building construction largely as a substitute for glass, especially where moulded shapes are required which would be too difficult or too expensive to make in glass. The material was first made in the 1950s as part of the research into polyesters and was marketed as Lexan sheet in the early 1960s. Polycarbonate is made by polymerisation, where a polymer is melted and extruded into strands which are chopped to produce polycarbonate granules. The granules can then be extruded or moulded to form single sheet, twin-wall sheet or complex shapes.

Allianz Arena, Munich, Germany. Architect; Herzog + de Meuron

Centre Georges Pompidou, Paris, France. Architect: Renzo Piano and Richard Rogers



Polycarbonate stress strain diagram

Centre Georges Pompidou, Paris, France.
Architect: Renzo Piano and Richard Rogers

Properties and data
Density : 1140 -1210 kg/m^3
(71 to 76 lb/ft^3)
Tensile strength = 59 N/mm^2 to 70 N/mm^2 (1.2 x 10^6 to 1.5 x 10^6 lbf/ft^2)
Compressive strength = 100 N/mm^2 to 120 N/mm^2
(2.1 x 10^6 to 2.5 x 10^6 lbf/ft^2)
Young's Modulus = 2.0 - 2.4 kN/mm^2 (4.1 x 10^7 to 5.0 x 10^7 lbf/ft^2)
Coefficient of Thermal Expansion :
60 - 75 x10^{-6} K^{-1}
(33.5 x 10^{-6} to 41.7 x 10^{-6} ^{0}F^{-1})
Thermal conductivity :
0.18 - 0.22 W/m^{o}C (0.10 to 0.13 BTU/hr.ft.^{0}F)
Specific heat capacity = 1200 - 1300 J/kg^{o}C (0.29 – 0.31 BTU/lb ^{0}F)

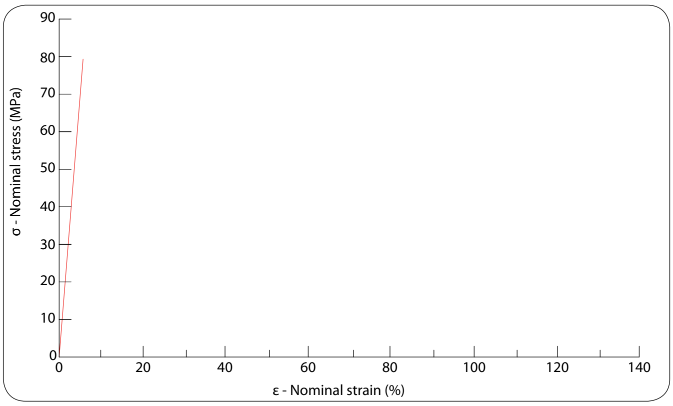
Polycarbonate has the following general properties:

- A strong material with low stiffness.
- High transparency can be obtained.
- A tough but ductile material.
- High impact resistance.
- Flame resistant, tending to melt rather than ignite, but is still combustible.
- Poor scratch resistance without silicone coatings.
- Recyclable.

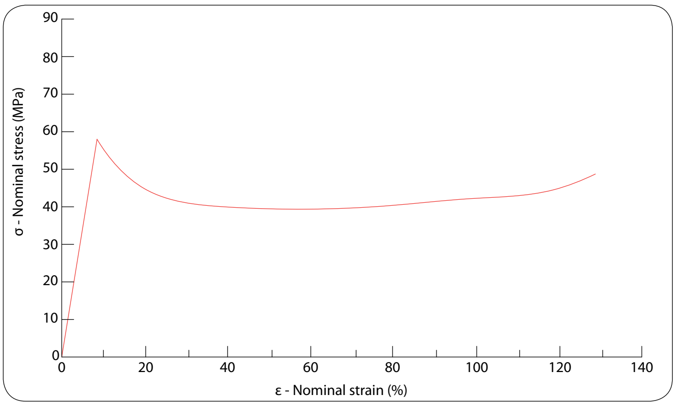
Material selection
Polycarbonate is a thermoplastic used for its high strength, ductility, lightness and transparency. It is fire retardant, and can be easily moulded to complex shapes. The use of polycarbonate is limited by its combustibility. Polycarbonate is an extruded materal used as sheets and sections. Polycarbonate sheet is available in thicknesses from 2mm to 25mm (1/16in to 1in). Its impact resistance is higher than that of toughened or laminated glass. The two main disadvantages of polycarbonate over glass are that it is less durable, scratching easily which makes the surface dull with time, and its greater combustibility. Polycarbonate also has greater thermal expansion than glass.

Twin-walled sheet is an extrusion of two layers separated by parallel fins, giving the material greater rigidity for use as a board. The air gap between the two layers provides a degree of thermal insulation. The maximum sheet size is approximately 2 x 6 metres. It can be sawn, cut and drilled. It expands 20% more than glass. For example, a 1.5 metre (5ft) wide sheet will expand up to 3mm (1/8in). The material has a density of 1200 kg/m^3, which is half that of glass, although in practice the real weight saving is about one third.

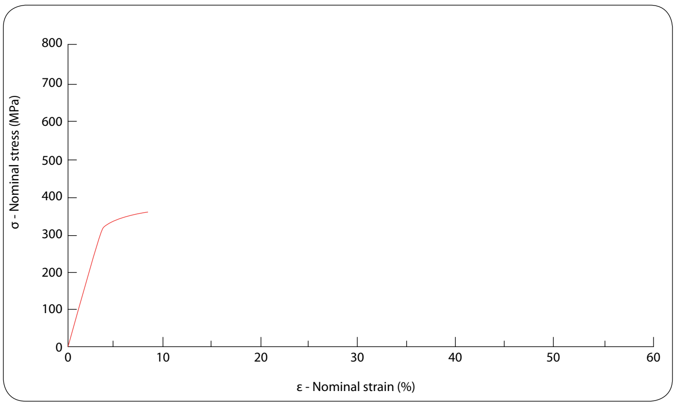
Polycarbonate can be coated with acrylic to prevent yellowing, and other coatings are used to enhance abrasion resistance. It provides an average of 85% light transmission for a sheet 5 to 6mm thick.



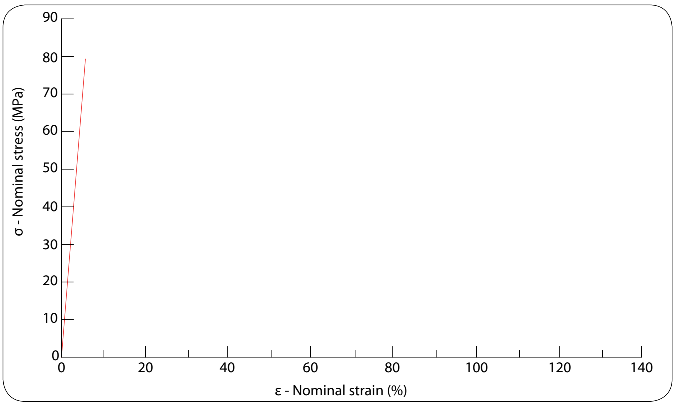
PMMA stress strain diagram



PVC-U stress strain diagram



GRP stress strain diagram



Polymers stress strain diagram

Acrylic Sheet

Acrylic sheet, developed as Perspex in the 1930s, is a plastic based on polymers of acrylic acid. The most common is polymethyl methacrylate, or PMMA, made by polymerising an MMA monomer with a catalyst to form a powder which can then be extruded, moulded or cast.

Properties and data
Density :1150 - 1220 kg/m^3
(72 to 76 lb/ft^3)
Tensile strength = 38 N/mm^2 to 80 N/mm^2
(7.9 x 10^5 to 1.7 x 10^6 lbf/ft^2)
Compressive strength = 45 N/mm^2 to 80 N/mm^2
(9.4 x 10^5 to 1.7 x 10^6 lbf/ft^2)
Young's Modulus = 2.2 - 3.8 kN/mm^2
(46 x 10^6 to 79 x 10^6 lbf/ft^2)
Coefficient of Thermal Expansion
81 x 10^{-6} K^{-1} (45 x 10^{-6} ^{O}F^{-1})
Thermal conductivity : 0.2 W/m^{º}C
(0.12 BTU/hr.ft.^{O}F)
Specific heat capacity
= 1280 - 1500 J/kg^{º}C (0.30 – 0.36 BTU/lb ^{O}F)

Acrylic sheet has the following general properties:

- High transparency and optical clarity.
- Weathers well with high resistance to yellowing.
- Hard but brittle.
- Poor scratch resistance.
- Easily recycled.
- Combustible.

PVC-U

The term PVC-U, or UPVC, denotes the unplasticised form of polyvinyl chloride, or PVC. This rigid form of PVC is used for a wide range of building components from guttering and ground drainage pipes to window frames. The material can be easily extruded or moulded to complex shapes and is available in a range of colours. The low thermal conductivity and flexibility of the material, combined with its ability to be extruded, makes it very suitable for window frames where the material is, in effect, its own thermal break, minimising the risk of condensation on the face of the frame inside the building.

Properties and data
Density : 1400 kg/m^3 (87 lb/ft^3)
Tensile strength = 35 N/mm^2 to 52 N/mm^2
(7.3 x 10^5 to 1.1 x 10^6 lbf/ft^2)
Young's Modulus = 2.1 to 4.1 kN/mm^2
(43 x 10^6 to 85x 10^6 lbf/ft^2)
Coefficient of Thermal Expansion
= 50 x 10^{-6} K^{-1} (28 x 10^{-6} ^{O}F^{-1})
Thermal conductivity = 0.19W/m^{º}C (0.11 BTU/hr.ft.^{O}F)
Specific heat capacity = 1300 J/kg^{º}C (0.31 BTU/lb ^{O}F)

PVC-U has the following general properties:

- Available in a range of colours.
- Weathers well but is susceptible to fading, particularly with brighter colours.
- Tough but flexible.
- Recyclable.
- Combustible.

Chanel Contemporary Art Container, Mobile.
Architect: Zaha Hadid Architects

Olympiastadion, Munich, Germany.
Architect: Frei Otto

Chanel Contemporary Art Container, Mobile.
Architect: Zaha Hadid Architects

Beijing National Aquatics Centre, Beijing, China. Architect: PTW Architects

Glass Reinforced Polyester (GRP)

This material was first commercially available in the 1930s from the Owens-Corning Fiberglas Co. in the U.S.A., but has only slowly been introduced into building. Its main use is in specially fabricated wall cladding panels. Glass reinforced polyester, or GRP, is made from a combination of glass fibre mat and polyester resin. It is a thermosetting composite which has high tensile, shear and compressive strength combined with lightness and resistance to corrosion. However, like aluminium, it deflects considerably under high loads and requires stiffening.

Properties and data

Density : 1600 -1950 kg/m^3 (100 to 121 lb/ft^3)
Tensile strength = 300 N/mm^2 to 1100 N/mm^2
(6.3×10^6 to 23×10^6 lbf/ft^2)
Compressive strength =360N/mm^2 to 880N/mm^2
(7.5×10^6 to 18×10^6 lbf/ft^2)
Young's Modulus : = 35 - 45 kN/mm^2
(7.3×10^8 to 9.4×10^8 lbf/ft^2)
Coefficient of Thermal Expansion :
21.5×10^{-6} K^{-1} (11.9×10^{-6} $^{O}F^{-1}$)
Thermal conductivity: 0.4 - 1.2W/m^{o}C
(0.23 to 0.7 BTU/hr.ft.^{O}F)
Specific heat capacity = 1000 - 1400 J/kg^{o}C
(0.23 – 0.34 BTU/lb ^{O}F)

GRP has the following general properties:

- Strong but light.
- High stiffness compared with plastics.
- High impact resistance.

Working with the material

GRP is made by embedding glass fibres, usually as a woven cloth, into a polyester resin which is then hardened by a catalyst. Glass fibre is a flexible sheet material formed from fibres drawn from molten glass, and has a tensile strength ten times that of steel. Polyester resin, the other component of GRP, becomes a solid material when a chemical catalyst is added. The material is made either by craft-based open moulding methods to make panels or by pultrusion to make continuous sections in the manner of extrusions in other materials. Injection moulding is sometimes used but this is usually limited to small components. The craft-based methods use either the hand lay-up technique, where glass-fibre or glass-fibre cloth is laid in an open mould and coated with resin and catalyst, or the spray technique where a mixture of fibres and resins is sprayed onto the mould. Air bubbles are removed by hand-rolling or by a suction method. The face of the mould is coated with a releasing agent to facilitate removal when set.

The manufacture of GRP panels is a craft-based workshop activity rather than a machine-based industrial technique. It is formed in moulds but without high temperatures or expensive equipment. This is in contrast to the emerging technique of pultrusion where machinery is used to draw a mixture of resin and chopped fibres through a die to produce a material with constant cross-section. A wide range of sections is now available from I-sections to channels, tubes and planks for use in footbridges. Sections can be bolted together using techniques broadly similar to those used in steel construction.

Vanna Venturi House, Chestnut Hill, Philadelphia, Pennsylvania, U.S.A. Architect: Robert Venturi

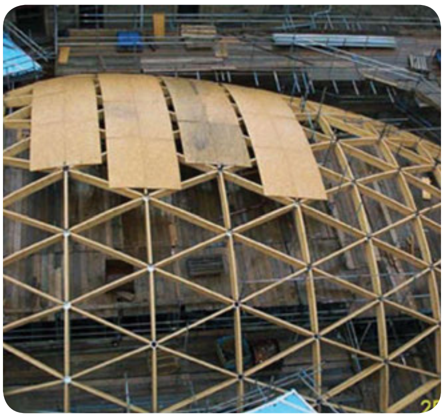
Teatro del Mondo, Mobile. Architect: Aldo Rossi

An increased interest in the use of timber is in gridshells, which are shown in the structures chapter. In contrast to large scale structures currently being developed in new projects is the enduring use of timber to make small-scale rectilinear enclosures based on cut timber sections up to around 3.5 metres long, conditioned by the size of cut natural timber, which conditions the size of rooms in domestic construction. The 19th century British railway was designed with this constraint, to make an economic single room building that can be glazed along its walls as required to give clear views up and down the railway track. A 20th century echo of this building type is the Vanna Venturi House, designed by Robert Venturi and completed in 1964. The design can be viewed as a reaction to the 'free' plan of Modernist architecture. In mainstream Modernism, the design is generated from the plan, providing buildings which are largely extruded from the plan. Instead, Venturi's timber buildings of the 1950s draw on vernacular 'types', so that buildings might look like their imagined typologies as well as being specific to their site, rather than being largely independent of the historical built context. Consequently, a school should look like a 'school'; a house should look like a traditional home, with communal spaces on the ground floor and private rooms on the upper floor.

In contrast to this approach are the early homes of Richard Meier, using timber construction for Modernist designs, often contrasting open glazed facades with opaque enclosed walls. Timber is used as a material that can provide a smooth continuous surface to contrast with the glazing rather than allow the specific form of construction to be expressed. This approach follows a Modernist interest in linking inside and outside spaces across screens of glass, through the use of the 'open plan' of linked internal spaces. In Meier's houses, spaces are differentiated by the introduction of double height volumes that link spaces together to differentiate spatial experience in a building. This is a different approach to the spatial complexity of house projects designed by Meier's contemporary Peter Eisenman, for example, who introduced a second overlaid grid into his designs for timber buildings to create spatial complexity while following regular construction methods for this material. The use of a second grid at a different angle, used by Eisenman, follows on to some extent from the work of Louis Kahn, with his 'buildings within buildings' ideas in the Exeter Library and the Indian Institute of Management in Ahmadabad.

A contemporary of both architects is Aldo Rossi, whose interest in simple geometric forms can be seen in his design for the mobile theatre, the Teatro del Mondo, with its independence from context, allowing an abstracted typology of theatre to become the primary forms of architectural expression in the design. Here the timber construction is used in the form of long timber boards to create large flat surfaces, with timber framed windows set into them. The design follows traditional principles of timber construction at this scale.

Another strand of timber construction is that of traditional timber shipbuilding, where large scale structures, the equivalent of three or four storey buildings, were formed in shapes of complex geometry required to propel them through water efficiently. An essential feature of traditional shipbuilding, particularly for fighting ships, is the solid nature of their construction, more like the solid cross laminated timber panels of contemporary construction than the frame with lightweight timber cladding attached. Sailing ships of the 18th and 19th centuries had thick timber hulls clad in additional timber, rather than having a skeletal frame with timber boards spanning between them. This form of construction can be seen as a parallel to the solid hardwood timber frames of medieval construction, which are seeing a revival in England. The timber frames use timber sections of around 300mm square, typically set at around 2000mm centres, rather than the small softwood timbers of 100mmx50mm set at 300mm centres or less. However, the constructional sophistication of sailing ships is only just beginning to find its way into contemporary solid timber frame construction.



Napier University, Edinburgh, U.K.
Architect: Building Design Partnership

Instant Cabin at Massachusetts Institute of Technology (MIT), U.S.A.

Large scale timber frame.

Unlike sailing sips, which were entirely clad in timber on the outside, sometimes with an additional thin metal skin on the lower part of the hull, medieval timber construction of buildings sets the cladding material as an infill between the structural members. While historically this resulted in cracks between structural frame and infill, causing possible leaks, contemporary materials can achieve considerably higher performing walls using the same principle. This approach may be one to follow in the coming years.

A mixture of large scale timber construction and its smaller scale platform frame equivalent can be seen in traditional Japanese construction, where timber frames vary in scale to suit both their structural purpose and their use within a building. The use of pegs and interlocking joints to create joints that work in tension as well as compression have produced a rich tradition of hand built, large scale structures seen in the design of sailing ships immediately prior to the Industrial Revolution.

A contemporary parallel of this approach of mixed timber techniques can be seen in the early work of Morphosis Architects in the US. Their early unrealised designs have small scale structures are linked in a building composition that would have ideally suited this approach of mixed timber construction. The designs, while visually striking, do not exceed the limits of the construction material which would have required additional structural support in a different material system. The use of small scale structures to create larger buildings from these components avoids the need to change material or use laminated timber.

Tension joints in timber are difficult to form without metal connectors or glues, but the ability to form joints without their use has been explored in the design of the Instant Cabin at Massachusetts Institute of Technology (MIT). The form of construction used is one of interlocking components and pegs all formed from plywood sheet. While experimental, this design demonstrated the possibilities of construction based on the use of digital tools for both design and construction. The plywood sheets were cut with a CNC router in a way that produced little waste material by laying out cutting patterns in a digital file used by the cutting machine. This approach of CNC routing can be approximated at the smaller scale through the use of laser cutters to make small scale models of the real components. This method of rapid prototyping is ideally suited to timber construction, where issues of fabrication in the real building can be studied and resolved during the design development of the building. This contrasts with other machines used for rapid prototyping, which provide ways of making sometimes complex forms in an unspecified building material. An essential aspect of digital fabrication techniques in timber is their ability to bring the full range of design development back to the design studio, allowing constraints of material systems in timber to inform the design at all stages of development.

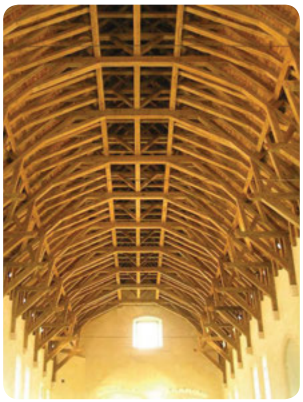
Timber has the following general properties:

- Fibrous and elastic, making it strong in tension and compression. Like metals, it performs better in tension than in buckling.
- Undergoes varying degrees of moisture movement.
- Straight grain is stronger than an irregular grain and is easier to work.

An irregular grain gives a rich, textured appearance, usually resulting from knots which weaken the timber. Knots are actually where the branches were located and leave a distinct pattern in the cut timber.

- Timber is prone to rot, particularly where it cannot be adequately ventilated or is subject to continuous cycles of wetting and drying.
- Theoretically, wood will last forever if it stays either completely dry or completely wet.

Wooden piles rot only in the area of fluctuation in the water table or tide. The causes of decay are a mixture of trapped air and water, where fresh air cannot ventilate and dry the wet



Hammerbeam Roof,
Stirling Palace, Scotland, U.K.

Eltham Palace Hall, Eltham,
London, U.K.

Westminster Hall Ceiling, the Houses of Parliament, London, U.K.

material. This results in the growth of fungi, causing dry rot or insect attack. This is prevented by impregnating the outer zones of timber with preservative chemicals, but these can harm the natural environment if the chemicals are allowed to leach into the ground.

Material selection

Commercial timber is classified as either softwood, from conifers, or hardwood, from broad-leaf trees. Softwood is used for most structural timber, as it is easily worked due to its softness and straightness of grain, though oak is common for exposed structural timber frames. Typical types are cedar, Douglas fir, western hemlock, pine, redwood (scots pine), spruce, whitewood and yew. Most softwood comes from the coniferous forests of the northern hemisphere. Hardwoods have high strength and durability, a rich grain and varied colour. They are more expensive than softwoods which make them too expensive for most current structural use, but suitable for joinery and finishes. Typical varieties of hardwood are ash, beech, birch, cedar, iroko, mahogany, maple, oak, teak and walnut. Hardwood occurs in most parts of the world but is obtained mainly from both northern temperate forests and tropical rainforests. Since hardwoods constitute a large proportion of the rainforests, and take much longer to grow than softwoods, the world's supply is depleting at an alarming rate. As a result, the use of certain tropical hardwoods has come under considerable scrutiny in recent years.

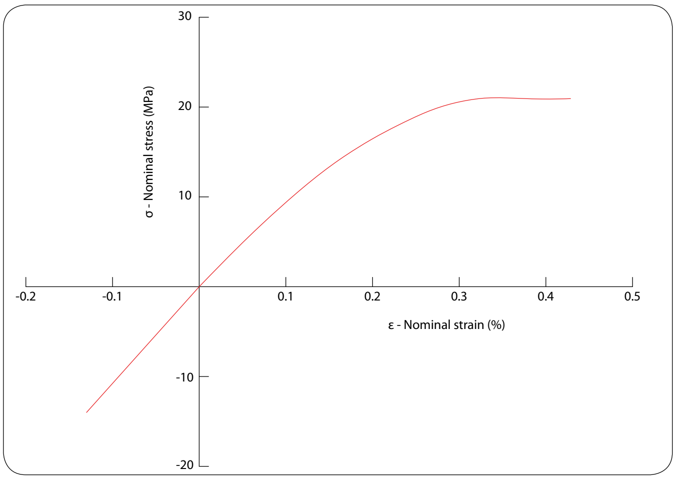
Laminated timber is constructed from planks glued together to form sections which are larger than could be achieved with natural timber. Laminated timber works well in both tension and compression. As the natural growth defects of timber reduce strength, individual boards are positioned so as to reduce the cumulative effect on the strength of the overall member. The strength of laminated timber therefore approaches that of defect-free solid timber.

Plywood sheet was invented in the U.S.A. in the 1930s, and is made by bonding together veneers peeled from logs. Both softwoods and hardwoods are used. They are layered so that the grain of each veneer is set at right angles to the one either side, providing strength in both directions as well as minimising thermal movement. Good quality plywood has very little thermal movement. Plywood is graded according to its resistance to moisture penetration which is determined mainly by the glue used. The most common types are interior grade, exterior grade and marine grade. The face veneers vary from a rough finish, such as Douglas fir, to a smooth one like birch. The different veneers have little influence on either moisture penetration or strength. Because plywood performs well in shear, it is used as sheathing to timber wall panels. Plywood also has high impact resistance. It can be bent to small radii, sometimes using a steam treatment.

Recent developments in plywood have produced blockboard and laminboard which are made by applying veneers to a core made from solid timber core blocks also known as a stave-core The core consists of strips of solid wood ranging from 7 to 30mm (1/4in to 1 3/16in) thick. Laminboard, a heavier material than blockboard, has a core of solid strips up to 7mm (1/4in) thick, laminated together. The grain of the face veneers is set at right angles to that of the core strips. These boards are not suitable for forming curves. The advantage of these panels is that they are lighter and cheaper than plywood. Laminboard is useful where weight is important, but is unstable in wet areas because the endgrain to the blocks is exposed which can deteriorate rapidly.

Chipboard, medium density fibreboard (MDF), and hardboard are the most common particleboards. All are made from mixing wood particles, normally wood waste, with an additive to form a sheet material that is cured between heated plates. Chipboard was developed primarily for the furniture industry in the 1960s. However, it is also used as a flooring material in wood construction as a cheaper alternative to plywood or timber boards. Chipboard is not as strong, or as rigid, as an equivalent plywood sheet, since the wood fibres are shorter. Like plywoods, it resists shear forces but is less capable of withstanding impact damage and is harder to fix with screws and nails. Also, it cannot be curved except in a pre-formed process. Chipboard is also more prone to creep under prolonged loading than plywood and timber. MDF has smooth faces and a uniform cross section. This gives it a great advantage over other boards of having smooth exposed edges that require no lipping or trim when cut. For this reason it is often used for built-in furniture and interior panel systems.

Examples showing a parallel timber technology: the construction of timber sailing ships.



Timber stress strain diagram

Working with the material

Before the 20th century most timber joints were made to work in compression, so the high tensile strength of the material was not used at junctions. However, the development of modern glues and metal connectors has resulted in a wide range of contemporary tension and compression joints. The most common joints in timber that perform well in tension and compression are the bolted metal connector, split ring connector and the nail-plate connector.

The bolted connector is a thin plate of galvanised steel with projecting teeth. The connector is set between the timber sections being joined, and is embedded into both sections as the bolt fixing is tightened. The split ring connector works in a similar way. Both fixings transmit shear forces at the joint across the bolted connection.

The nail-plate, also called a gangnail plate, is a galvanised thin metal plate which is pressed to form a series of nail-like projections on one side. The plate is pressed into the timber sections being joined to form a patch connection on either side. This is done under factory-controlled conditions, and is most commonly used in prefabricated floor and roof trusses.

Glued connections in timber are glue-welded joints that are as strong as the wood itself. Widely used types are urea-formaldehyde, phenol-formaldehyde and resorcinol. Glued connections provide structural continuity at the joint. They do not break down when exposed to the weather or changes in temperature.

In joinery, particularly for built-in items, simple jointing techniques that allow parts to be made quickly and efficiently tend to be used. Most joints are designed to be manufactured easily using machinery, which has led to the demise of traditional techniques such as dovetailing. However, the availability of adhesives has enabled simple mitred and butt joints to be used.

Properties and data

Density:
Softwood (C22) = 340 kg/m^3 (21.2 lb/ft^3)
Hardwood (D40) = 590 kg/ m^3 (36.8 lb/ft^3)

Design strength:
Softwood (C22) = 6.8 N/mm² (1.4 x 10^5 lbf/ft^2) bending
Hardwood (D40) = 12.5 N/mm² (2.6x10^5 lbf/ft^2) bending

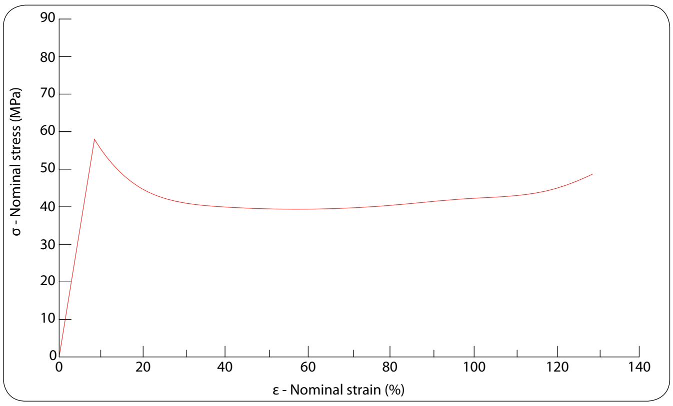
Young's Modulus ($E_{0,mean}$)
Softwood (C22)= 9.7 kN/mm² (2.0 x 10^8 lbf/ft^2)
Hardwood (D40) = 10.9 kN/mm² (2.3 x 10^8 lbf/ft^2)

Coefficient of thermal expansion:
Softwood (C22) = 34 x 10^{-6} K^{-1} (18.8 x 10^{-6} F^{-1}) across grain
3.5 x 10^{-6} K^{-1} (1.9 x 10^{-6} F^{-1}) along grain
Hardwood (D40) = 40 x 10^{-6} K^{-1} (22.2 x 10^{-6} F^{-1}) across grain
4.0 x 10^{-6} K^{-1} (2.2 x 10^{-6} F^{-1}) along grain

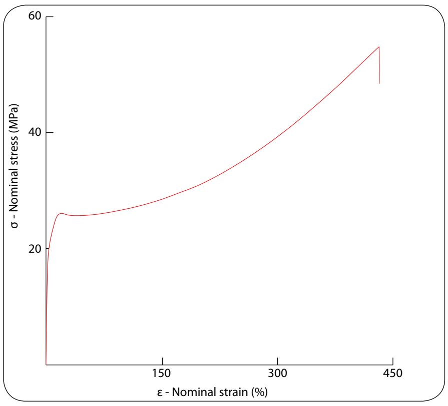
Thermal conductivity:
Softwood (C22) = 0.14 W/mºC (8.1 x 10^{-2} BTU/hr.ft.^{O}F) across grain
Hardwood (D40) = 0.21 W/mºC (12.1 x 10^{-2} BTU/hr.ft.^{O}F) along grain

Specific heat capacity = 3.0 J/kgºC (7.2 x 10^{-4} BTU/lb^{O}F)

Standard sheet sizes:
Plywood 1220 x 2440mm (4'x8')
1525 x 3660mm (5'x12')
Thicknesses 4mm to 25mm (1/4" to 1")
Chipboard 1200 x 2400 mm
1200 x 4800mm
Thicknesses 4mm to 25mm (1/4" to 1")
MDF 1220 x 1525mm
2440 x 3050mm
Thicknesses 4mm to 25mm (1/4" to 1")



PVC-U stress strain diagram



EFTE stress strain diagram

PVC membranes

PVC (polyvinyl chloride) roof membranes have been in use since the 1960s as a very lightweight and relatively economic roofing material, and have become widely used in recent years. Membranes in this material were first developed in Europe in the late 1960s and were used in the US from the 1970s onwards. PVC sheet material is usually reinforced with glass fibre to give it increased rigidity that is easier to bond to the substrate.The PVC used in membranes is plasticised (PVC-P), unlike the unplasticised PVC (PVC-U, or uPVC) used to make window frames and rainwater drainage components. PVC-P is rigid at normal external temperatures, but softens when heated, making it flexible and allowing strips or sheets to be welded together to form a continuous membrane without the need for standing seams or visible joints. Plasticisers and filler material in PVC-P is added to give the material greater flexibility. The material has very low levels of shrinkage, is dimensionally stable and does not creep visibly with age. The material experiences only very small amounts of movement under full wind load.

Membranes are reinforced with glass fibre sheet or polyester fabric. These layers are bonded into the material. The glass fibre provides dimensional stability, making it more stable for bonding to the substrate. The woven polyester fabric, used in tent membrane structures, has high tensile strength and to resist wind loads the mechanically fixed method is used. A typical build-up for a single layer membrane is a concrete deck with a vapour barrier set on top, with thermal insulation above that, sealed on top with a single layer membrane. PVC-P membranes are typically 1.5mm - 3.0mm thick, while EPDM membranes are typically 1.0mm - 1.5mm thick.

FPO (TPO) membranes

A recent development in thermoplastic membrane types are polypropylene- and polyethylene-based materials. They have greater flexibility than PVC-P membranes, but still require reinforcement in glass fibre sheet for increased dimensional stability and polyester fabric to give greater tensile strength. Fire retardant is added to provide fire resistance, unlike PVC-P which is self-extinguishing when flame is applied.

ETFE

ETFE (ethylene-tetra-flouro-ethylene) is a polymer similar to PTFE (marketed as Teflon) which is made by extrusion as a sheet material. Thicknesses vary but 0.2mm is a common thickness of material for ETFE cushions, allowing them to be very light in weight at around 350g/m² for this thickness of sheet. Heavier gauge sheet at 0.5mm thickness weighs around 1000g/m². Inner layers of ETFE sheet that provide separate chambers within the cushion are often made from 0.1mm thick sheet. The material is also used for its high level of transparency, with 95% light transmission, and its durability when compared to other fabric materials, with a life expectancy of 25-35 years based on visual criteria. In order to provide translucent areas of roof (or facade) using the same material, a white coloured translucent sheet is manufactured which allows around 40% light transmission. ETFE does not provide a barrier to the passage of UV light, making it ideal for use in buildings where extensive planting is displayed, though the translucent white sheet has greatly reduced UV light transmission. Solar shading can be provided by a pattern of dots printed onto the surface of the ETFE cushion, with a reflective silver colour being a popular choice, though other colours and patterns can be developed for individual projects. The printed dots on a clear ETFE sheet reduce the light transmission to around 50-60%, but this can be increased further by printing dots on two faces of the air-filled cushion in areas of the roof where more shading is required. The amount of solar shading provided can be varied by allowing the middle layer to move as a result of changing the air pressure within the cushion. The middle layer moves either outwards or inwards to increase the overlap of the printed screen of dots which has the effect of varying the amount of solar shading provided.

The sound absorption of ETFE cushions is low, so that sound travels easily through the material. While this can be an advantage in noisy internal environments, it can be an inappropriate material if external noise is able to travel through the roof to internal spaces where a quiet environment is required. Cushions can also produce a drumming effect during rain resulting from the use of a thin, stretched membrane material.

Busan stadium, Busan, South Korea. Architect: Space Group

The toughness of ETFE sheet is combined with a high resistance to tear. Damage by sharp objects puncturing an outer membrane does not spread easily into a larger tear. Birds can puncture the outer membrane, but they have great difficulty in coming to rest on the roof itself, except on the clamping plates, where wire is sometimes fitted to avoid providing any spaces for birds to stand. The material has fairly high resistance to surface fading from UV light where there is a gradual loss of surface reflectivity. ETFE sheet is also highly resistant to attack from chemicals and from airborne pollution in urban areas. Its low level of surface friction ensures that cushions do not hold dirt and dust easily, making cushion roofs relatively easy to maintain. ETFE roofs are usually cleaned as a result of rain in temperate climates, though access for maintenance is required, usually provided by walking along the external clamping plates with cable assistance or from external structure. Roofs are designed so as to ensure rainwater drains easily from the roof. Gutters are introduced on long span roofs between sets of clamping plates, as shown in (F). Cushions are repaired by the use of ETFE tape, which is visible, or by complete replacement of the panel, depending largely on the visual requirements of the roof design. A major concern in the use of polymer materials for single layer and multiple layer fabric roofs is their performance in fire. ETFE sheet is not easily inflammable and will self-extinguish quickly under direct flame. Few burning fragments will fall below during a fire, since the material melts rather than burns, with most of the burnt material being carried away in the rising hot air of a fire. ETFE sheet melts at around 275°C, forming holes in the fabric which allows the heat and smoke of a fire to escape. However, some roofs still require smoke vents, since this may not always occur during a fire if the smoke and heat is being generated in an area away from the roof, where the ETFE cushions are not affected by the fire. The small amounts of material used in ETFE cushions, with an average wall thickness of 0.2mm, result in little material being deposited during a fire.

PVC/polyester fabrics

PVC/polyester fabrics are made from polyester cloth which is coated on both sides with a layer of PVC. The coating protects the fabric against the effects of rain and of UV light. The PVC coating is a mixture of PVC powder, softeners and plasticisers, UV stabilisers, pigments and fire retardants. An additional outer coat of lacquer slows down the effect in the PVC coating of becoming increasingly brittle with age, which results from the softeners within the material gradually moving to the surface of the PVC coating. The lacquer coating also slows down the fading effects of the colour pigments. A PVDF lacquer (a fluorinated polymer) is typically used, which also ensures that the surface has low surface friction so that it will attract little dust and dirt, and allows the membrane to be cleaned easily. Acrylic lacquers are also used. The typical weight of a roof using this material is 500 - 800g/m². A PVC/polyester membrane roof will last around 15 - 25 years.

PTFE/glass fibre membranes are made from a glass fibre mat which is coated with a PTFE layer such as Teflon. As with PVC/polyester membranes, the coating protects the fabric from the effects of both the weather and UV light as well as forming a low friction surface to reduce the collection of dirt and dust. Most dirt is washed away by rain, but some cleaning is needed using the same methods as for PVC/polyester roofs. Typically it weighs 800 - 1500g/m². The life expectancy of a PTFE/glass fibre membrane roof is longer than PVC/polyester membranes at around 30 - 40 years.

Comparison of types

Both PVC/polyester and PTFE/glass fibre have high tensile strength and high flexibility, making them very suitable for curved and double curved roof membranes. They both have a light transmission of 5 - 20% depending on the thickness of membrane used, reflecting 75 - 80% of light. Neither will catch fire easily, and both resist the deteriorating effects of UV light, though PVC/polyester becomes increasingly brittle with age. Both have almost no acoustic performance and have poor thermal insulation performance when used as a single membrane roof. PVC/polyester has a greater range of colours readily available, while PTFE/glass fibre is usually white, the colour to which it bleaches naturally from its manufactured beige colour after a few months of being exposed to sunlight. Weld marks that occur during fabrication also disappear as a result of bleaching in sunlight. PTFE/glass fibre has lower surface friction than PVC/polyester, allowing the former to remain

Plashet Unity Bridge, Lewisham, London, U.K.
Architect: Birds Portchmouth Russum

Hampshire Rose Bowl, Hampshire County Cricket Club, Southampton, U.K. Architect: Hopkins and Partners

Brentwood Mall, Burnaby, British Columbia, Canada. Architect: Musson Cattell Mackey Partnership

Chene Park Amphitheatre, Detroit, U.S.A. Architect: Kent Hubbell and Engineer Bob Darvas

cleaner, while PVC/polyester requires cleaning more frequently. PTFE/glass fibre requires greater care in transportation to site and erection than PVC/polyester, the latter capable of being folded without damage to the membrane.

Thermal insulation
A single layer membrane fabric roof in either PVC/polyester or PTFE/glass fibre typically has a U-value of around 6.0W/m2K. Where two layered membranes are used, with a minimum air gap of 200mm between the membranes, the U-value can be reduced to around 3.0 W/m2K. Double layer membranes are less commonly used as they have a severely reduced light transmission; the translucency of the material being one of its main advantages. Thermal insulation can be added to a double layer membrane by using a translucent fibre-based insulation, as used in fibre glass cladding panels discussed in the previous chapter. The insulation can be fixed to the inner face of either membrane, depending on how the roof void is ventilated. With the increasing importance of the role of thermal insulation in the reduction of energy use in buildings, the use of double layer fabric membranes is set to develop considerably over the next 10 years.

Acoustics
Like ETFE cushions discussed in the previous section, single layer membranes provide no significant reduction of noise through the roof. A double layer roof with an acoustic lining will provide some acoustic performance but will have the effect of losing most of the light transmission through the membranes. In addition, low frequency sound is difficult to absorb due to the low mass of the cladding material. In common with ETFE cushion roofs, the roofs are almost transparent to sound emitted from within the building.

Performance in fire
The performance of a membrane during a fire depends on both the fabric used and the stitching at the seams, where this joining method is used. Membranes lose their tension under high temperatures, with PVC/polyester stretching above 70-80°C, and PVC/polyester seams starting to peel at around 100°C. At 250°C the PVC melts, leaving holes in the membrane. PVC has fire retardants in the coating so that it self-extinguishes when the flame source is removed which results in few, if any, burning fragments to drop down from the roof. PTFE/glass fibre fabrics fail at around 1000°C, but seams will fail at a much lower temperature of around 270°C. With both materials, the failure of the

Food Court, Chatham Maritime Shopping Centre, Chatham, U.K.
Architect: Kemp Muir Wealleans

'Observatory: Air-Port City 2008', Hayward Gallery, London, U.K.
Designer: Thomas Saraceno

Buckingham Palace Ticket Office, London, U.K. Architect: Hopkins and Partners

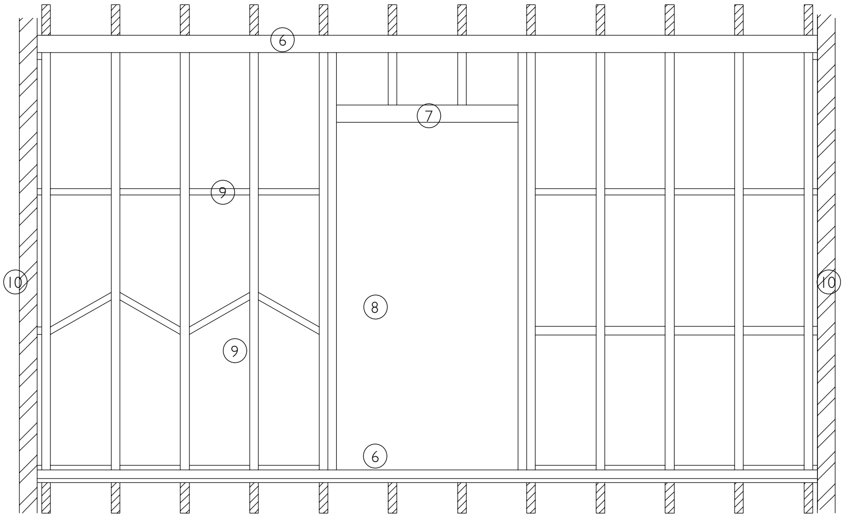
Ford Direct, Stevenage, U.K. Architect: DWW

membrane forms holes in the roof which allow heat and smoke to escape.

Membrane roof fabrication
In stitched panel joints, wider seams have more rows of stitching visible, with the material folded over itself to strengthen the joint. Joint widths vary from around 25mm to 100mm depending on the size of the membrane and its associated loads. Additional strips of fabric are usually bonded onto the outer (upper) face of the stitched seam to avoid rainwater penetration through the sewn thread. PVC/polyester panels can be stitched in conjunction with most lacquer types.

Welded seams are made by forming a lap between panels, then heating the lapped areas and pressing them together. Joint widths are similar to those required for stitched seams. Seams in PTFE/glass fibre panels are formed by hot element welding rather than by stitching or bonding, with an additional fabric strip added either on top or within the joint itself between the membranes to provide the required strength. For welded joints on PVC membranes, the edge of the panel being jointed has the PVDF lacquer removed before welding, which is applied again when the welding is complete to ensure that the PVC is fully welded and that the PVDF lacquer forms a continuous seal across the joint when formed. PVC/polyester can be both hot air welded and hot element welded; the advantage of hot air welding being that repair work and some complex jointing can be undertaken during erection on site. Fabric roofs with high structural loads within the membranes can be both welded and sewn to provide a stronger joint. If the joint is first sewn then welded, this avoids the need for an additional strip to be added to the upper surface, which can enhance the visual appearance of the membrane on its outer surface. Bonding with solvents is used on PVC/polyester fabrics only, but can be done in conjunction with most lacquers used on that material.

Details
1. Block, typically concrete or hollow brick
2. Timber stud frame
3. Plasterboard/drywall finish
4. Skirting or recessed trim as shown
5. Internal door
6. Floor joist
7. Door header
8. Stud
9. Bracing
10. Flank wall
11. Glass block
12. Bedding reinforcement
13. Silicone seal
14. Bedding compound
15. Stud partition
16. Steel frame to enclose glass block panel



Vertical section

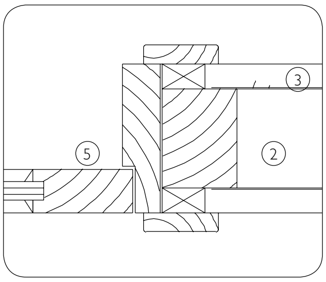
Blockwork
Partitions are non-loadbearing walls. The ease with which they can be removed or changed depends upon the type of construction. Blockwork partitions are constructed like external walls and provide high levels of sound insulation as a result of their mass. A blockwork partition is typically set onto a concrete floor or steel beam. The blockwork can be left as a self-finish, if fairfaced, or given a plaster finish. A gap is usually left between the top of the partition and the soffit (underside) of the floor above to allow both for thermal movement in the partition and deflections in the floor above. The gap is usually filled with a flexible strip such as mineral fibreboard.

Timber
Timber stud partitions are constructed like the external wall to the platform frame, using an internal quality lining such as plasterboard instead of plywood sheet. Sound insulation can be provided by an infill of board or quilt between the studs. An alternative method is to build the wall as two skins that are free to vibrate acoustically independent of one another. Complicated shapes and curved partitions are easy to construct. Stud partitions can also be made in metal. These are used in conjunction with an internal lining board, such as plasterboard, and as an alternative to timber. Metal studs are made from cold-formed galvanised steel sections.

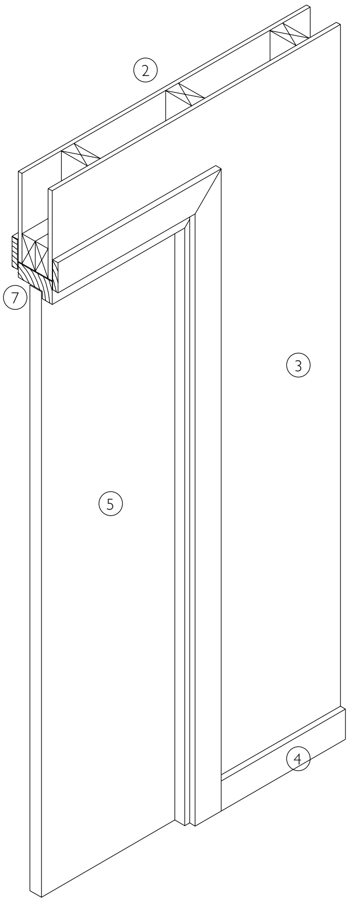
Glass blocks
Glass block partitions are built in panels of gridded blocks. The joints between blocks are reinforced with steel rods to overcome their inherent lack of structural stability. The rods are bedded either in a cement-based mortar or in silicone. Edges of blocks are sanded or coated to provide a key for the jointing material. Glass blocks can be made into panels approximately two metres (6ft 6in) square and can be built either in prefabricated form or as site-built panels. Panels are supported by a perimeter frame made from any structural material such as concrete, steel or timber. Expansion joints are provided around each panel.

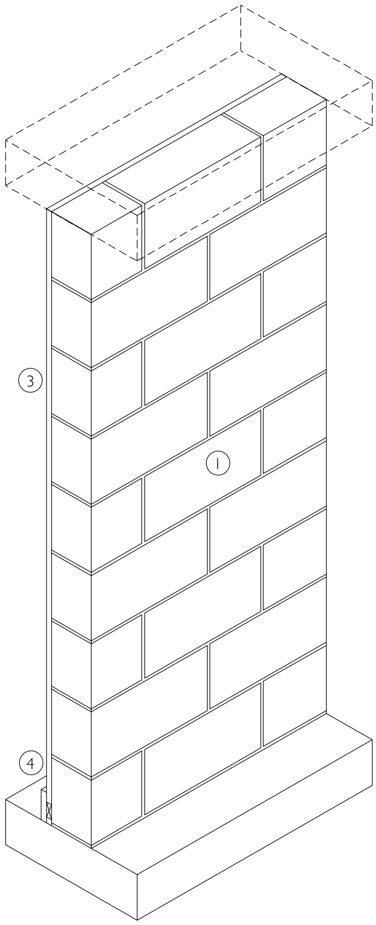
Glazing
Glazed partitions comprise sheets of toughened or laminated glass fixed either in a framing system in the manner of a large window, or are fixed without frames on their top and bottom edges only. Sheets are often made sufficiently thick to avoid the need for vertical framing members or mullions to provide rigidity. For example, a 10mm thick toughened glass sheet will span vertically to approximately 2.5 metres (8ft), depending upon intended use. Glass sheets are set with a vertical gap of approximately 10mm (3/8in) between them which is filled with a translucent or transparent silicone seal. The glass is secured top and bottom in small steel channels or steel angles set back to back. The channel or angle fixings are recessed into the floor and ceiling in order to provide an uninterrupted surface of glass. An alternative method is to bolt fix the glass, employing methods used in external walls which are described in the walls chapter. To avoid the problem of people walking into it, a line of manifestation marks is added to the glass where the partitions are used in public areas. They usually comprise a row of dots set at eye level and are either screen printed, etched or fritted onto the material.

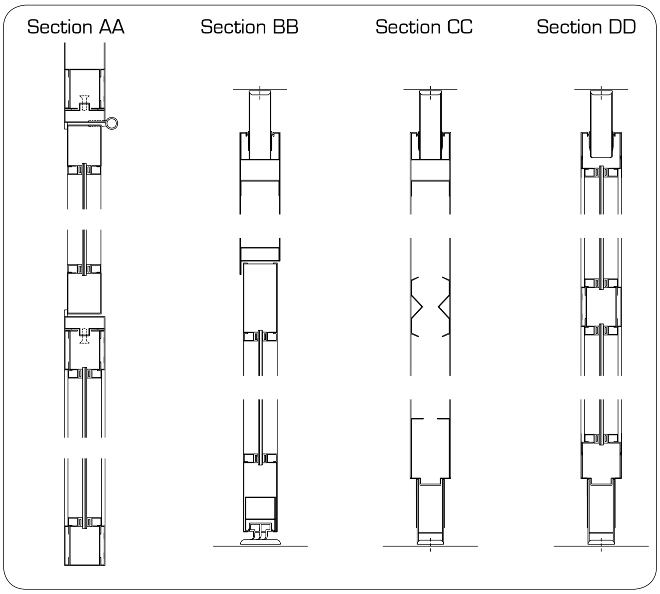
Demountable Partitions
Demountable partitions are used in office buildings where requirements for the subdivision of space change frequently in response to changing workloads and work patterns. Demountable partitions have been used for centuries in traditional Japanese construction. Sliding screens of translucent shoji panels and opaque fusuma panels are used for external walls and internal partitions. When they are used externally, an additional outer screen often protects them. These panels are all demountable and can create a variety of open and concealed spaces. Demountable partitions used in office buildings are available as a wide range of proprietary systems. Partitions can be moved easily with a minimum of disruption to the building in use. Manufactured demountable panels are often easily integrated with other systems for suspended ceilings and raised floors, to which they are usually fixed. Where a partition forms part of a fire break or smoke barrier, the voids above and below the partition, within the floor and ceiling zone, are sealed to form a continuous barrier. Solid panels often consist of a fabric finish stretched over plywood, or a laminate bonded to a board fixed in a frame. Glazed panels can be single or double-glazed. Venetian blinds are sometimes fixed between the two sheets of glass forming a double glazed panel to provide a variable degree of visual privacy.

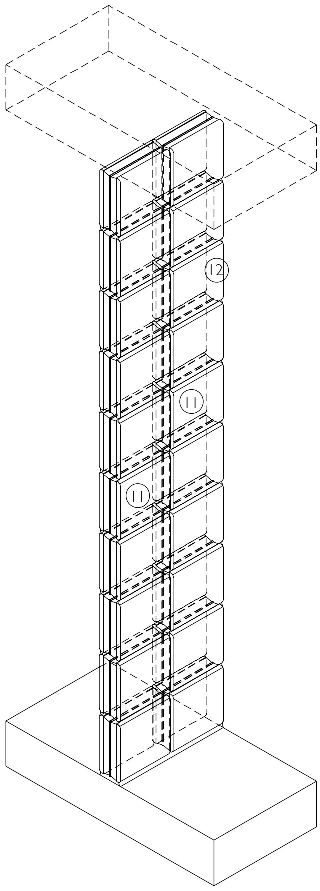


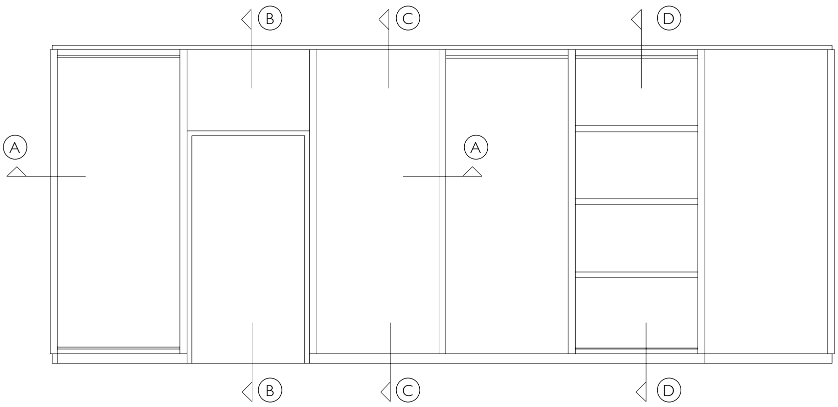
Horizontal elevation











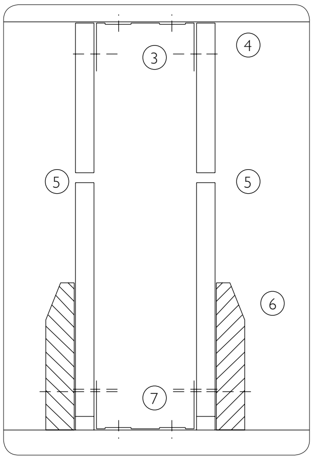
Part elevation

Plaster systems

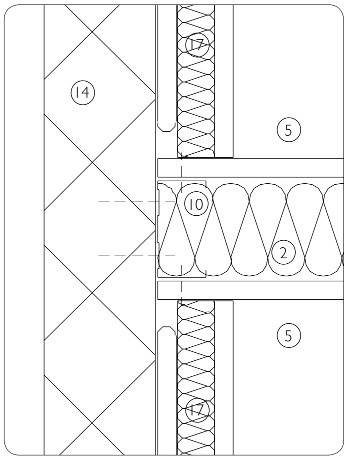
Plastered walls provide a smooth, continuous finish that is usually painted. Plastering is a traditional method that has been adapted for use on different wall backgrounds. An advantage of plaster is that complex shapes and edges can be formed. Dry pre-mixed plaster in powder form is used, in order to ensure a consistency of mix, and is mixed with water on site. Plasters are relatively soft and can have slots cut into the material easily for the passage of electrical wiring. This ease of use makes it a very practical wall finish which can be cut and patched to accommodate changes throughout the life of a building. Plastering is a labour-intensive operation that is carried out entirely on site and the quality of finish is very much dependant upon the skill of the individual plasterer. For this reason it is important to ask for sample areas of plastering to be provided on site to ensure that the required quality can be achieved. Like pouring concrete, plastering is a wet trade, which involves mixing the material with water and allowing it to dry out. This drying process can slow down other building operations, particularly where construction time is an important factor.

A wide range of plasters is used in different countries as a result of the availability of minerals varying between regions. Manufacturers should be consulted to advise on appropriate mixes for different applications. All plasters use either a sand-cement mix, a gypsum plaster (gypsum is a naturally occurring mineral) or a lightweight plaster made from minerals such as perlite or vermiculite. Plasters are usually applied in two coats, as an undercoat and finish. The finish coat has a finer texture in order to achieve a smooth surface by using a mix that would not be strong enough to be used as an undercoat. Plasters have different levels of surface hardness. For example, soft plasters might be used for exhibition spaces where paintings are frequently moved; acoustic plasters are used to increase sound insulation.

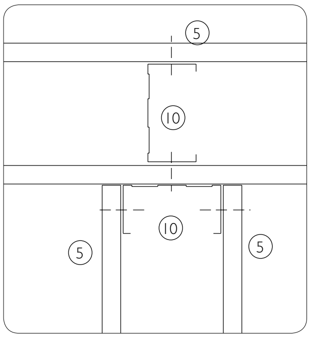
When detailing edges, junctions and openings in plastered walls, joints are needed where there is either a change in background material or a change in structure, such as where a wall meets a column. This is to accommodate thermal and structural movement at the junction between two materials. These junctions are treated either by a hairline joint, which is mostly concealed, or by a recessed joint that forms a shadow gap. The hairline joints use a layer of expanded metal lath that is nailed or screwed to the background and which spans the joint to form a continuous background. A breather membrane is set behind the metal lath to isolate the plaster if structural movement is expected. The plaster is then continued across the joint and is keyed into the lath where a different plaster mix, called isolating plaster, is sometimes used. Shadow gaps are often formed with galvanized steel trims to create a crisp line between the different backgrounds. The joint is revealed as a continuous groove down the joint. Both plaster and trim may be painted to create a homogeneous appearance. Plaster is also manufactured as lining boards that are fixed on site. The method used generally depends on the nature of the background surface where boards are preferred for use over uneven surfaces. Renders perform a similar function to plaster on the external surfaces of walls and soffits. Their characteristics are similar to plaster. They can also be used in a board form, fixed to a layer of rigid insulation.



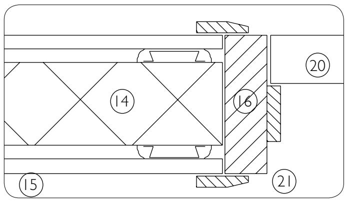
Vertical section



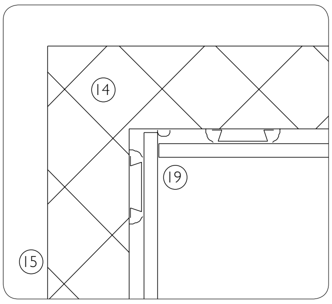
Vertical section



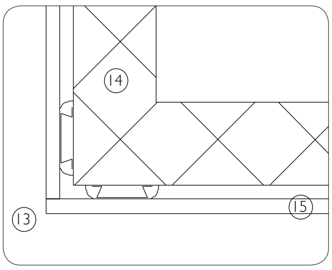
Horizontal section



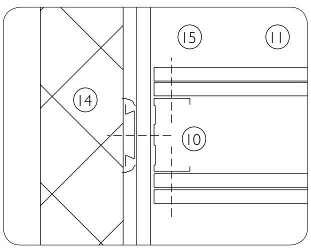
Horizontal section



Horizontal section

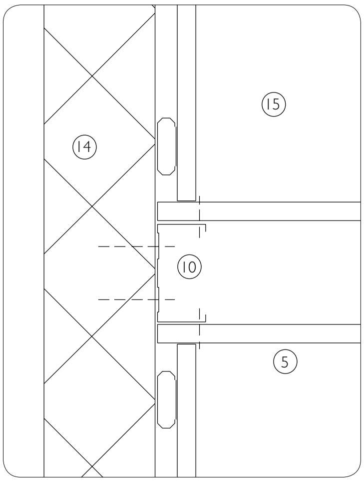


Horizontal section

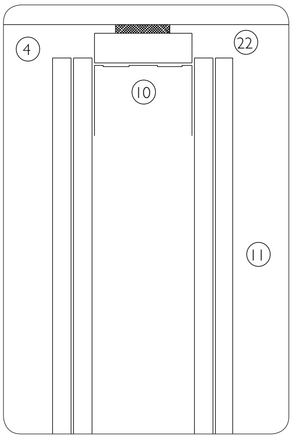


Horizontal section

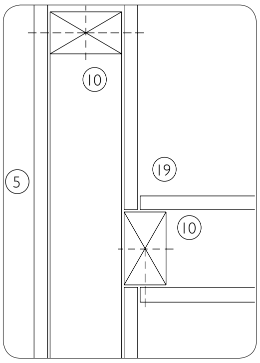
Details
1. Movement joint
2. Quilt insulation
3. Top rail in timber or metal (pressed steel shown)
4. Ceiling level
5. Plasterboard
6. Softwood skirting
7. Pressed steel bottom rail
8. Plasterboard
9. Floor level
10. Stud in timber or metal (pressed steel shown)
11. Two layers plasterboard/ drywall
12. Plasterboard/drywall laps adjacent run of partition
13. Plasterboard/drywall butt jointed at edge
14. Wall in different material (concrete block shown)
15. Plasterboard/drywall on battens or dabs
16. Internal timber door frame
17. Insulated board
18. Mineral quilt providing acoustic insulation
19. Plasterboard/drywall butt jointed at internal angle
20. Door leaf
21. Architrave
22. Packer



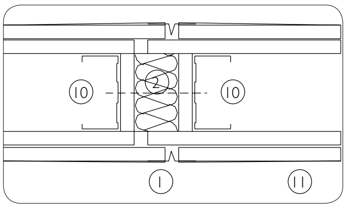
Horizontal section



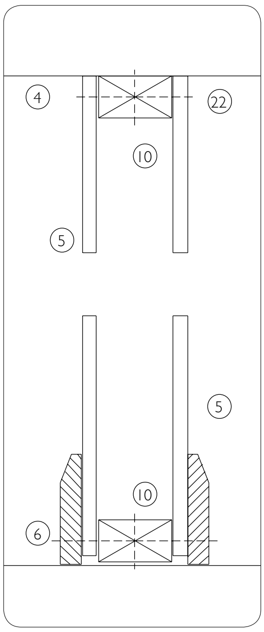
Vertical section



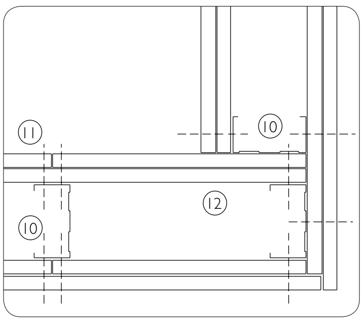
Horizontal section



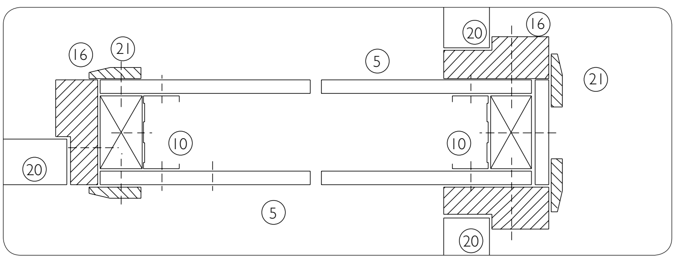
Horizontal section



Vertical section



Horizontal section



Horizontal section

Wallboard systems

Wallboard systems use gypsum plasterboard sheet to give a plastered wall finish to a variety of backgrounds. A thin skim coat finish over the plasterboard provides a continuous, dry fixed partition system that is fast to build. It is particularly useful on timber or metal-framed partitions where its use avoids the need for the more expensive traditional technique of plaster and lath. An alternative use of dry lining is to fix plasterboard sheets back to a masonry wall using either steel or timber battens which are screwed back to the background wall, or alternatively on plaster dabs which are literally dabs of plaster. A variety of gypsum plasterboard types is used; glass-fibre reinforced boards can be curved to form radiused corners. High-impact resistant boards are used where a hardwearing plaster finish is required, and fire-resistant boards are used in fire protection, particularly to structural steel frames.

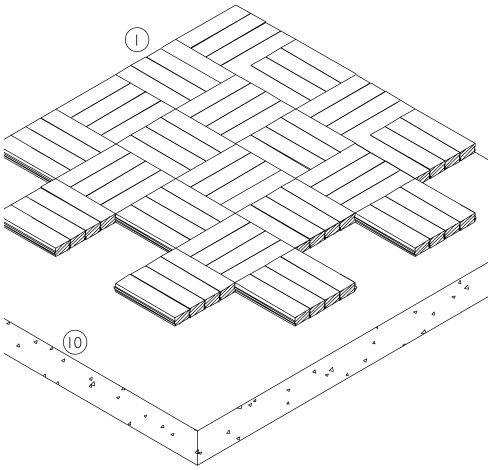
Wallboard systems are finished with either a 2 to 3mm (1/16 to 3/32 in) thick skim coat or a full 15mm (9/16in) plaster coat. In practice, the full plaster coat is not often used except, for example, on curved dry lining partitions in order to provide a very smooth finish. An alternative to a full skim is to use tapered edge plasterboard sheets to allow joints to be covered with paper tape and filled in order to avoid cracking. The wall is then coated to provide a surface ready for applied finishes such as painting. This almost 'dry' process allows following trades to start work sooner than with plaster, which requires much longer to dry.

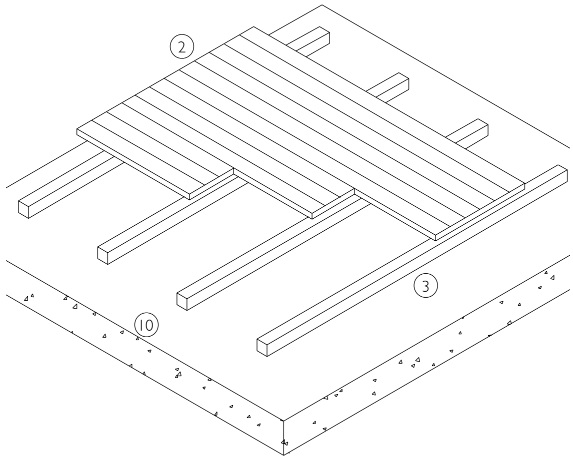
Wallboard covered stud partitions are assembled on site and can be easily modified either during or after construction. It is difficult to re-use plasterboard sheets although the studs can be recycled. Wallboard covered partitions often perform better acoustically than an equivalent blockwork partition. Partitions can be formed using three or more layers of plasterboard sheet without the use of studs to a maximum height of approximately three metres (10ft).

Timber stud partitions are limited to around 3.5 metres (11ft 8in) in height, since cut timber sections of greater length are more difficult to obtain and are expensive. Metal studs provide most flexibility in terms of partition thickness and height, spanning up to around eight metres (26ft 8in) without need for intermediary support. With longer spans, partition thickness can be reduced to around 150mm (6in) by setting studs at closer centres, typically 300mm (1ft) and by changing the stud type. Short vertical spans, up to around 3 metres (10ft) use cold formed pressed steel channel sections, while longer spans up to approximately 5 metres (16ft8in) use the same channels set face to face to form a box section, while spans up to 8 metres (26ft) use cold formed back-to-back channels that form an I-section. These studs are also available in varying depths to provide different overall partition thicknesses to accommodate the layering of sheets for varying amounts of stiffness, fire resistance and acoustic performance.

In common with plastered walls, expansion joints are required where there is a change in construction in order to accommodate thermal or structural movement at the junction of two different backgrounds. This typically occurs at the junction of a partition and a structural column. Junctions can be continuous if constructed using a latex-based plaster. Alternatively, a shadow gap is formed which uses galvanized steel trims to create the shape of the joint in a way that imitates a plaster recessed joint.

Details
1. Timber flooring block
2. Timber boards
3. Timber battens
4. Ceramic tile
5. Stone
6. Compressible seal
7. Compressible backing
8. Stainless steel angle
9. Bedding compound
10. Concrete floor





Fixed floor finishes are those which are not intended to be accessible or demountable and form a permanent part of the building. Floor finishes are usually harder and more resilient than the floor structure, or substrate, beneath. Since the properties of finishes and substrates are usually different, the finish used must be laid in a way that allows both it and the substrate to move together or be separated in order to avoid cracking in the floor finish. Where there are movement joints in the floor structure, the floor finish is usually broken to allow expansion and contraction. As a result, the finish can influence the design of the substrate. For example, a cast-in-place concrete slab may require contraction joints at centres which do not correspond to the module of a proposed tiling layout but which should be adjusted to suit the design of the floor finish.

Concrete

Concrete can be used as a self-finish to a floor slab, with its surface sometimes polished to provide a smooth, dust-free finish, either as a screed or as a power-floated finish to a floor deck. Grains of carborundum can be added to improve the wear of the floor. Concrete floors can be coated with floor paints which have improved enormously in recent years to provide fairly hardwearing surfaces that will last up to 5 years, but are not suitable for very heavy use which can cause the paint to wear away quickly. An epoxy coating is used where a harder surface finish is needed for heavy foot traffic, particularly for industrial applications. This polymer coating has excellent resistance to abrasion but is a very hard surface to walk on. A softer surface is provided by rubber-based compounds which are used in indoor sports facilities, but they have less abrasion resistance. Both epoxy and latex coatings, together with variations such as polyester resins, are referred to as poured floor finishes due to their ability to be poured in place to provide a self-levelling joint-free floor finish. They are poured over large floor areas to produce thicknesses of up to 6mm (1/4 in). Made by mixing a resin with a curing agent, they provide a hard, smooth finish which can be coloured and is resistant to chemical attack.

Terrazzo is a hardwearing floor finish that is applied to a concrete substrate. It consists of crushed marble aggregate mixed with cement. The material is applied as wet mix to a thickness of between 15 and 25mm (5/8in to 1in) depending on whether it is bonded directly to the screed or concrete slab beneath. Terrazzo is bonded by laying it on the concrete substrate while it is curing (but hard enough to walk on). It is laid in bays formed by movement joints (expansion and contraction joints) in the concrete substrate. The bays are separated by stainless steel, brass or bronze angles in a very similar way to ceramic tiles. Terrazzo is finished by grinding and polishing.

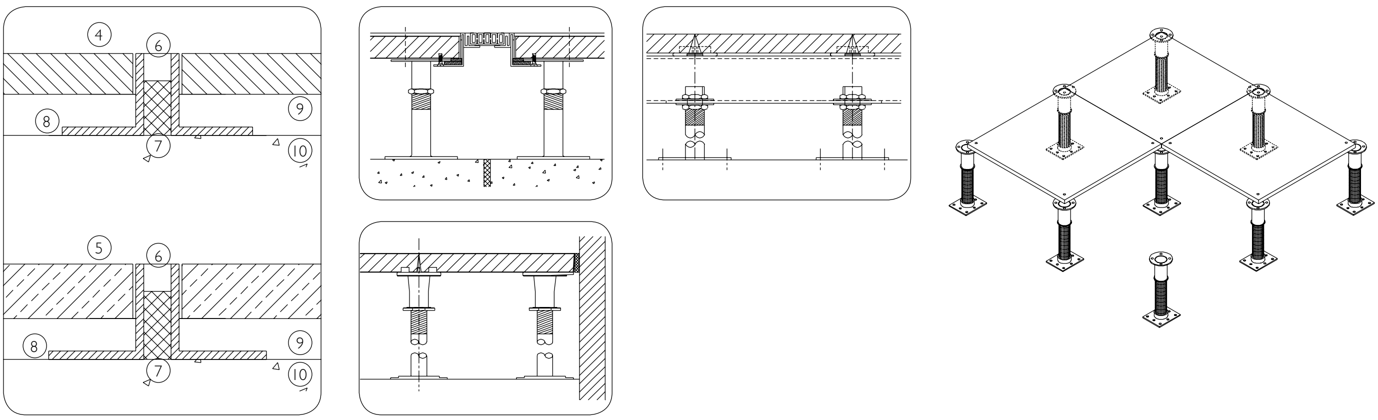
Stone

Stone is used as a fixed floor finish in the form of paving slabs that are bedded in a sand-cement screed and can be used both internally and externally. The thickness used depends on the strength and thickness of the stone and the size to which the stone can practically be cut from blocks. The most common thickness is 20 - 30mm (1in to 1 1/2in) with slab sizes adjusted to allow it to be carried by hand and laid in place. A common size is a module of 500 x 500mm (20 x 20in) or 600 x 600mm (2ft x 2ft) slabs, which allows 10mm for the joint between them. For small applications, stone can be ordered from choosing a sample, but for large areas, the material is cut to order and the architect should visit the quarry to choose the material. In common with other natural materials, it is difficult to define precise visual qualities since its natural formation produces an enormous variety of appearance. The usual method is to define 'extremes' of quality between the most and least marked, and the lightest and darkest in a set of sample slabs. Because stone has little strength in tension, the substrate must be firm, with very little structural movement or deflection.

Stone floors are ground before being laid to provide different surface finishes. They can be polished, using fine sanding wheels, or honed, using rougher grinding wheels. Floor sealers are often not recommended for some stones since some slabs will be more absorbent than others, resulting in exaggerated colour differences across a floor surface.

Timber

Timber flooring can be used as a floor finish on concrete, timber or cold-formed steel framed floors. In all three instances, the substrate is sealed with a vapour barrier to avoid the timber rotting. The timber is either loose-laid as solid strip flooring, fixed on bearers resting on the substrate, or bedded in mastic or bitumen as block flooring. Strip flooring has traditionally been used with timber strips less than 100mm (4") wide, while boards indicate anything wider up to a limit of around 150mm (6"). Nowadays strip flooring refers to all sizes of hardwood tongued



Vertical section

and grooved board. Thicknesses range from 9 to 38mm (3/8in to 1 1/2in). Almost all types are proprietary systems that are either fixed to supporting battens as a sprung floor, typically used in sports halls, or are held together by pressed steel clips as a continuous material that rests on the substrate. Beech and maple are the most common hardwoods used, which have a light-coloured appearance. A gap between the floor and the wall is left to accommodate movement in the wood due to changes in temperature and humidity. This gap is typically 10mm (3/8in) for a four metre (13ft) wide bay of strip flooring.

Wood block flooring consists of small hardwood blocks that are bonded with bitumen to a concrete floor. Block sizes vary from 25 to 100mm (1 to 4 in) wide and 150 to 300mm (6 to 12 in) long. Depths vary from 19 to 38mm (3/4 to 1 1/2in). Blocks are bonded directly to the concrete with a bitumen-latex adhesive. Simple rectangular patterns or herringbone patterns are the most common ways of laying blocks. Both strip flooring and block flooring require a surface seal, such as polyurethane sealer, to avoid dirt being trodden into the grain. This is re-applied every few years depending on the amount of wear experienced by the floor.

Floor tiles
There are two types of tiles for flooring; these are ceramic and quarry tiles. Ceramic tiles are manufactured from refined clays, while quarry tiles are made by extruding or pressing natural clays. Whereas the former are available in a wide range of colours, the latter are produced only in their natural colours of reds, browns and blues.

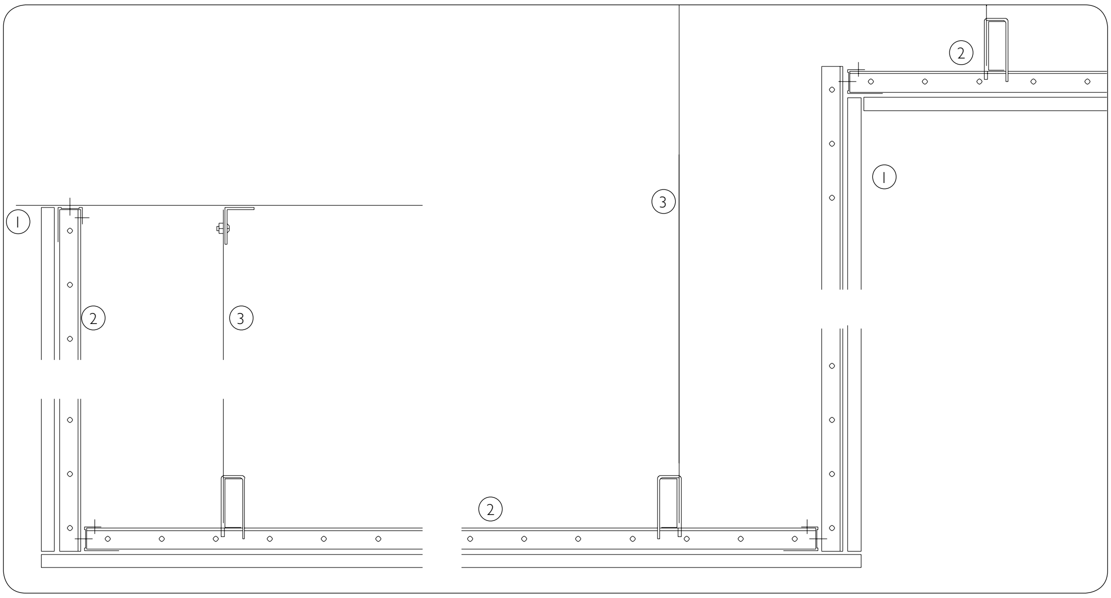
Floor tiles are made in many sizes and thicknesses. They are laid either on a bed of sand-cement mix or adhesive. Each bay of tiles is edged with a 6mm (1/4in) wide movement joint, which can be filled with a flexible seal, such as polysulphide. Maximum bay size is usually six metres x six metres (20 x 20 ft). The bay size depends on whether the area is reached by sunlight and/or moisture. Metal edging strips, or a rigid sealant such as epoxy-polysulphide, is used to protect bay edges in large areas of tiling.

Raised Floors
Raised floors were first used as computer floors to provide a zone for electrical cables and air handling ducts to large computers housed in a separate room. They are now used throughout office buildings as a means of providing a zone for mechanical and electrical services including ventilation, as either a complement or replacement for those used in suspended ceilings. Raised floors are used as a method of bringing electrical cables under the floor to a large number of points while allowing tiles to be moved to accommodate changing servicing requirements. Completely open voids can also be used as an air plenum to supply or extract air in a mechanical ventilation system.

Raised floors are manufactured as proprietary systems with different loading capabilities, designed to be either fully accessible or semi-accessible, depending on the ease of use and frequency of access required to the floor void beneath. Fully accessible types have a much greater range of void depth, ranging from 100mm (4in) to around 2000mm (6ft). Semi-accessible types are restricted to low floor voids of around 150mm (6in). The fully accessible types are generally steel composite panels with a concrete-based infill, supported on variable height pedestals. Semi-accessible types are generally made from timber composite panels supported on concrete pads or timber battens. The two types have varying degrees of rigidity in their framework to suit the degree of accessibility required. In some systems, structural stability of the frame is lost if too many modules are removed for maintenance access.

Fully accessible floors are made with a variety of construction methods. Some are made as a support framework with legs beneath. The panels fit into the frame to be supported on all four sides. Others have self-supporting panels supported on an adjustable leg in each corner. Semi-accessible systems vary even further in their design. Some comprise a single precast concrete tray with integral legs. These are laid side by side directly onto the floor slab. Others are very similar to the timber sprung floors used in sports halls, consisting of a rectilinear grid of softwood battens resting on acoustic pads to prevent sound transmission. Timber composite boards are screwed down to the frame.

Ventilation grilles and electrical socket boxes can be incorporated into all types. Floors typically have carpet tiles loose laid on top, to provide both a comfortable walking surface and for acoustic purposes. Carpet can be separately bonded to each tile or be loose laid off the grid to conceal joints in the floor beneath.



Vertical section

Suspended ceilings are used primarily to provide a service void between a ceiling plane and the underside (soffit) of the structural slab above. This zone is used to house recessed light fittings, ducts for mechanical ventilation and associated equipment. There are two generic types of suspended ceiling. The fixed version is used where a continuous plastered surface is required and where there is no need to access the ceiling void from below. Accessible types are used primarily in office buildings where they integrate with a modular layout of partitions. They are designed to suit both cellular office layouts and open office areas requiring individual lighting and mechanical ventilation.

Fixed suspended ceilings consist of either layers of plasterboard sheets or wet-applied plaster on metal laths which are supported on a frame suspended from the soffit of a structural slab or floor on either wires or galvanized steel strips. They can be designed as a simple timber or metal supporting frame or be specified as proprietary manufacturers' systems.

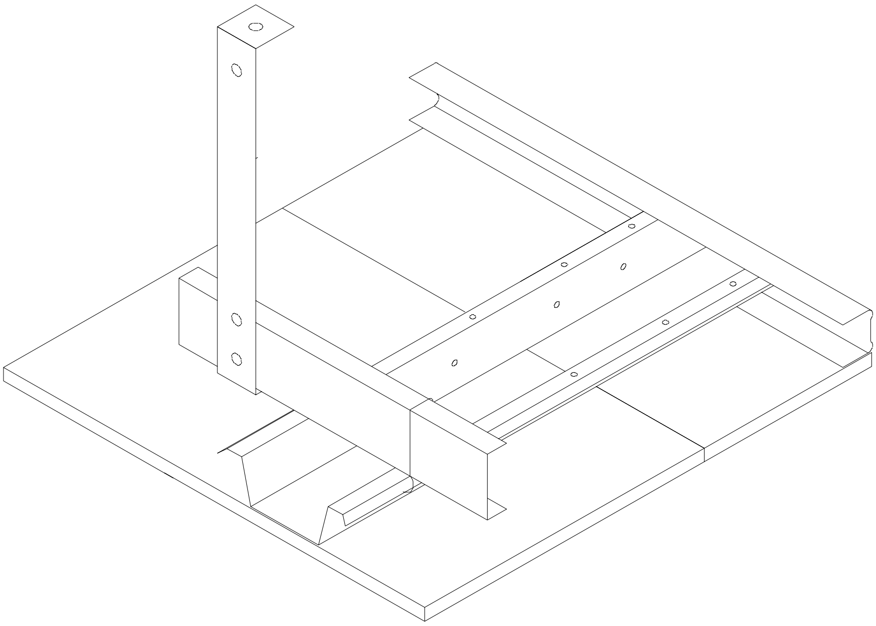
Fixed ceilings create a smooth, continuous soffit for recessed lighting and a ceiling plenum for ducts that do not require access. They can also provide a fire-resistive layer where this is not provided by the supporting floor structure. Access hatches can be used but are difficult to conceal. Fixed suspended ceilings can be used to form single direction curves by bending plasterboard around a modelled frame.

Complex shapes can be formed with metal laths. Fibrous plaster is often used, which provides a smooth surface that is easy to work but lacks the strength of other plasters. As a result, it is applied onto a reinforcing mesh in a very similar way to ferro-cement. Fibrous plaster is used where curves in two directions are required as well as in repetitive decoration, where items can be made in a workshop and later fixed to the ceiling.

Accessible ceilings use a supporting grid in steel or aluminium. The two most commonly used types are the T-section and the spring clip. Both are designed to be as light as possible with varying degrees of strength and rigidity, which are defined by the loads imposed on the ceiling by services from above and by partitions fixed to it from beneath. In some manufacturers' systems, dimensional stability of the frame is lost if too many tiles are removed during maintenance access. The T-section uses an inverted T-shaped aluminium extrusion which holds the ceiling tile in place. The tile either sits directly on the section, creating an exposed grid, or is set hanging partially below the frame in a semi-concealed grid. The spring clip system allows the tile to be slotted into the support grid from beneath in a concealed system. The support grid can also be concealed by fixing the tile onto a T-section grid from beneath. This is done where aluminium or steel sheet is countersunk screwed to the support frame. Noise control within a room, or between adjacent spaces, is achieved by setting a sound-absorbent board or quilt onto the upper face of the ceiling tiles. The tiles are usually perforated to allow sound to pass through to the insulation behind.

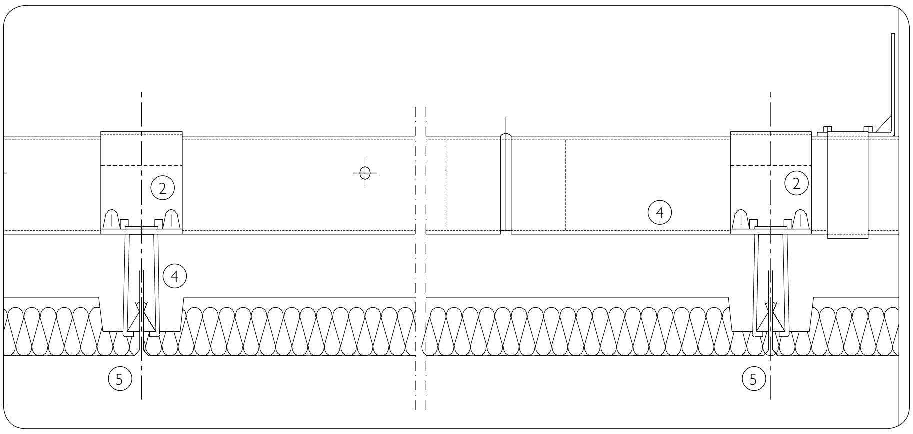
The most common support grids are the one-way grid and the two-way grid. The one-way system has identical sections set parallel, at centres corresponding to the width of the tiles. Tiles are supported on two sides and span between the sections of the grid. Partitions beneath can be supported continuously in one direction but are supported only at points in the other direction. The reduced flexibility makes the system economical. A two-way system uses either metal cross tees that span between the main runners or by using the same sections set perpendicular to one another to create a full grid. The latter type is made by half-jointing the main runners where they cross. The increased flexibility of the two-way system makes it more expensive. The frame is fixed back to the soffit with members of varying rigidity: wires, rods and angles. Suspension wires are not usually appropriate if partitions are fixed in such a way as to exert pressure from below.

Like their supporting grids, ceiling tiles are designed to be lightweight. The most economical generic tile is mineral fibreboard, which provides high acoustic insulation but is limited to smaller spans due to its lack of rigidity. Greater thicknesses of board add considerably to the weight of the ceiling. The typical grid size in this material is 600 x 600mm (2ft x 2ft). Larger tiles are made from perforated steel trays. Since steel is a poor absorber of sound, it is perforated to enhance its acoustic performance, and in addition can be lined on the upper face of panels with either thin mineral quilt or an acoustic pad. Ceiling grids up to around 2000 x 3000mm (6ft 6in x 9ft 10in) are possible. Aluminium sheet can also be used but it requires a greater depth of vertical edging to attain the spanning capability of steel. This increases the overall depth of the ceiling.

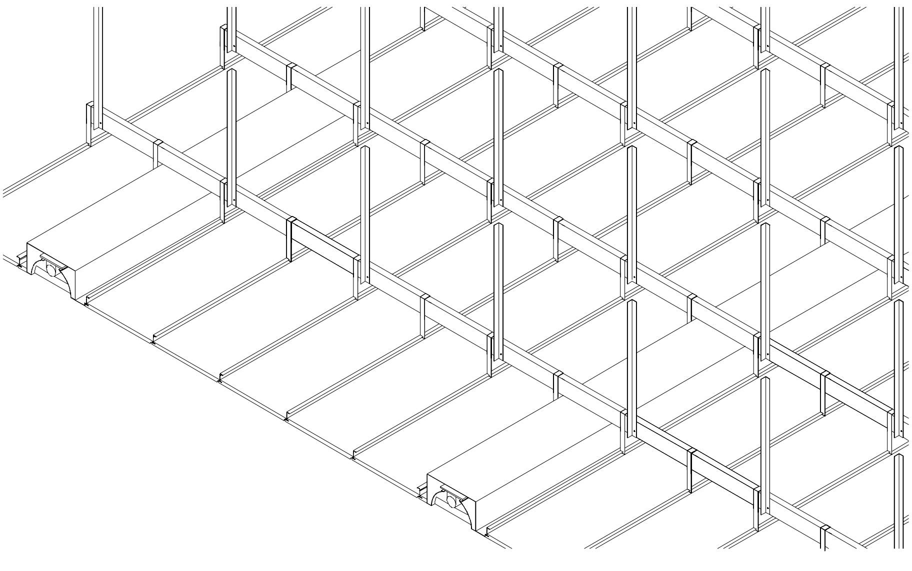


Details
1. Plasterboard/drywall
2. Fixing rails
3. Suspension rod, wire or pressed metal strip
4. Clip to secure panel
5. Ceiling panel (perforated metal panel with acoustic lining shown)

Details
1. Plasterboard/drywall
2. Fixing rails
3. Suspension rod, wire or pressed metal strip
4. Clip to secure panel
5. Ceiling panel (perforated metal panel with acoustic lining shown)



Vertical section



Movement transducers are fixed to structural supports that are not affected significantly by the wind pressures created by an aero engine. Transducers are calibrated and checked to ensure their reliability during testing.

The digital types shown provide a continuous set of readings during a dynamic air pressure water penetration test. The wall sample is checked visually throughout the duration of the test to check for any signs of water penetration.

An array of water spray nozzles around a glass rooflight is used to check the water tightness of silicone sealed joints.

A test rig with additional architectural elements added to combine a performance test mock-up and visual quality mock-up as a single item.

The performance testing of facade systems is undertaken for a number of reasons, the most important usually being the weather tightness of the system. Where twin wall facades and external solar shading devices form a part of the system, overall stability under wind load forms an important part of the testing. A range of tests simulate the worst conditions, and combinations of conditions, that can be expected to occur during the life of the facade. Performance testing is a check of the design approach, both visually and technically. It also assists the fabricators to understand the complexities of making the components and assemblies as well as assisting the installers by familiarising themselves with the system and allowing them to make adjustments during the construction of the mock-up at the laboratory. The test mock-up also serves as a way of agreeing how to achieve the required quality of construction, which may range from flatness of glass to smoothness of welding and surface textures. The test mock-up for a facade is both a vehicle for learning during its assembly and a checking of the required performance during its lifetime. Along with test results, which it is hoped will show the design to have been successful, there is much information that can be accumulated about ease of construction, avoiding surface damage and the visual checking of components that can inform the complete facade installation on the actual building.

The test rig

Test rigs are assembled at test laboratories that are specially equipped to deal with building facades, and so are in part a simulated building site, and in part a scientific laboratory. Facade panels are set into a test rig, comprising a well-sealed chamber, made usually from a steel frame clad in steel sheet and plywood, accessed through a door in the chamber that can be sealed. The test panel is fixed with its external face outwards and is supported by a rigid steelwork frame, usually of I-sections designed to simulate the actual fixing conditions of the facade to the primary structure. The facade panel is erected at the test facility and is enclosed and sealed into the chamber.

A measurement of static pressure is taken inside the chamber, with readings taken in a position that is not affected by the velocity of air supply into, or out of, the chamber. A fan, usually connected to ductwork, is fixed to the test rig to create positive or negative pressure in the chamber, that is, higher or lower than atmospheric pressure. The fan provides a constant airflow at fixed pressure for the duration of the tests.

A wind generator, usually a propeller-type aircraft engine, is used to create positive pressure differentials during dynamic air pressure water tightness testing. It is mounted in front of the external face of the facade panel. A positive pressure differential is where the pressure against the external face of the facade panel being tested is greater than that against the interior of the chamber.

The effect of rain is simulated by a water spray system with nozzles spaced at regular centres, both vertically and horizontally, usually around 700mm (2ft 3in) apart and set 400mm (1ft 4in) from the face of the test panel. The nozzles have a wide angle spray to cover the facade panel with water as evenly as possible. A hydraulic jack is used to displace the test rig support beam

An impact resistance test on a glazed panel.

A site-based hose test to check the performance of the tested system when installed in a building.

A pull-out test on a balustrade checks that the unusual design will not generate a significant deflection when installed.

Bolt torques of facade assemblies are checked on site to ensure that components can accommodate expected structural movement.

to simulate structural movements in the supporting structural frame or backing wall.

Deflection transducers are used to measure the deflection of principal framing members to within an accuracy of around 0.25mm. Transducers are telescopic-like devices where a rod is held in a sleeve and is pushed in or out as it is held against a facade panel. Gauges are installed on a separate support frame in order not to be influenced by the application of pressure or loading to the facade panel.

Air infiltration and exfiltration
Measurements of airflow are taken at a positive pressure differential of 600 Pa (Pascals). The first test has the chamber sealed to determine the chamber leakage. Joints in the facade are taped up in order to provide a reliable seal. The test is repeated with the tape removed, but with any opening lights sealed. The difference between the two readings is the airflow through the facade. The average flow rate for fixed glazing at 600 Pa should not exceed 1.1m^3 per hour per m^2. For opening lights the figure is 1.4m^3 per hour per metre length of internally visible joint.

Static air pressure water penetration
Water is sprayed continuously at a rate of 3.4 litres/m^2/minute, if internationally recognised ASTM standards are applied, onto the facade panel, with a pressure differential of 600Pa applied across the panel and maintained for 15 minutes. Throughout the test the interior face of the panel is checked for water penetration.

Dynamic air pressure water penetration
Deflection measurements are taken on several cladding members at a positive static air pressure differential of 600Pa. A wind generator is mounted adjacent to the exterior face of the facade panel. The generator output is adjusted so that the average deflections of the member matches the deflections measured at the previous 600Pa pressure differential. Water is sprayed onto the facade panel at a rate of up to 3.4 litres/m^2/minute for 15 minutes, depending on the standards used. The interior face of the facade member is checked for water penetration.

In both static and dynamic tests the aim is to check that no water has penetrated through to the inside face of the panel that could stain or damage any part of the building. Any water entering the system should be contained and be drained to the exterior. If the test is unsuccessful then remedial work is done to the design and to the test mock-up.

Impact resistance
Impact resistance is measured with a soft body impactor, which consists of a canvas bag, in a hanging spherical or conical shape filled with glass balls. The weight of the bag is usually 50kg and is suspended from a cord around 3 metres (10 ft) long. The impactor is positioned so that it hangs at rest in a position that just touches the facade panel. For horizontal or inclined facade panels, the impactor may be dropped vertically onto the facade panel. The bag is swung from the top of the rope. In either case the impact energies are the same and are usually set at 120Nm, for a drop height of 0.25m for serve-

3 test rigs used to assess the performance of a range of wall types.

An aero engine generating strong air movement is set in front of a rack of water spray nozzles that simulate wind and rain at different pressures.

An opaque glass rainscreen wall has projecting glass fins which are being tested for their rigidity.

A bolt fixed glazing system has high expected deflections when compared to a framed system.

ability, and 350Nm for a drop of 0.71 metres (2ft 4in) used for safety. In the serveability test, for a test to be successful there must be no damage to the panel, and air and water penetration performance must not be reduced. In the safety test, no components can become detached from the system, and the impactor must not pass through the wall. The impact resistance test is performed on joints and panels in materials other than glass.

Wind resistance serviceability test
In this test, instruments are positioned to measure deflections of representative framing members. One positive or negative pressure differential of 50% of the positive or negative design wind pressure, held for 10 seconds, is applied to the panel. After a recovery time of one or two minutes, the displacement transducers are set to zero. A positive pressure differential is then applied to the panel and held for 10 seconds, in order to take the readings, at 50%, 75% and 100% of the positive or negative design wind pressure. After a recovery time of 1-5 minutes, readings are taken for any remaining deflections. In a successful test, no permanent damage will have occurred at both positive and negative applications of peak test pressure, set at the design wind pressure. In addition, the maximum deflections will not exceed the following figures, which are given for general guidance only:

General framing members: 1/175 of clear span, to a maximum of 19mm
Glazing framing members: 1/240 of span
Framing members when finished material is attached: 1/360 of clear span
Framing members for support of natural stone: 1/500 of clear span

At 1.5 times design wind pressure, for both positive and negative pressures, there must be no permanent damage to framing members, panels or fixings. Glazing beads and copings will have remained in place and gaskets not displaced. Permanent deformation to wall framing members will not have exceeded 0.2% of span up to one hour after loading has been removed.

Seismic building movement test
A mid-height support beam is displaced horizontally and then back to its original position. At each stage, visual observations are made, with the test being conducted three times. Displacements, in terms of mm, are determined as 'probable' or 'credible' displacements. In the 'credible' test, there must be no permanent damage to the framing members, panels or fixings. Glazing beads and cappings must be held securely and gaskets not be displaced. In the probable test, no racking or distortion of members occurs. The panel must then pass the subsequent air and water penetration tests.

Inter-storey movement
The mid-span point of the mid-height support beam is displaced by a fixed distance vertically downwards then back to the centre, tested three times, during which no racking or distortion of the members is allowed to occur. The panel must pass the subsequent air and water penetration tests.

Mock-ups are designed and fabricated from parametric models with three purposes in mind for each assembly: visual approval by the design team; using the actual fabrication method proposed for the project to see how this can be made more cost effective; performance testing for essential weather resistance under dynamic conditions as proof-of-concept.

Wind resistance safety test

Instruments are positioned to measure deflection of representative framing members. One positive or negative pressure differential pulse of 75% of the positive or negative design wind pressure, held for 10 seconds, is applied to prepare the panel. After a recovery time of 1-5 minutes, the displacement transducers are set to zero.

One positive or negative pressure differential pulse of 150% of the positive or negative design wind pressure is applied and held for 10 seconds. After a recovery period of 1-5 minutes, readings are taken for any remaining deflections. At both positive and negative application of peak pressure, there must be no permanent damage to framing members, panels or fixings. For a glazed wall test panel, for example, pressure plates and decorative cappings must remain securely held and gaskets must not be displaced. Permanent deformation of wall framing members must not exceed 1/500 of the span, which is measured between the fixing points, usually measured one hour after the loading has been removed. At the end of tests the facade panel is dismantled in controlled conditions to check that it complies with the design drawing. In the event of test failure, any water that has penetrated into the system is recorded.

Site hose test

In addition to laboratory tests, a facade system can be checked on site with a controlled hose pipe test. This test is conducted using a nozzle that produces a solid cone of water droplets with a spread of approximately 30°. The pressure is around 220 kPa (30-35 psi) at the nozzle with a flow rate of around 22 litres per minute. Typically, water from a hose is directed at the area of completed facade on site, perpendicular to the face of the wall. The direction of water from the hose is set 300mm (1ft) away from the wall and is directed in a linear direction across 1500mm (5ft) of the wall for 5 minutes. The test starts from the bottom of the wall upwards to determine when leaks start to occur within the system. The inside face is continuously checked for leaking. If no leaks are found, the hose moves on to the next adjacent area of facade under test. If leaks occur, the system is allowed to dry out then is completely taped up at the joints. Starting again at the bottom, the tape is gradually removed while applying water from the hose again until the location of the leak is found.

Post test conclusions

In addition to verifying the performance of the facade system, any adjustments required during the mock-up must be carried out on site. The quality of construction for the mock-up can also be used as a 'benchmark' or quality control sample for the completed facade. This can avoid many difficulties later on site, where the earlier expectations at the drawing stage can mature at the mock-up stage before installation commences, allowing all parties on the building project to agree to visual appearance and quality of assembly before proceeding to production.

The testing of a roof system is undertaken typically with a small test panel that contains the full range of joints that comprise the system as well as the maximum span that the system can accommodate. This is to ensure that adequate weatherproofing can be provided while the system experiences maximum deflections from both positive and negative wind pressures.

Testing of water tightness of mock-ups has until recently been restricted mainly to facades. Roof structures are usually tested in a specialist laboratory when they differ technically from standard systems, or have an unusual combination of standard systems. Testing is usually restricted to systems in metal, glass and plastics. Concrete, timber and fabric do not usually require test mock-ups, since their performance is well established both in the systems used, and as industry-wide specifications. Test rigs determine the ability of the mock-up to remain watertight and airtight when the various design loads are applied to the mock-up. In addition, the effect of a falling object onto the roof is tested when it is considered essential to withstand the load to protect building users beneath when they are at possible risk, from higher buildings adjacent to the roof, for example. A test that is particular to roofs, and is not undertaken in facades, is the flood test. An area of roof is filled with water up to a level anticipated in the event of rainwater outlets being blocked and left standing for up to several days. This is usually undertaken on flat roofs where there would be standing water in the event of blocked outlets, and applies to pitched roofs only at gutters or drainage points. This test is usually undertaken on site, typically for single membrane roofs on a flat roof deck in either concrete, steel or timber.

Mock-ups for performance testing have the added benefit of revealing the installation problems inherent in the system, particularly if some innovation is involved, and allowing the design team to see how the roof will appear before proceeding with the work in the workshop or on site. The mock-up can also be used to establish an accepted level of quality of construction, particularly with regard to visual crispness of assembly, flatness of materials, visible joint widths, finishes and colour.

The workshop usually has at least one panel or set of joints that covers an area sufficiently large to provide full structural deflections of framing members, as well as internal ventilation and drainage in the case of glazed roofs. There is little point in testing a panel 300mm x 300mm in size that includes only one joint, since the overall effects of movement under full design wind load cannot be determined unless a full panel is tested. The test mock-up panel is set at the same angle at which it is to be used in the completed installation. Where a range of angles are encountered, the most vulnerable, or extreme, angles are taken to form the mock-up. The roof mock-up is set 1500mm to 2000mm above the ground level to allow the underside to be inspected easily, and set typically on a concrete slab. The roof sample is usually supported on a steel frame at its edges in a way that simulates the structure used in the building. The space beneath the roof is then enclosed, usually with plywood sheets which are sealed at the interfaces with the mock-up and with the floor slab or deck beneath to provide as air tight an enclosure as possible. A door is provided into the chamber which is able to be clamped shut during the testing.

The test chamber is pressurised with an air supply in order to establish the amount of air infiltration through the system. The air supply is provided usually by a flexible hose that passes through an opening in the plywood chamber enclosure. The hose is connected to a centrifugal fan which can either supply air to, or extract air from, the test chamber.

The largest external component in the testing is an aero engine with propellers which acts as a generator for the wind pressures applied to the test mock-up. A grid of water spray nozzles is set above the mock-up in order to simulate rainfall onto the roof.

A canvas bag filled with small diameter glass spheres is provided for the soft body impact test, which is typically dropped from a mobile platform or temporary scaffolding tower set next to the test sample.

Air infiltration test
In order to establish the rate at which air filtrates through the assembly, the mock-up is first subjected to a single positive pressure 'pulse' which is held for 10 seconds, which corresponds to half of the design pressure for the roof system. This is done in order to pressurise the test chamber and ensure that the

The test chamber, which is capable of being fully sealed, is fitted with an air supply to provide both positive and negative air pressures on the internal face of the roof sample panel.

chamber has been properly sealed. This is done before testing commences. The pressure inside the chamber is now increased to a difference of 600 Pascals between inside and outside. The roof sample is first sealed with tape to determine chamber leakage, and measurements of airflow are taken, which, for fixed rooflights should not, typically, exceed 1.1 m^3 per hour per m^2. The airflow test is repeated with the tape removed. The difference between the two readings indicates the air infiltration rate through the roof sample.

Water penetration tests

These tests are conducted both under static air pressure, that is, with no significant wind blowing across the sample, and at dynamic air pressure, where an aero engine blows air onto the sample. In the first test, the static air pressure water penetration test, water is sprayed from the nozzles onto the roof mock-up at a rate of at least 3.4 litres/ m^2 /minute. The water spray nozzles are set out on a grid so that nozzles are no more than 700mm apart, and are fixed at around 400mm from the face of the sample. This ensures that all parts of the roof sample are sprayed with water. A pressure differential corresponding to 600 Pascals is applied across the sample for 15 minutes. The interior face of the mock-up is checked for any water penetration. The test is repeated at the same pressure with a propeller-type aero engine to provide the same 600 Pascal pressure difference across the sample. The underside of the mock-up, inside the chamber, is checked to ensure that no water drops are visible as a result of penetrating the roof assembly.

Wind resistance tests

In these tests, pressure transducers are fixed to the inside face of the roof sample, in positions where the deflectors are most critical, such as at the centre of framing members, or the centre of panels. Transducers are telescopic gauges that measure deflections, usually to an accuracy of 0.25mm. Readings are taken digitally at a distance from the test chamber. The transducers are set by applying a positive pressure 'pulse' of 50% of the positive wind pressure for 10 seconds. After a recovery period of up to 5 minutes, the pressure transducers are set to zero to establish a 'zero' level for the test. A positive pressure is then applied to the roof mock-up and held for 10 seconds at different pressure deflections. Readings are taken at 50%, 75% and 100% of the positive design wind pressure. After a period of up to 5 minutes, any remaining (or permanent deflections) in the sample are recorded. This process is repeated for negative wind pressure, where air is drawn out of the test chamber. The test starts again from the beginning, with a 50% pulse held for 10 seconds in order to establish a 'zero' level for the transducers.

These two sets of tests for positive and negative wind pressures establish whether the mock-up deflects within the limits set out in the design, at the design wind pressure (typically 1400 Pascals). These two tests are repeated at 1.5 times the design wind pressure in a safety test. The pressure is then increased to a maximum of 2.0 times design wind pressure to examine what would happen in the event of failure if this limit is not reached. Typically, failure occurs in a seal in the roof assembly, or a glass panel may break in a rooflight, but this occurs usually when the 2.0 times design wind pressure is exceeded.

Impact resistance test

The ability of a lightweight roof, typically a glazed or plastic-based rooflight, to withstand an object falling on it is simulated with a canvas bag 400mm in diameter, filled with the glass balls already described, to a mass of around 50kg. The bag is dropped from a height of around 750mm to simulate an impact energy of around 350 Nm in a safety test. The test is performed on joints and panels to establish that the complete roof assembly would not fail under these impact energies.

Dismantling of sample

When the tests are complete, the roof mock-up is dismantled to ensure that the mock-up was built exactly in the way it would be applied on the roof of the finished building. In the event of a test failure, this dismantle assists the design team to understand how to resolve the matter, and prepare the mock-up for a second round of testing if required.

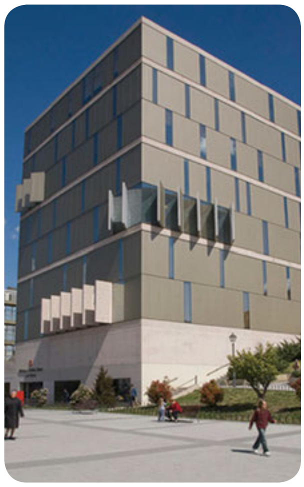
2

WALLS

metal sheet: Jewish Museum, Berlin, Germany. Architect: Daniel Libeskind

metal sheet: Falmouth School's Design and Technology Block, Falmouth, U.K.
Architect: Urban Salon

metal rainscreen: Lock-keeper's Graduate Centre, Queen Mary, University of London, U.K.
Architect: Surface Architects



metal composite panel: Usera Public Library, Madrid, Spain.
Architect: Ábalos & Herreros

Significant changes in the design of external walls in recent years have increased thermal performance and solar control, greater water tightness and a reduction in air infiltration rates through wall assemblies, and a limited return to natural ventilation where possible as a partial alternative to mechanical ventilation in larger scale buildings. These changes have led to a shift in design priorities. During the late 1980s, the increased use of thermal insulation brought with it an increased risk of condensation occurring in cladding assemblies. This condensation can occur both inside the panel and on the inner face of wall assemblies. The avoidance of condensation has been the result of technical development since. The increased use of natural ventilation, both as air supply and as a means of cooling buildings at night has had an effect on cladding design, particularly in the integration of opening lights and louvered slots in panels. The arrival of the deep plan building, with distances of up to 18 metres between external walls has led to a need for greater levels of daylight entering a building. This, in turn, has increased the need for both solar shading and glare control. In addition, the cost of photovoltaic cells, which can generate electricity when exposed to sunlight, has reduced considerably over the past 15 years. As a result, they are increasingly used in large-scale applications for buildings. These energy-led changes in wall design have generated a range of technical developments, which have changed the emphasis of facade design. The architectural interest in the expression of structure in buildings has been replaced by an interest in energy conservation. This is largely because the effect of additional layers of external insulation, blinds, shading and so on often renders the structure almost invisible.

Thermal insulation

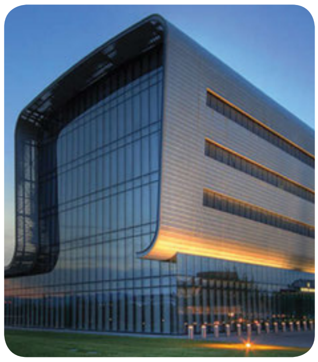
The use of thermal insulation has increased dramatically during the past 15 years with wall assemblies achieving a U-value of 0.25 W/m2K as a minimum standard. This compares with a typical level of 0.6 W/m2K in the early 1980s. There is an accompanying risk of interstitial condensation occurring within a wall assembly from damp air that penetrates a wall assembly where it may condense and cause damage. In addition to dew point calculations undertaken at the design stage to assess risk, vapour barriers are added to halt the passage of damp air into wall assemblies where interstitial condensation can occur, typically on the warm (in winter) side of the insulation. Alternatively, the internal construction can be ventilated in order to draw away damp air.

Condensation can also occur on the inner face of a wall in temperate climates, typically where there is continuity in a material from the outside to the inside of a building that allows a direct passage of heat or cold through the external envelope. When this 'thermal bridging' occurs, condensation can form on the inner face of the wall where it can drip down, resulting in inconvenience to building users and damage to the construction. Thermal bridges are avoided by providing a separating component in a low conductivity material, called a 'thermal break', that prevents heat or cold from being transmitted between inside and outside. An example of its use is in glazed walling, where the construction of a frame of mullions and transoms requires some continuity of metal from outside to inside. Plastic spacers of low thermal conductivity are positioned to provide a thermal break that also enhances the structural integrity of the construction.

Two generic types of thermal insulation have emerged for use in wall systems: rigid foam and flexible quilt types. The rigid foam type is made typically from either a polymer-based board such as polyurethane foam. Since both are non-hygroscopic or 'closed cell', they can be used in situations where the thermal insulation can become wet without any significant reduction in its performance. Closed cell insulation is also used to form the structural core of metal-faced composite panels as well as in facing the inner leaf of cavity walls. In contrast, flexible quilt is made typically from a mineral fibre quilt, cut to fit voids in panel frames more easily than board, but its lack of rigidity makes it unsuitable for use externally. While heavier insulation helps to provide a more rigid, water resistant material, the lighter, less rigid types provide better thermal insulation. As a result, the choice of core is a balance between the needs of rigidity and thermal performance.

metal screen: Sun Tower Office Building, Seoul, South Korea. Architect: Morphosis Architecture

metal louvre screen: Nordic Embassy, Berlin, Germany. Architect: Berger & Parkkinen



top left: metal profiled cladding: Vacheron Constantin Headquarters, Geneva, Switzerland. Architect: Bernard Tschumi
top right: metal screen: St Andrews Beach, Victoria, Australia. Architect: Sean Godsell
bottom: metal screen: Maison Folie, France. Architect: NOX

Rainscreens

Rainscreen cladding is a development of the rainscreen for pressure-equalised walls researched during the 1960s. It was found that water commonly penetrates joints in walling because of the outside air pressure being greater than that inside the joint. Water arriving by a variety of means, mainly gravity, wind and capillary action, was able to penetrate the outer seals of joints. The introduction of rainscreen framing systems and panel systems overcame this problem by creating an outer 'screen' layer or seal that stops most of the water entering the joint, but ensuring that the air pressure in the void behind the panel or joint is the same as that outside it. Rainscreen systems have three essential functions:

- To protect joints in the cladding assembly from the worst effects of windblown rain.
- To provide a decorative screen for a waterproofing system whose appearance is not suitable for an external wall. The same principle applies to roof cladding.
- To provide an outer protective layer to thermal insulation fixed on the external face of a high thermal mass construction such as concrete.

Drained and ventilated systems

There has been a move away from 'hermetically' sealed systems, which rely entirely on a single weatherproof outer skin, towards 'drained' systems. This is common to virtually all sealed facade types. Drained systems accept that the air pressure differences between the outside of the wall and the inside will allow small amounts of rainwater to penetrate the outer seal. This effect can be countered through two means; the water can be drained away within the metal framing that supports the cladding panels, and the pressure differences can be equalised by ventilating the system by providing slots at drainage points, usually set at the base of the wall. This ensures that water is not trapped within the panel framing, nor is the water discharged at vulnerable points in the construction where staining and damage can occur on the face of the panel. The use of ventilation within an assembly, on the external side of a thermal insulation layer, allows cladding systems to dry out once water has penetrated. Where water or water vapour penetrates a material in a wall or roof it is stopped from travelling further by the vapour barrier or waterproof membrane. At this point, it can be difficult for the water to dry out. A void is sometimes formed at the vapour barrier to allow the water to evaporate and prevent the adjacent material from being damaged. This is particularly important in the case of timber, where eventual rot can occur. The development of drained systems accepts that externally applied seals will leak small amounts of water and that it is better to design for that eventuality. Even systems with a single outer seal can be designed to drain away water within their construction.

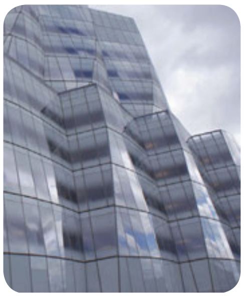
Use of materials in facade systems

The different material systems for facades are very much influenced by the particular material chosen. The essential issues in working with each material in facade assemblies are described in the following paragraphs.

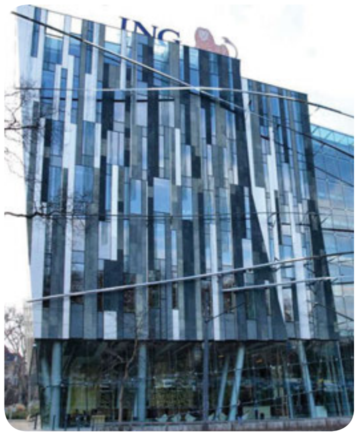
Metals

Metals used in facade systems are based mainly on sheets, extrusions and castings. Thin sheet metal is made in narrow strips up to 1000mm wide, making it necessary to form simple, reliable joints at close centres when joining the material together to form a weather tight surface. This is done by folding the metal together at the edges to form a continuous seam that projects from the wall surface, making it difficult for water to penetrate from outside. Standing seams are economic to make, but need to be done with care to avoid uneven joint lines. Because it is difficult to achieve crisp lines with this method, which relies on site-based workmanship rather than the use of workshop-based machines, the uneven 'oil canning' appearance can be accepted as an uneven texture forming part of the design. Because sheet metal used in facades is thin in order to fold it and work it, it requires support from underneath. The support surface conveniently forms a base for a backing waterproof layer which is needed behind sheet metal since it is unable to exclude rainwater. Sheet metal can be welded together to form a continuous waterproof sheet material, but thermal expansion needs to be allowed for with standing seam joints that prevent the material from deforming as the metal expands.





Top left: clamped glazing system: Rheinisches Landesmuseum, Bonn, Germany.
Architect: Archtektengruppe, Stuttgart
Top middle: clamped glazing system: Mediatheque, Sendai, Japan, Architect: Toyo Ito & Associates
Top right: unitised glazing system: IAC Headquarters, New York, U.S.A.
Architect: Frank Gehry & Studios Architecture
Bottom left: glass blocks: Maison Hermes, Tokyo, Japan.
Architect: Renzo Piano Building Workshop
Bottom right: bolt fixed glazing system: Tower Bridge House, London, U.K.
Architect: Rogers Stirk Harbour + Partners



Stick glazing system: ING Headquarters, Budapest, Hungary.
Architect: Erick van Egeraat

The number of joints on a facade can be reduced by increasing the size of the metal sheet being used. Profiled metal sheet can be formed in very long lengths, and in widths up to around 1500mm. Joints between sheets are formed by lapping sheets both horizontally and vertically with sealant set between adjacent sheets to provide a waterproof joint. This allows the sheet material to span between the supports of a framed supporting structure behind, rather than needing continuous support. Fixing profiled sheet to the supporting structure requires fixings that penetrate through the outside of the sheet to the inside, which presents a potentially weak point for waterproofing. This penetration through the material by fixings is avoided in standing seam sheet metal. Fixings for profiled sheet are made to be fixed easily, using a self-tapping screw, which has a waterproof washer on the outside and a drill bit on the front of the screw to make a hole. The self-tapping sealed screw is essential to the success of profiled metal sheeting, and corner trims and folded copings in the same material ensure the watertightness of junctions.

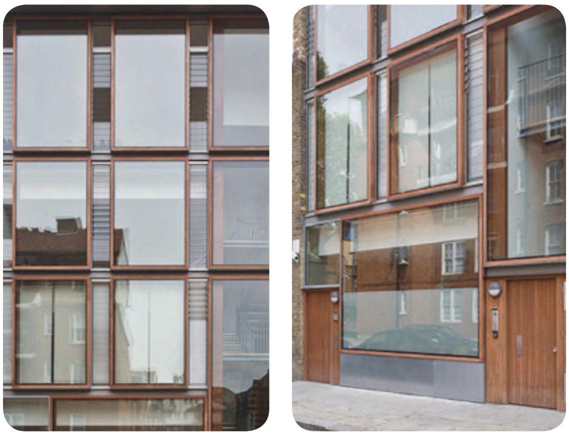
Sheet metal has been developed in recent years to be bonded to closed cell insulation, since both materials are used very economically in combination, so that the stiffness of insulation is combined with the watertightness and durability of metal. The successful bonding of rigid insulation to thin metal has been essential to the success of composite metal panels. These panels are joined with tongue-and-groove joints, usually on two sides. While this is a reliable joint, the joint on the opposite two sides is usually less accomplished, normally being a butt joint sealed with silicone, with an additional top hat metal profile to enhance the seal. Four sided tongue-and-groove jointed panels are more difficult to fix and more difficult to remove if damaged. The tongue-and-groove joint incorporates a void in the centre that allows water to drain down. The basic principle with sealing joints between composite panels is to ensure that any water entering the joint will drain down an internal cavity that drains water away to the outside at the bottom of the panels.

Glass

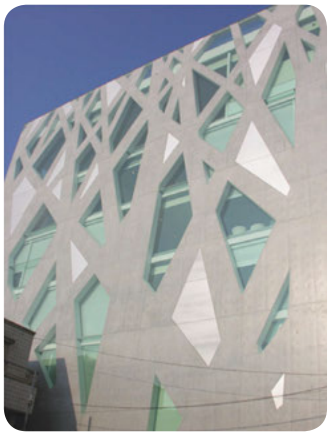
Glass in facades is supported either by edge frames or by fixing it at points. Glass facades are beginning to be glued together without any metal fixings but the design of such structures is in its early stages. Frames supporting the glass must both hold the glass in place and prevent rainwater from penetrating the seals. Difficulties in providing reliable rubber-based seals have led to the 'pressure equalised' or 'drained and ventilated' frames discussed earlier in this section. Water penetration in frames has traditionally been caused by capillary action where the air pressure inside the frame becomes higher than the outside atmospheric pressure, drawing water into the frame and potentially causing leaks. The problem of capillary action has been overcome, not by increasing the pressure on the seal between frame and glass, but by ventilating the void inside the frame so that any water that penetrates the outer seal is drained away safely down the cavity to the outside. The drained and ventilated cavity provides a second line of defence against rainwater penetration through the outer seal. The principle of pressure equalisation, with an inner chamber behind an outer seal is essential to current framed glazing systems. An alternative method of glazing is to avoid a frame entirely in order to increase the effect of transparency given by the glass. In point fixed glazing, the glass is held at only at a few points by small brackets or bolts. Glass is clamped together with plates, and bolted together through the joints between the glass. Alternatively, holes are drilled in the glass and the sheets are held by bolts secured directly through the holes in the glass without plates, using discs or a countersunk profile to the bolt connector. Joints are sealed with silicone in a single line of defence. While the material does not suffer problems of water being drawn through it as with clamped rubber seals, good workmanship is essential to the success of these single seals.

Walls built in glass blocks are constructed by bonding the blocks together with either a cement-based mortar or silicone. Because blocks are set with continuous vertical and horizontal joints giving them their characteristic appearance, panels are structurally inherently weak, and this is dealt with by introducing

Metal windows: Matsunoyama Museum of Natural Science, Matsunoyama, Japan. Architect: Tezuka Architects



Timber windows: Old Nichol Street, London, U.K. Architect: Maccreanor Lavington Architects



steel or aluminium reinforcing strips or rods into both vertical and horizontal joints as reinforcement. However, this limits glass block panel sizes to modest dimensions when compared to other glass wall systems. The principle of stack bonding limits panel sizes but is usually overcome by making the supporting structure lightweight yet rigid in order to minimise its visual effect. More heavyweight supporting structures make the blocks appear more like individual panels set into a visual grid.

Concrete

An essential aspect of concrete is that it is a material formed in a mould, leaving a surface finish which is the mirror image of that mould, or formwork. Consequently, an important aspect of concrete detailing is to understand how formwork and moulds are fitted together. Formwork can be made to almost any shape, from plywood or GRP (glass reinforced polyester), though specially-made formwork can be expensive to make. Joints between formwork panels are visible in the finished concrete, and if this is not to be overclad with another material, then joints need to be arranged to suit the architectural concept for the facades. Complex shapes for facade panels can be made more easily in precast concrete where, in a workshop, concrete is poured into a mould which is laid flat, making it much easier to take up complex shapes and textures which would be much harder to form vertically. Ferro-cement is capable of a high degree of surface modelling, being made as a cement mortar-based mix with a high proportion of steel reinforcement. This material ensures very smooth finishes, but is more commonly used for yacht hulls.

In-situ cast concrete is a monolithic material that provides an almost continuous waterproof surface. Rainwater penetrates only a few centimetres into the depth of the material, but in temperate climates this leads to visible surface staining. This can be overcome by colouring the concrete, adding textures, or ensuring that rainwater does not wash off surfaces where dirt can collect, which would cause staining on an area of wall beneath. Movement joints with in-situ concrete require careful attention so that they are waterproof but do not leave strong lines that are at odds with the overall concept of the facade. The facade designer must always be aware of where joints occur and how wide they will be in order to avoid disappointment during construction.

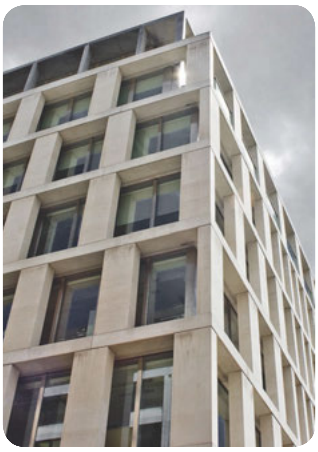
Precast concrete panels are jointed with pressure equalised drainage chambers behind vertical joints, which drain out of horizontal joints. Like in-situ cast concrete, the general areas of concrete are waterproof, but the joints require careful attention to avoid their becoming too wide as a result of wanting to achieve a consistent joint width both verticality and horizontally across the facade. Horizontal joints have to accommodate deflections and movement from the supporting structure if the panels are supported from floor slabs, as is usually the case due to their self-weight. Vertical joints are usually required to be thinner in order to exclude rainwater. The visual balance of joint widths, although a seemingly small issue, is critical to the visual success of precast panels. Notching and grooves are introduced around openings to ensure that windows and doors can be inserted in a way that provides weather protection as well as concealing part of the frame to avoid visible seals around the edge of the openings. Highly visible seals can also lead to very disappointing visual results.

Masonry

Loadbearing walls in brick, stone and concrete block have the advantage of being able to avoid the visible movement joints associated with non-loadbearing cladding, which can enhance the massive visual quality of traditionally built walls. An essential issue in loadbearing construction is to ensure that the wall is sufficiently thick to avoid rainwater penetration as well as being able to provide thermal insulation, either in the wall construction or on the inner face. The sealing of windows and doors into openings follows principles of reinforced concrete discussed in the previous paragraph.

In masonry cavity walls, two masonry skins are tied together to form a single wall, and here the detailing of openings in walls is undergoing continual refinement in order to reduce thermal

Concrete panels:
Housing Villaverde, Madrid, Spain.
Architect: Chipperfield Architects



Masonry loadbearing walls:
30 Finsbury Square, London, U.K.
Architect: Eric Parry Architects

Masonry loadbearing walls:
Bluecoat Art Gallery, Liverpool, U.K.
Architect: BIQ Architects

Masonry cavity walls:
Private residence, Dublin, Ireland.
Architect: Boyd Cody Architects

bridges. The top of an opening is supported with a lintel that both closes the opening and ties the two skins together while forming as small a thermal bridge as possible. Proprietary cavity closers and insulated lintels are used but these tend to match the shorter lifecycle of the windows rather than that of the supporting structure, which is usually longer. Providing a continuity between the thermal insulation in the cavity, fixed to the inner skin in the case of blockwork or masonry units, can lead to wide joints around windows, which needs careful attention to avoid visual clumsiness. This issue is easier to resolve if the thermal insulation forms part of the inner skin as is the case with inner skins in timber framing or light gauge steel frames.

In stone cladding, panels are mortared together and supported on fixings at each floor level, where each stone is individually restrained back to an inner wall that provides lateral restraint from wind loads. Windows and doors typically are fixed to, and supported by, the inner wall. The gap between the outer thin stone and the windows fixed to the inner walls is usually achieved by either putting a trim around the reveal in the same material as the window (usually metal) or by adding stone panels around the opening. When stone panels are used around the opening there is always a choice of either revealing the edge of the stone of the reveal trim (or the edge of the adjacent stone in the facade), or alternatively mitring the junction between the two stones. Since the thickness of stone cladding is seen only at external corners, the choice of revealing or concealing its actual thickness, rather than the massive stone quality the facade may aim to convey. Thin stone cladding is often used for its surface texture rather than conveying an idea of massiveness. The choice of easily commercially available stones has increased dramatically in recent years, widening the choice to thinner sandstones and limestones which have physical properties closer to those of weak granites. Masonry rainscreens are a recent development and comprise extruded terracotta panels that are fixed in a variety of ways depending on their size. Since they are completely independent of backing walls they present enormous freedom in design.

Plastics

Plastic-based cladding achieved a certain popularity in the 1960s and 1970s, presenting a fresh approach in building construction based on lightness in weight and a craft-based working method in economic materials that appealed to designers. Since then its use has been more modest, with concerns about durability and colour fading, which have largely been overcome in the plastic-based materials available today. Sealed plastic-based cladding uses mainly polycarbonate and GRP sheet that is either fixed into frames generally used for glazed curtain walling, or is fixed together as self-supporting panels in a way similar to metal composite panels. Most types are available as proprietary systems, with manufacturers having their own details for window openings, parapets, cills and corners.

When polycarbonate sheet is used, the material often has up to five layers within the material that provides a high level of thermal insulation. Some manufacturers use thermally broken sections, but the more visually appealing sections have no thermal breaks. Since these sections are made from aluminium extrusions, the opportunity exists continually to improve the system in conjunction with manufacturers. An essential aspect of working with proprietary systems is that some have standard window and door sections which have an appearance that may not suit other design approaches. The challenge here is to be able to modify the windows, doors and trims to suit the overall design for the facade. Other polycarbonate sheet systems have little provision for windows and doors and usually have no standard method of interacting with the supporting structure. These have to be developed with the manufacturer to suit a particular design. Because polycarbonate is used for its qualities of transparency and translucency, the supporting framework is very visible, even with translucent wall panels, so trims to support framing should be designed as carefully as those for glazed curtain walling. In common with glazed walls, polycarbonate panels can be either fixed into frames or be fixed at points with bolts and brackets. Silicone-based

Masonry stone and block cavity walls:
NoLi Housing, Philadelphia, U.S.A.
Architect: Erdy McHenry Architecture

Masonry cladding:
Archaeology museum Almeria, Spain.
Architect: Paredes/Pedrosa

Masonry stone and block cavity walls:
Thermae Spa, Bath, U.K. Architect: Grimshaw Architects

Small precast concrete panels: St Albans Pavillion, St Albans, U.K. Architect: MUF Architects

sealants are commonly used to seal between panels in the manner of bolt fixed glazing.

GRP panels are also fixed into glazing systems, but can be fixed together as sealed cladding units with pre-formed standing seams like some proprietary systems for profiled metal sheet. They can also be formed into flat rainscreen panels with visible or concealed fixings. An important aspect of detailing in this material is its relatively high thermal expansion which leads to larger gaps between components than is the case with other materials. The economic nature of plastic-based cladding is beginning to be recognised in new buildings, particularly with the ability of plastics to be coated in different colours economically, unlike the dominant use of pre-coated coil in metal panels, but the prejudice against the material for its discoloration in older examples has yet to be overcome in architectural applications.

Timber

Timber is susceptible to more movement than the other materials described, mostly as a result of changes in moisture level within the material. Consequently, timber used in facade cladding is allowed to accommodate movement as well as being ventilated to ensure that bowing, twisting and warping of timber components is minimised. In detailing timber it is difficult to form joints that perform well in tension without the need to introduce another material, usually metal. Metal pin connections, nail plates, cleats and angles are an integral part of the language of timber joints.

Although timber can be used as both cladding panels and as rainscreen panels over a different background wall, the timber boards in both cases are set clear of the backing wall to ensure that both sides are well ventilated. When timber boards are used to clad a platform frame, the same general principles apply as for the construction of individual timber cladding panels, except for the vertical joints. Vertical joints between boards in the platform frame can have timber trims and fillets added that protect the end grain of the timber from rainwater, where the timber is particularly vulnerable. Joints between timber cladding panels use a mixture of metal trims and rubber-based seals in the manner of unitised glazed walls, with a drained and ventilated chamber behind the outer timber cladding.

An important consideration in the detailing of timber is that the thermal conductivity of both softwoods and hardwoods is very low, from 0.14 – 0.21 W/m2 K, compared to 45 W/m2 K for steel and 2000 W/m2 K for aluminium. Thermal breaks are not a significant issue in timber construction, which eases considerably any issues of thermal bridging around openings. This allows enormous flexibility in timber detailing with a reduced risk of condensation occurring either within the construction or on the inside face of the wall in temperate climates. Openings in timber walls are increasingly using metal trims to enhance the visual refinement of details. Metal trims can also support fly screens, awnings and related metal attachments to window and door openings. Timber wall construction is relatively thin, at around 150mm overall, compared to 300mm for concrete and masonry-based facades, resulting in smaller window reveals which are easy to detail with modest trims and cills. Window frames are sometimes set on the outside face of the wall to reduce any risk of rainwater penetration as well as providing internal window cills.

Timber rainscreens vary enormously from big timber sections fixed back individually to a backing wall, in the manner of an open jointed timber deck set vertically, to timber panels with louvres and sliding slatted panels. The positioning of metal fixings is critical to the visual success of all these timber cladding methods. Corner brackets and fixings have a tendency to be large in order to give a secure fixing, so attention to detail of brackets and fixings is essential to achieving an elegant appearance. Traditional techniques used lapping of timber boards, with concealed nails and screws to protect fixings from corrosion, but contemporary detailing has much less emphasis on lapping in order to give greater visual precision to the construction.

Masonry rainscreen:
Walsall Art Gallery, U.K.
Architect: Caruso St John Architects

Plastic-based cladding:
Dance Studio, Tooting & Mitcham Football Club, U.K. Architect: Clash Associates

Plastic rainscreen:
Reiss store, London, U.K. Architect: Squire & Partners

This section discusses changes over the past ten years in the 17 generic non-loadbearing cladding types set out in this chapter and further identifies a smaller set of six generic types from this list. The application of this set of cladding types in 'thin' and 'layered' facades is discussed as well as how these facades are slowly developing from the use of technology from other industries.

The generic types are as follows:

1. Fully supported sheet metal
2. Profiled cladding
3. Composite metal panels
4. Metal rainscreens
5. Metal mesh screens
6. Glass stick systems
7. Glass unitised systems
8. Point fixed glazing (clamped and bolt fixed)
9. Glass blocks
10. Steel framed glazing
11. Precast concrete panels
12. Masonry facings to cavity walls (brick, block, stone)
13. Stone cladding
14. Terracotta rainscreen
15. Polycarbonate insulated systems
16. Timber cladding to platform frame
17. Timber rainscreens

All these systems still in use have undergone technical development to improve performance, largely concerned with energy conservation. Reports over the past ten years have suggested that no clear pattern of use has emerged in the use of cladding systems. The choice of cladding system is very much affected by building type and the number of a particular type built in a given year. The full range of cladding systems in this book is in full use. The preference for one system over another is very much driven by the building type and particular performance criteria and budgets of individual projects. A clear pattern that is emerging is that the choice of cladding systems available has not affected the move towards the emergence of a new set of generic types, which are common to all the 17 cladding types. From these generic types it is clear that the different types are supported by either a monolithic structure, or a backing wall to a frame, or alternatively to an open structural frame. Each generic type is rarely supported by both structural types. Since framed construction is more recent, the more recently developed techniques of glazing are used in conjunction with frames. Traditional loadbearing structures continue to be used in conjunction with traditionally-based techniques. Structurally, the traditionally based cladding is characterised by techniques that use materials in short spans.

From the list, these short span generic types for monolithic structures (and backing walls to frames) are as follows:

Fully supported sheet metal
- Metal rainscreens
- Masonry facings to cavity walls (brick, block, stone)
- Stone cladding
- Terracotta rainscreens
- Timber cladding to platform frame
- Timber rainscreens

Also from the list, generic types for open framed structures are as follows:
- Metal profiled cladding
- Metal composite panels
- Metal mesh screens
- Glass stick systems
- Glass unitised systems
- Point fixed glazing (clamped and bolt fixed)
- Glass blocks
- Steel framed glazing
- Precast concrete panels
- Polycarbonate insulated systems

Timber cladding panels:
Carmarthen Place, London, U.K.
Architect: Architects in Residence

Timber frame:
Harmood Children's Centre, London, U.K.
Architect: Greenhill Jenner Architects

Timber frame:
Private residence, London, U.K.
Architect: Lynch Architects

Generic forms

Six generic cladding types are identified below which are common to both non-glazed and glazed cladding systems. The first three types are used for small span applications with a backing wall. The second three types are used for large span applications without a backing wall.

Three types for small span applications with a backing wall:

1. Fully supported sheet with sealed joints
2. Facings with sealed joints: facings to masonry cavity walls, glass blocks, masonry cladding, timber boarding
3. Rainscreens with open joints: masonry, timber boarding, metal, mesh screens

Three types for large span applications without a backing wall:
4. Self-supporting profiled sheet
5. Stick systems: metal, glass, point fixed glazing, insulated polycarbonate
6. Panel systems: Precast concrete, timber, metal composite, glass unitised

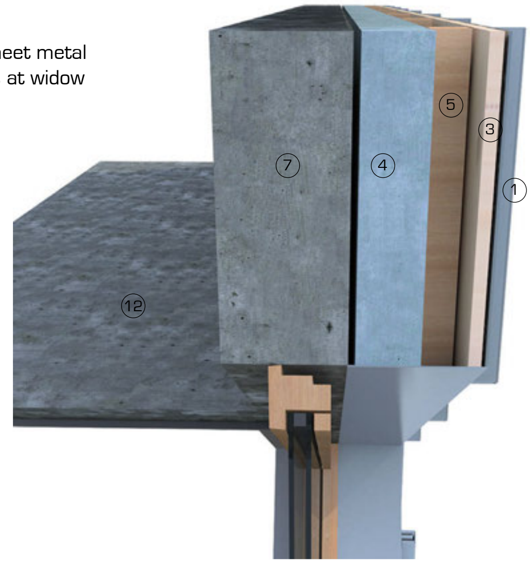
The application of these generic types in 'thin' and 'layered' facades

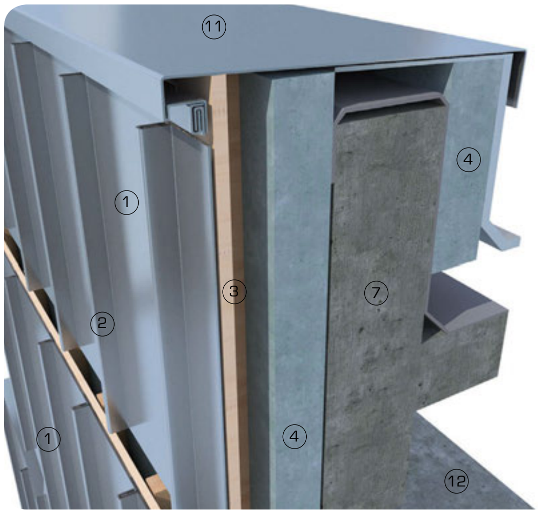
Modern single-sealed glass framing systems used in building construction, which rely on silicone bonding and rubber-based pressure seals, together with tempered, body-tinted glasses, are based on techniques developed by glass manufacturers for the car industry. Car manufacturers are relatively few in number, but they place very large orders for a restricted range of specially designed glass products such as windscreens. The building industry, in contrast, generates relatively small orders from a huge number of customers all of whom have quite different requirements. The current custom built nature of building construction does not encourage, in itself, glass manufacturers to invest significantly in new systems. As a result, most recent developments in glazing for buildings have followed in the wake of those developed for use in cars. Performance specifications for car glazing systems apply a complex set of criteria to a single very narrow 'wall' thickness. The use of glass with a structural capability, coupled with controlled light and heat transmission, is a strong influence in the design of facades. It reduces thickness of external walls, allowing floor areas to be maximised. It allows a single, competitively priced product, such as body tinted tempered glass, to fulfil a range of functions. In these 'thin' or 'compressed' facades, functions of weatherproofing, thermal insulation, air handling and glare control are compressed into a very thin wall.

Over the past 15 years, this principle has been developed to incorporate other components within a narrow depth. Louvred blinds and mechanical ventilation can now be incorporated. Heat from solar radiation can be partially absorbed by blinds set within the depth of a 100mm to 300mm deep double glazed unit. Air passes through the unit, drawing away heat from the blinds, providing a thin external wall whose performance is a balance between different, and sometimes conflicting, criteria. In these thin facades, the integrated blind will absorb heat during periods of high solar gain when blinds must be orientated to act as a radiator of heat. This can conflict with occupants' requirements for daylight. Each facade will respond differently to the changing weather conditions, by either manual or electrical means.

An alternative approach for external walls is the separation and layering of the functions of weatherproofing, ventilation, thermal insulation, and daylight/glare control. With this 'layered' approach, specific layers in the envelope system are created to deal with specific tasks of excluding rainwater and controlling heat loss and heat gain, glare and ventilation. To achieve this, a layered system superimposes generic types. A current disadvantage of this system is that a layered facade requires considerably more depth of 'wall', from around one metre where external solar shading is provided, to about three metres, where the zone between the inner and outer wall becomes a usable space in a building in the manner of a conservatory or winter garden.

(Right) 3D detail views showing sheet metal wall system with window openings at widow opening and parapet conditions



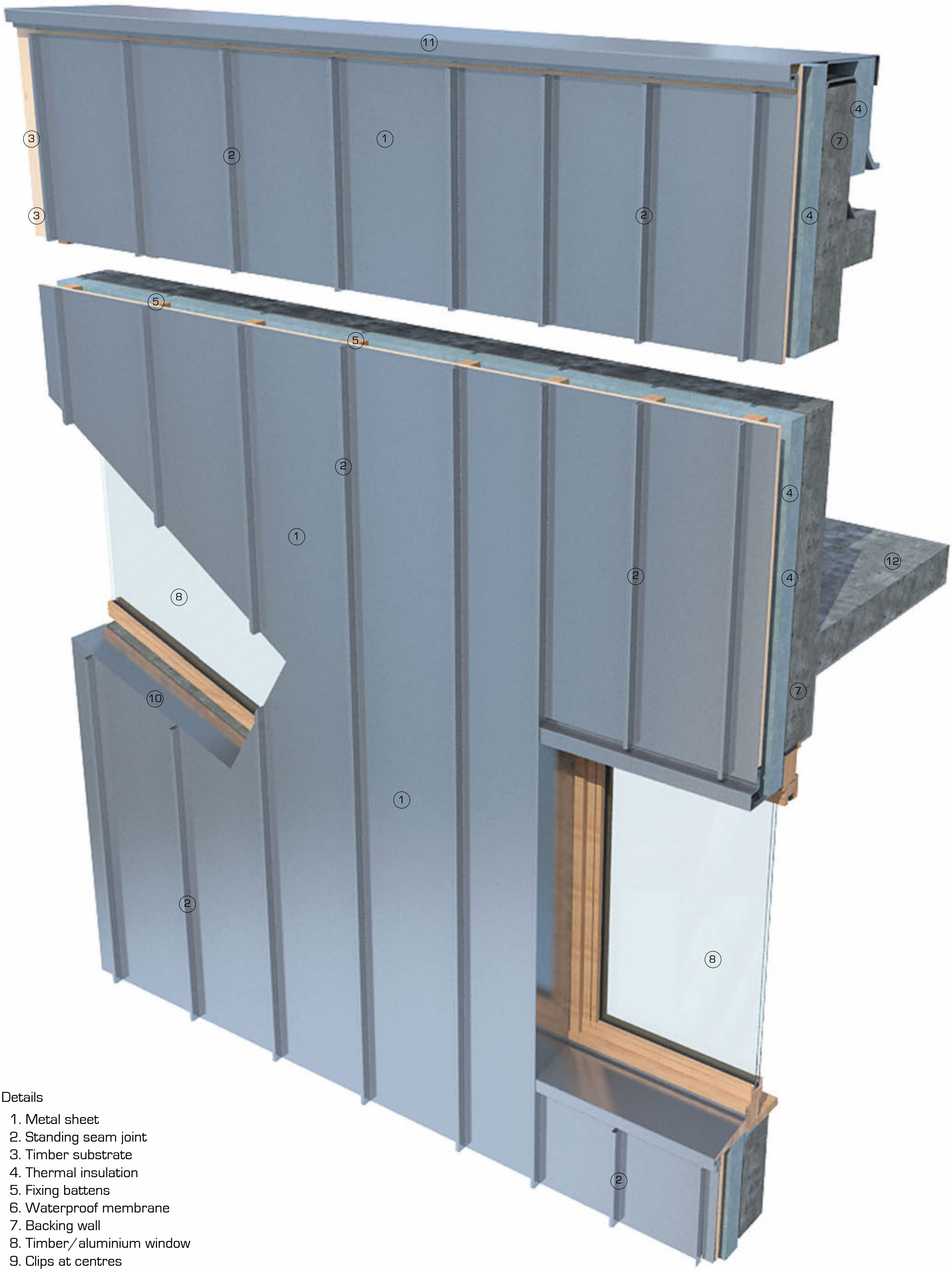


3D view of sheet metal wall system with window openings

System design
Sheet metal is typically supported directly on a substrate, providing a system formed from thin sheet which can closely follow a complex geometry with relative ease, making it very suitable as a covering to a highly modelled facade. This material system has developed from its traditional use in roofing, where the standing seam technique is well established, to a facade material that can cover projecting windows, externally set structure and areas of flat facade with equal ease. In recent years sheet metal has been used to enclose forms of complex geometry, on either folded or curved facades. Consequently, this system also provides an economic outer covering in projects where wall and roof are combined in a single form, or where the external envelope is highly modelled in a single form where one material is required for the complete envelope. The principles of rainwater exclusion used on roofs can be applied for use on facades, with continuous joint lines, to form a complete envelope from a (nominally) flat roof to a vertical wall, to inverted soffit conditions.

The two generic methods for supporting sheet metal facades that suit different conditions are continuous standing seams and tiled shingles. Standing seams are suited where long, straight or continuous joint lines are required or where the facade has gentle curves which can be picked out by the joint lines. Tiled shingles are suited to complex geometries and smaller scale applications where a high degree of surface modelling is required. Metal sheet can also be laid onto a timber-based substrate as an outer covering to a complex form. Both methods set the thermal insulation behind the substrate, typically creating a ventilated void between substrate and insulation, but this is dependent on the construction of the backing wall rather than on the sheet metal layer.

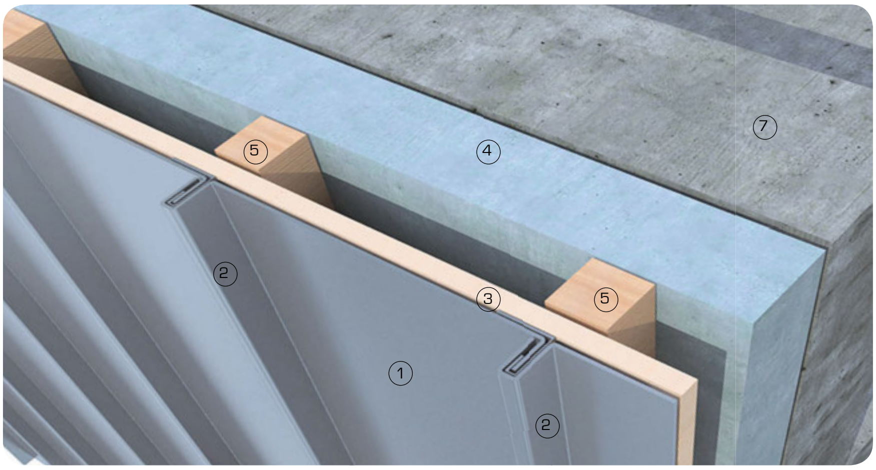
Standing seam roofs have traditionally had a slightly uneven appearance due to the softer, more ductile metals used, mainly lead, zinc and copper, whose ductility allows them to be formed more easily when used in traditional, site based installations. The 'oil canning' effects of sheet metals, which are visible immediately after installation when used in facades, tend to diminish visually as the surface weathers to the characteristic patina of the metal used. The texture remains with weathering, giving a hand crafted appearance which suits visually vibrant facades. Some recent buildings have even slightly exaggerated this effect before installation to create a highly textured surface finish to the metal. Standing seam metal facades have the essential visual characteristic of highly visible joints at relatively close centres of between 450 - 600mm. This construction method, used traditionally as a roofing system, is used increasingly in facades as an economic system that is easy to combine with other facade elements such as glazing without the need for reveals and visible flashings.



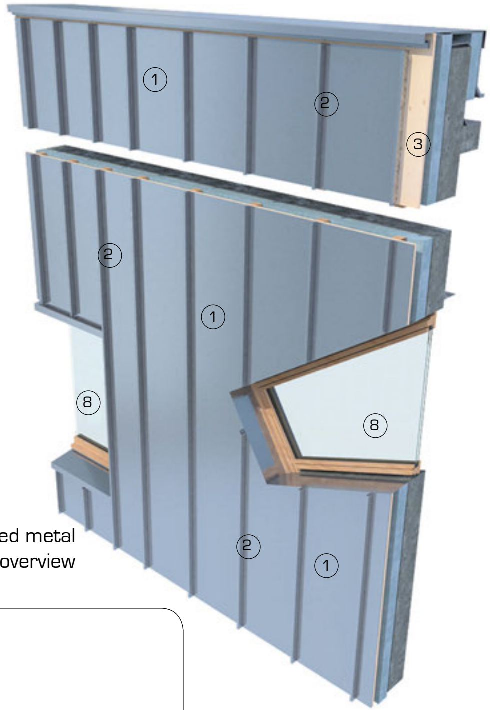
Details

1. Metal sheet
2. Standing seam joint
3. Timber substrate
4. Thermal insulation
5. Fixing battens
6. Waterproof membrane
7. Backing wall
8. Timber/aluminium window
9. Clips at centres
10. Folded metal profile
11. Metal flashing
12. Concrete floor slab

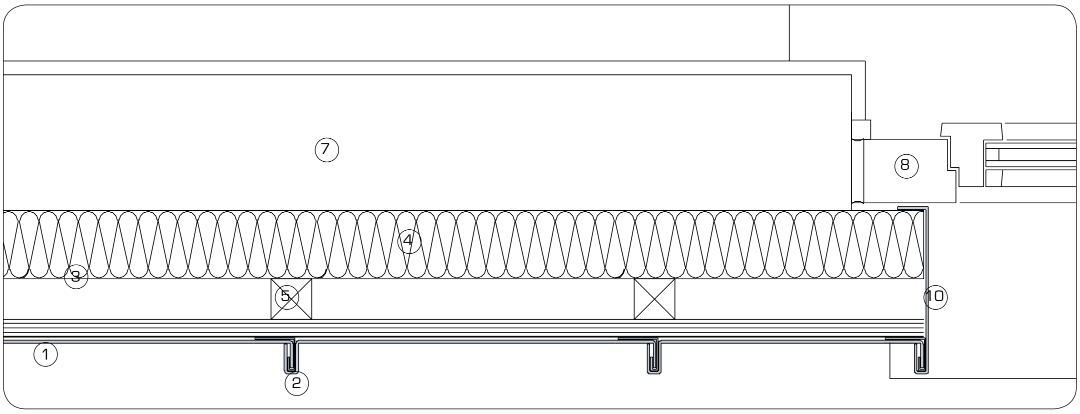
3D view of wall system with window opening and parapet detail



3D detail view showing profiled metal sheet wall construction



3D view showing profiled metal sheet wall construction overview



Horizontal section 1:10. Profiled metal sheet fixed to concrete backing wall

Details
1. Metal sheet
2. Standing seam joint
3. Timber substrate
4. Thermal insulation
5. Fixing battens
6. Waterproof membrane
7. Backing wall
8. Timber/aluminium window
9. Clips at centres
10. Folded metal profile
11. Metal flashing
12. Concrete floor slab

System details

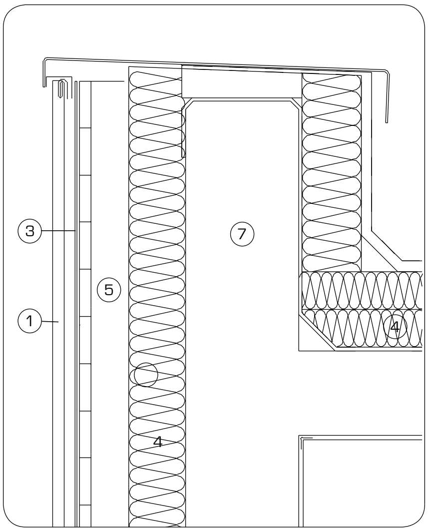
Continuously supported sheet metal provides a rhythm of standing seams that do not need to be visually coordinated with openings and junctions in the facade. Flashings can be formed at window and door openings without modular co-ordination and do not require to be specifically aligned with an adjacent standing seam or shingle edge for a reliable joint to be formed. When joints are at visually close centres, at around 400mm, the joint pattern provides an overall texture for a facade rather than defining rows of joints. When used in long lengths from rolls, the material allows horizontal joints to be avoided in smaller scale applications, up to around 12 metres in length, but curved or highly modelled facade/roof combinations require shorter distances between horizontal joints to accommodate the curvature. In such situations, tapered joints are often used, sometimes with staggers set into them as used at the centre of traditional circular metal roofs.

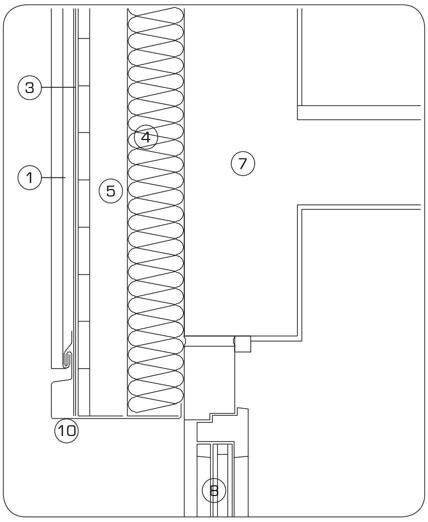
Where crisp, straight lines are required in the design, the standing seam method is used on vertical joints in a variety of configurations to suit visual requirements. The choice of seam is primarily visual, ranging from the wide rolled seam of traditional lead roofing to the thin folded projecting seam of traditional zinc and copper roofing. Horizontal joints are folded to form a flattened seam that allows rainwater to run off it without finding its way into a joint.

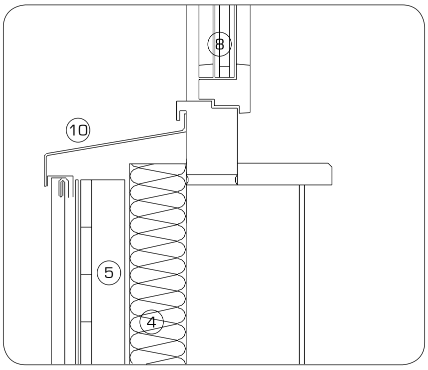
Tiled or 'shingled' standing seam metal facades use flattened folded seams on all sides of the panel. Since the same source material of metal strip is used, metal tiles are usually in widths of around 450-600mm depending on the metal used. The jointing system also performs well when the tiles are set diagonally, with 45° being most commonly used in practice.

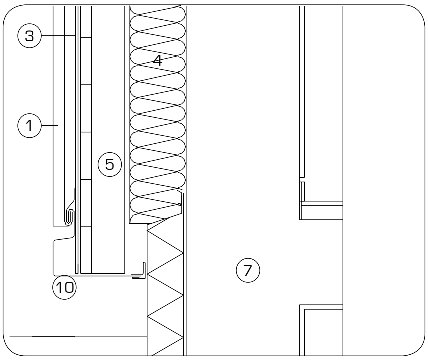
Both methods use a continuous supporting material, typically plywood sheet for its ability to form complex surfaces with ease. Timber boards are also used, but mainly in open jointed configuration to support zinc sheet, which requires ventilation on its internal face to avoid corrosion. Timber substrates are usually ventilated on their internal face in order to reduce the possibility of damage associated with trapped moisture.

For both standing seam joints and shingled tiles, openings and edge flashings, including parapets, are formed with folded metal flashings in the same material. Flashings can be set below the material at junctions which reduces their visibility, enhancing the texture of the facade material where required. Flashings are typically of two visual types: those that formed a visible strip that laps over the face of the adjacent area of metal sheet, and those that form a shadow gap between the flashing and the surface of the adjacent metal. Since sheet metal surfaces are formed by folding over edges of narrow sheets to form a continuous metal surface, they do not have a natural link into windows and doors set into a typical facade. Windows are often sealed against the backing wall in which they are held rather than sealing them against the sheet metal wall.



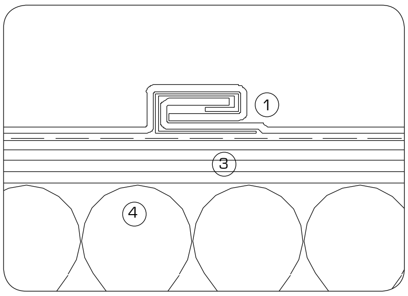


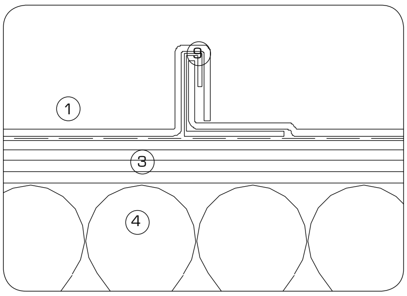




Vertical section 1:10. Typical wall system

3D detail view showing window head detail within profiled metal sheet system

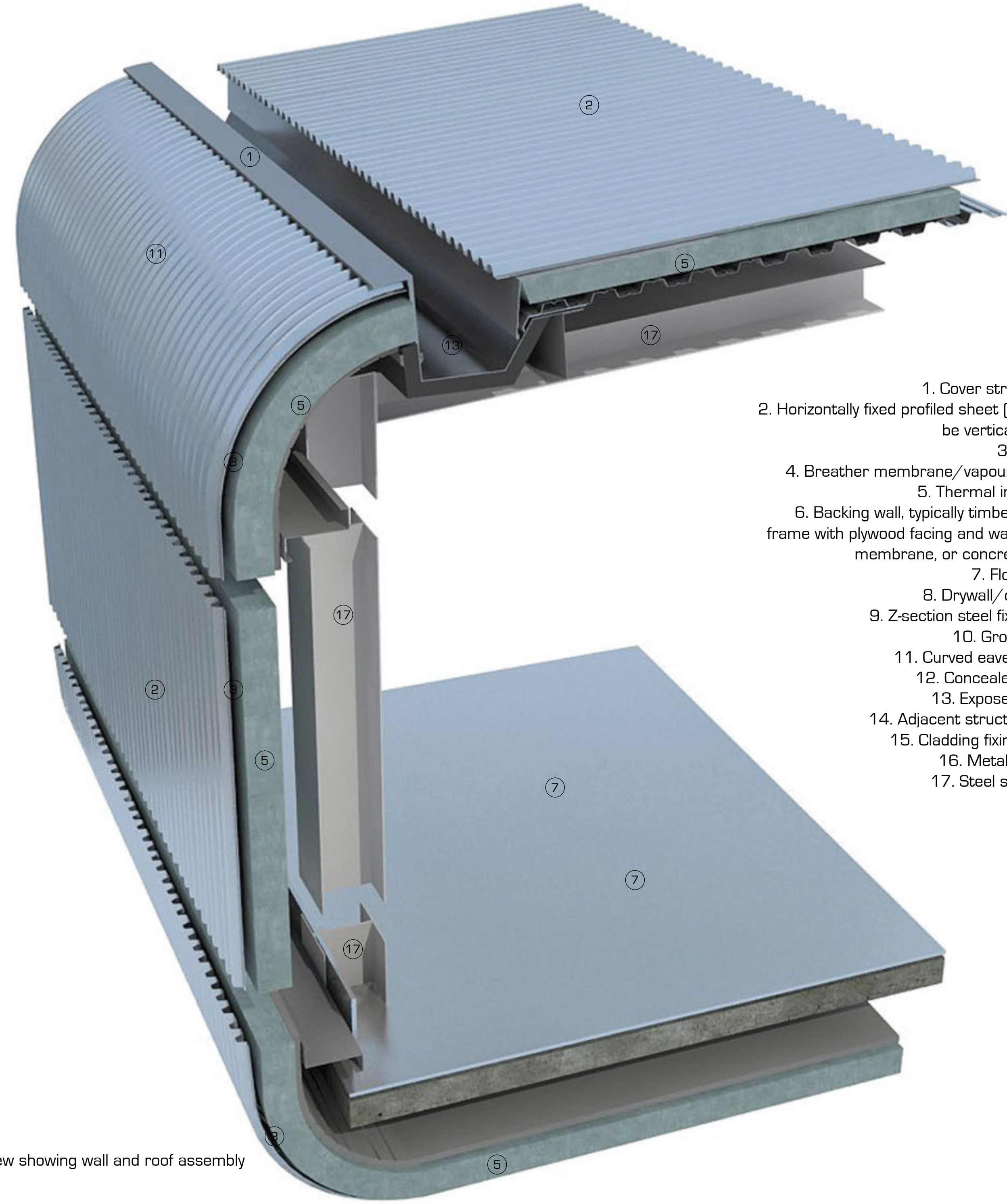




Plan 1:5. Standing seam profiles

3D detail view showing window cill detail within profiled metal sheet system

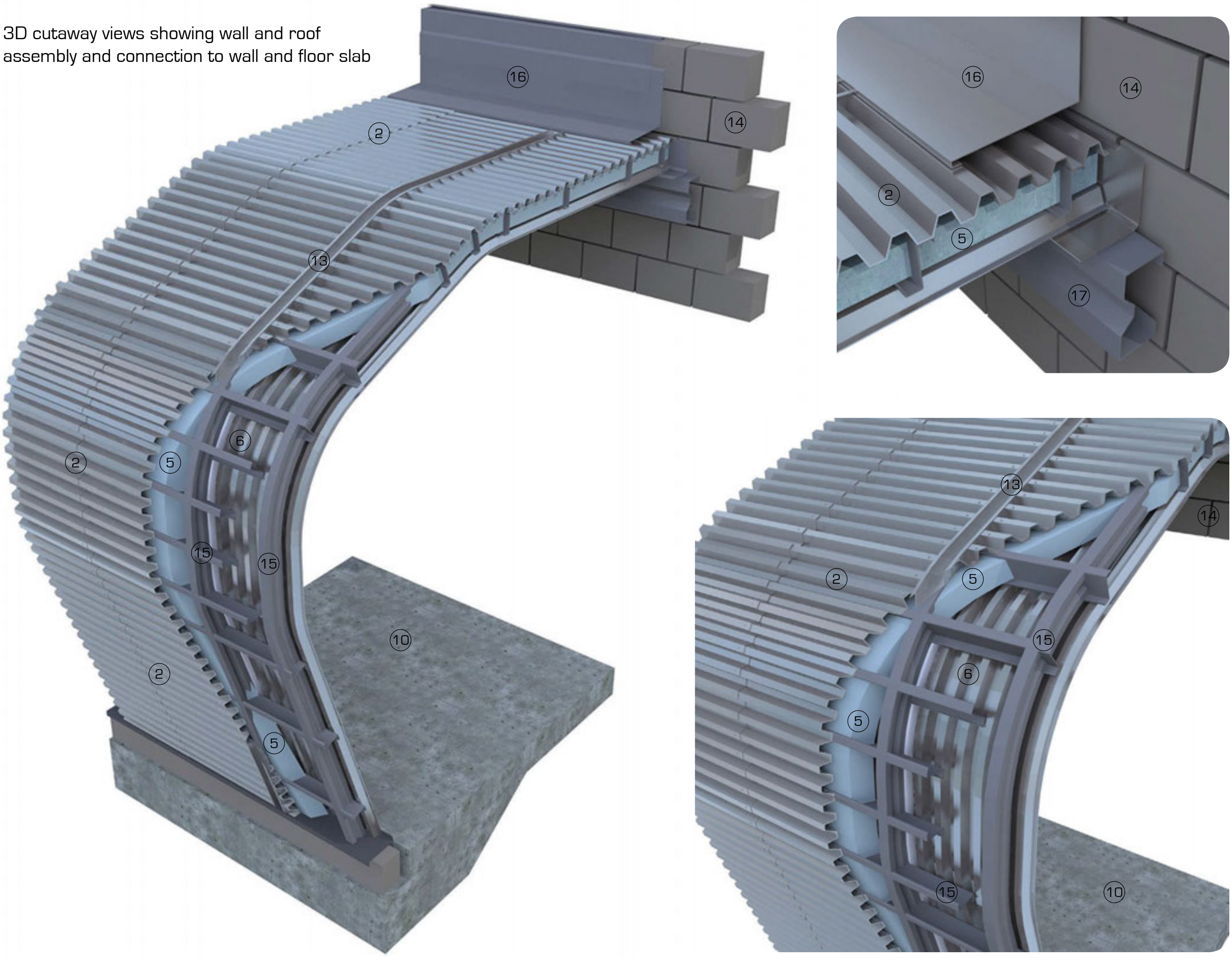
3D detail views showing close-up of gutter



Details
1. Cover strip profile
2. Horizontally fixed profiled sheet (can also be vertically fixed)
3. Air gap
4. Breather membrane/vapour barrier
5. Thermal insulation
6. Backing wall, typically timber/metal frame with plywood facing and waterproof membrane, or concrete block
7. Floor finish
8. Drywall/dry lining
9. Z-section steel fixing rails
10. Ground slab
11. Curved eaves profile
12. Concealed gutter
13. Exposed gutter
14. Adjacent structural wall
15. Cladding fixing frame
16. Metal flashing
17. Steel structure

3D view showing wall and roof assembly

3D cutaway views showing wall and roof assembly and connection to wall and floor slab

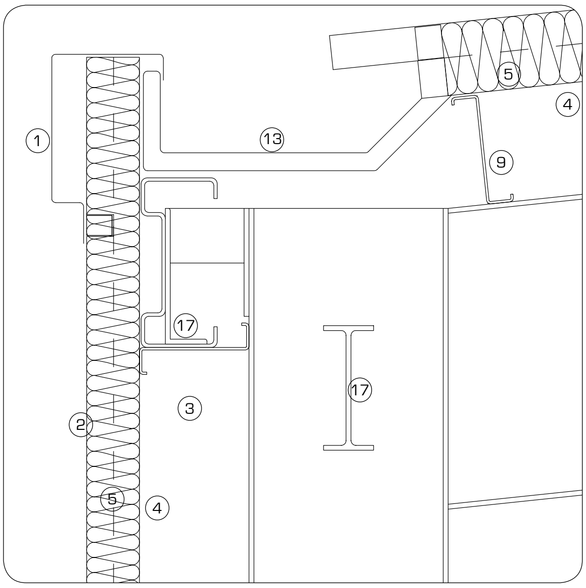


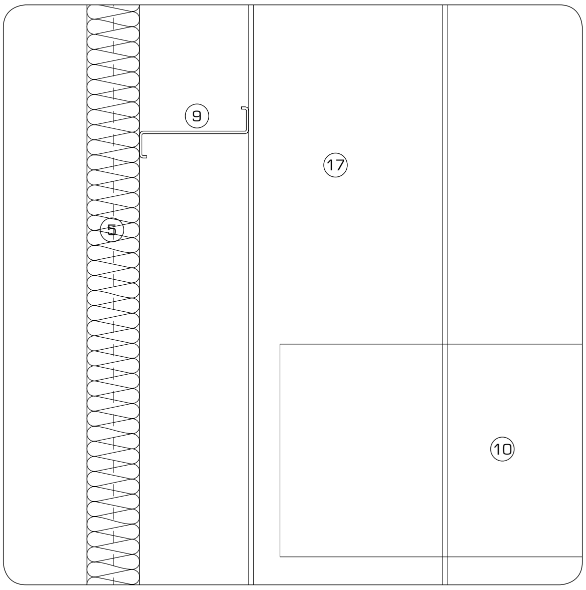
System design

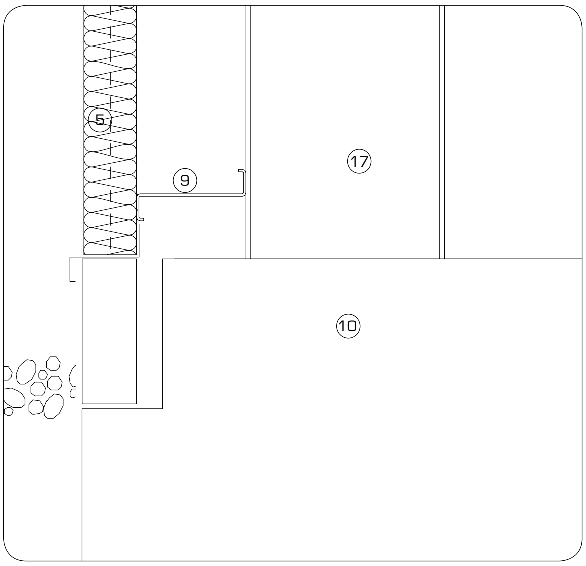
The main difference between profiled metal cladding and the continuously supported type is that profiled sheet can span 3-5 metres between supports, depending on the (sectional) profile used. The profile depth provides rigidity of the material in one direction, allowing it to be fixed directly to a structural frame rather than requiring the continuous support of an additional substrate. Its profile allows the sheet to be gently curved in one direction during installation on site, with the material still lapped on all edges regardless of its orientation. Profiled sheet can be curved along its rigid length by crimping in the factory, usually to form curved corner pieces for horizontally-set cladding, or curved eaves pieces for vertically-set cladding. Proprietary systems offer a range of curved components as well as 90° corners where short lengths of sheet are welded to form a crisp corner panel. The wide range of profiles available, from small wave profiles to deep profiled sections, gives a wide range of visual effects.

Profiled metal cladding has developed from its initial application in industrial buildings in the 1970s to wider architectural applications. This material system uses a single metal, either steel or aluminium, for the complete cladding of, typically, manufacturing or storage buildings which have large shallow pitched roofs and a relatively small facade area in relation to that of the roof. The all-metal envelope evolved, in an architectural sense, with the introduction of curved eaves and concealed gutter with walls and roof appearing to be a continuous form. The profiled metal sheet was set with the ribs running from top to bottom of the roof and continued down the facades in the same alignment. As its use in facades developed, profiled metal cladding was used horizontally rather than vertically, in order to curve the wall profile when seen in section, and at different angles, in order to introduce an expression of complex geometry.

As a material system, the profiled nature of the material requires continuity of the profile from sheet to sheet, making it difficult to create visual offsets in the setting out of the material. Where a change of orientation or direction is needed by the design, a projecting cover strip or recessed shadow gap joint is needed, which creates a break in the system. Since the shape of the profile cannot be varied in regular manufacture, the lines of the sheet and visible joints at geometric changes in the system, dominate its appearance. In common with standing seam metal, profiled metal sheet does not have windows and doors that form part of the material system, though these items can be made in the same material and finish. Because windows and doors are made by different manufacturers, it is important to ensure either colour matching at the fabrication stage, or contrasting colours/finishes that work together visually. Where the inner lining of the wall is also formed in profiled metal sheet (typically flatter, and sometimes perforated for acoustic performance) a similar approach is taken.





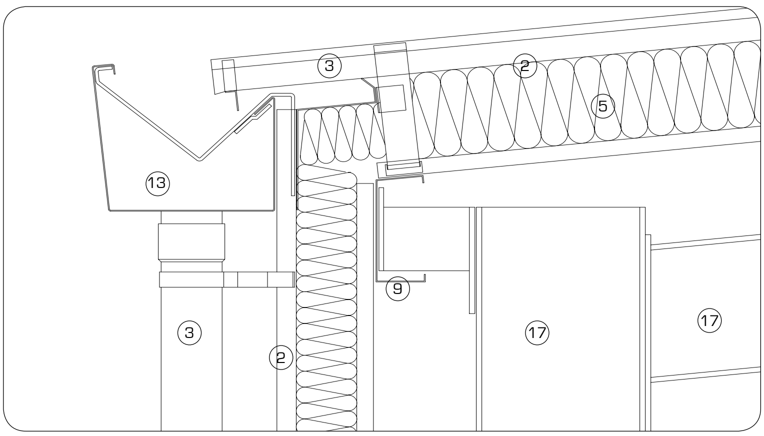


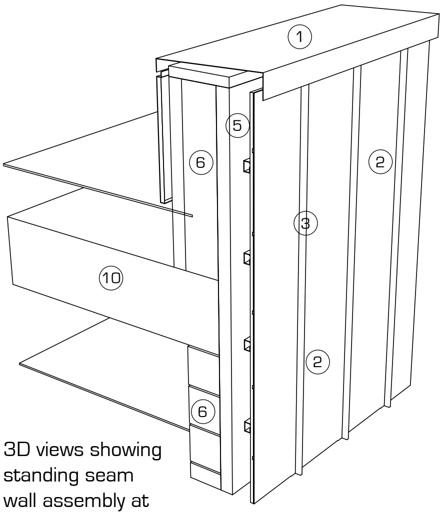
Vertical section 1:10. Profiled cladding wall construction

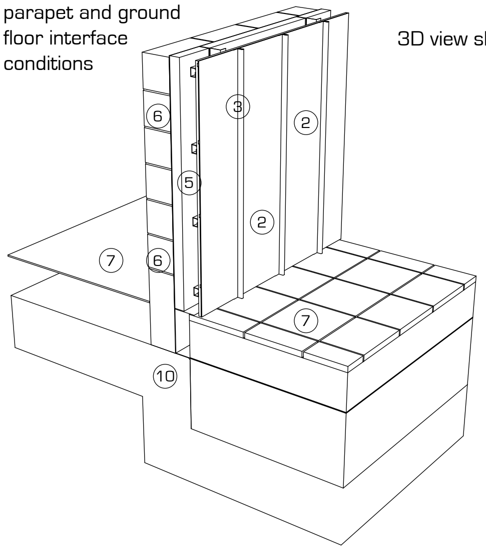
(Right) Vertical section 1:10. Gutter

3D view showing wall and roof assembly

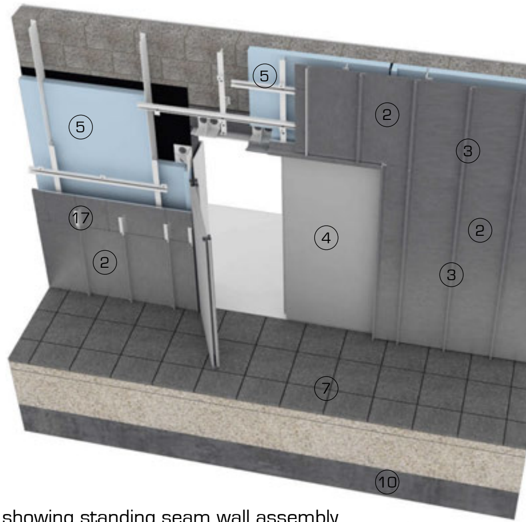
(Below) 3D view showing gutter detail in profiled cladding wall construction





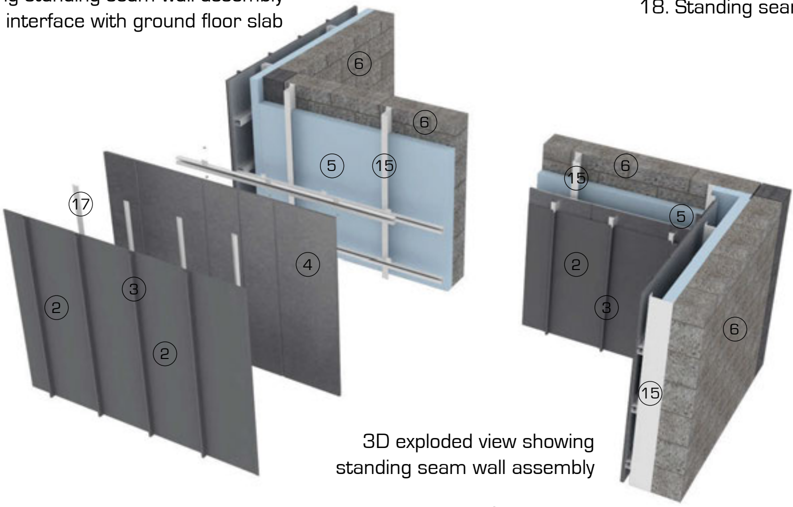


3D views showing standing seam wall assembly at parapet and ground floor interface conditions



3D view showing standing seam wall assembly and interface with ground floor slab

Details
1. Cover strip profile
2. Metal sheet
3. Metal standing seam
4. Breather membrane/vapour barrier
5. Thermal insulation
6. Blockwork backing wall
7. Floor finish
8. Drywall/dry lining
9. Z-section steel fixing rails
10. Floor slab
11. Curved eaves profile
12. Concealed gutter
13. Exposed gutter
14. Adjacent structural wall
15. Cladding fixing frame
16. Metal flashing
17. Steel structure
18. Standing seam clips



3D exploded view showing standing seam wall assembly

System details

Vertically-set sheeting requires folded metal flashings at the top and bottom of the wall to form parapets and cills, as well as corners, usually made from flat sheet. Some manufacturers provide crimped flashings for corners in order to provide visual continuity between adjacent facades. Where flat sheet is used at corners, plastic or foam-based filler pieces form part of the system to close the gaps between the profiled sheet and the flat metal flashings that are usually set onto the face of the profiled sheet. The visual impact of these filler pieces needs to be assessed within the design. Horizontally-set sheeting can be formed as continuous cladding with barely visible joints resulting from lapping the sheets. Alternatively, the profiled sheet can be divided into bays, formed with vertical joints closed with cover strips or with recessed pressed (top hat) sections.

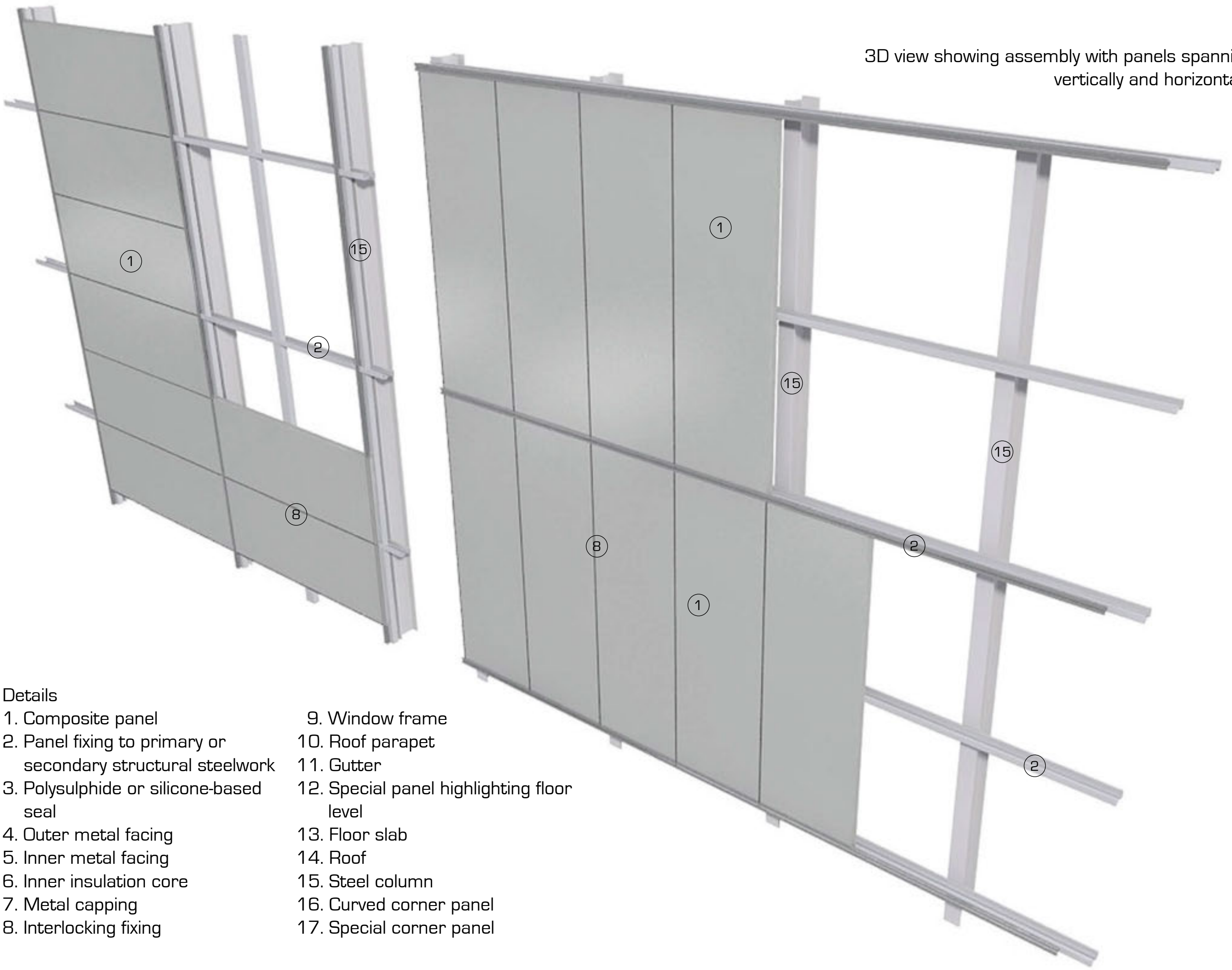
At roof level, parapets are formed with a pressed metal coping with another flashing beneath. A metal flashing is used to close the gap between the roof deck and the parapet upstand where the roof is also clad in profiled metal sheet. Where only a low upstand is required, as at the gable, a folded flashing is fixed to the roof surface to form a sealed edge. A metal coping flashing is then fixed to the upstand and is folded down the face of the external wall. Although the thermal insulation forming part of the wall construction is made continuous with that of the roof, the void in the parapet is usually filled with thermal insulation to avoid high temperature variations between outside and inside the construction.

The void behind the sheet is filled with thermal insulation which requires a vapour barrier on its internal (warm in winter) face. The internal lining of the wall can be in any material, though dry lining or an additional layer of profiled metal sheet is typical. Some manufacturers have proprietary lining sheets in metal which are flatter than the external profiled sheet to suit the typical requirements of internal finishes.

Openings for windows and doors are sealed with metal flashings that can be determined as much by visual requirements as by the needs of weather proofing. Window openings often have wide cover strips around the edges of the opening to provide a full weather tight seal which forms a highly visible part of the design.

Corners can be made from either externally set cover strips or by recessed corner flashings to suit the design. The recessed version requires careful installation of the cladding sheets on site in order to achieve the relatively narrow corner joint widths. Cover strips usually have their edge folded back to provide a crisp line around the profile. Folded flashings are usually in two parts, with an inner seal between cladding and window, and an additional outer flashing which is sealed with silicone back to the profiled metal.

Although proprietary systems are available, it is easy to adapt these systems, where the facade fabricator makes flashings to suit individual requirements. Principles of details are well understood by fabricators and complete proprietary systems are not always required.



3D view showing assembly with panels spanning vertically and horizontally

Details
1. Composite panel
2. Panel fixing to primary or secondary structural steelwork
3. Polysulphide or silicone-based seal
4. Outer metal facing
5. Inner metal facing
6. Inner insulation core
7. Metal capping
8. Interlocking fixing
9. Window frame
10. Roof parapet
11. Gutter
12. Special panel highlighting floor level
13. Floor slab
14. Roof
15. Steel column
16. Curved corner panel
17. Special corner panel

System design

This material system provides a complete wall assembly in a single panel form, sometimes with integral windows and doors that interlock with the regular panels. Panels consist of an inner core of rigid thermal insulation onto which a thin metal sheet is bonded to each side, with a specially formed profile around the edges of the panel that forms a weathertight connection with adjacent panels. This material system is made as complete proprietary systems, each with varying levels of interchangeability and surface finish in relation to their cost. Their main visual advantage is the smoothness of the panel faces that form a complete system with integral panels for corners, parapets and window openings. Their main technical advantage is in providing a complete wall construction in a thin panel which is also highly thermally insulated. Panels are typically made in widths of 1100mm to 1400mm to suit the manufactured width of metal coil, but are long, up to around 15 metres, where transportation of the panels becomes a primary consideration of their size.

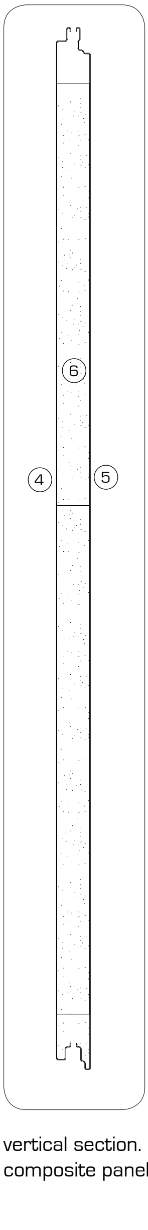
Panels typically have interlocking joints on two sides, forming an integral part of their fabrication, with panels being set either vertically or horizontally. Joints are typically formed to avoid a thermal bridge from inside to outside, by creating a small break between inside and outside layers of metal, and are shaped to ensure that rainwater runs back out of the panel. Joints between panels at their short ends, where there is no interlocking joint, are butt jointed and sealed with cover strips. Panel systems are also used with interlocking joints on all four sides, and these are usually made in sizes that can easily integrate doors and windows which also form part of proprietary systems.

Vertically-set panels that interlock on two sides are usually storey height. Where panels are stacked over more than one storey, the horizontal joints between panels are usually sealed with metal flashings. Panels are supported on horizontal rails, typically at floor level to allow a floor to ceiling panel arrangement without intermediary structure that would be visible from inside the building. Horizontally-set panels that interlock on two sides are stacked one above the other, with tongue and groove horizontal joints, which usually contrast visually with the vertical joints which have wider sight lines in order to accommodate a metal cover strip, a rubber-based gasket, or their combination. Since vertically set panels are typically separated by the flashings, vertical joints can be discontinuous, allowing windows to be set in specific locations on a floor-by-floor basis, with each floor having its own arrangement of composite panels that is not aligned with those on the floor below. This has given rise to the use of mixed panels, set both vertically and horizontally, in a tiled arrangement rather than the exclusive use of the rectilinear grid seen until recently.

In four-sided interlocking panels, joints usually incorporate an inner chamber set between an inner and outer seal in order that the system be internally drained and pressure equalised. Window and door frames interlock into the surrounding panels

3D detail view showing connection profile for vertical two-way interlocking profiled panels

3D view showing composite panel with vertical capping and interlocking horizontal joints



vertical section. Interlocking composite panel profile

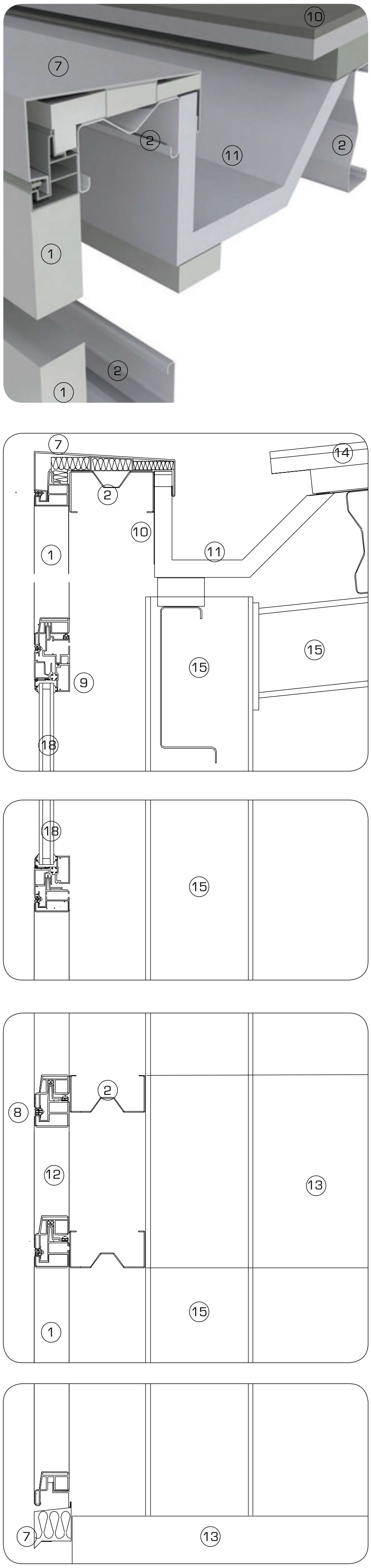
3D view showing interlocking composite panel profile system overview

3D detail view showing metal bracket and capping fixed to structural frame

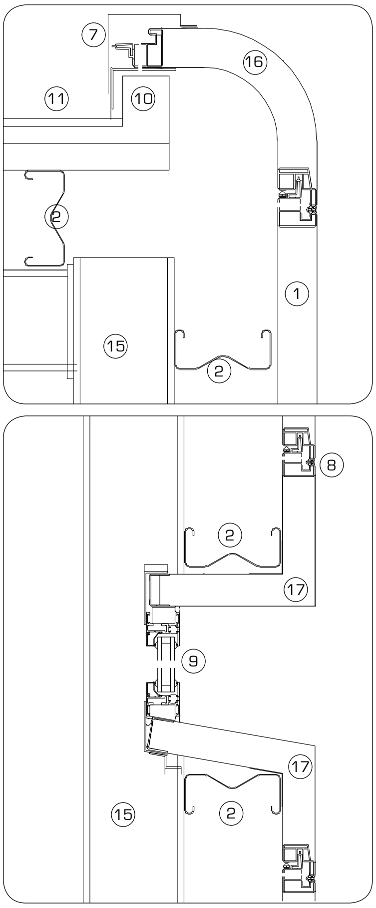
3D detail view showing metal bracket and capping supporting panels

Details
1. Composite panel
2. Panel fixing to primary or secondary structural steelwork
3. Polysulphide or silicone-based seal
4. Outer metal facing
5. Inner metal facing
6. Inner insulation core
7. Metal capping
8. Interlocking fixing
9. Window frame
10. Roof parapet
11. Gutter
12. Special panel highlighting floor level
13. Floor slab
14. Roof
15. Steel column
16. Curved corner panel
17. Special corner panel
18. Double glazing

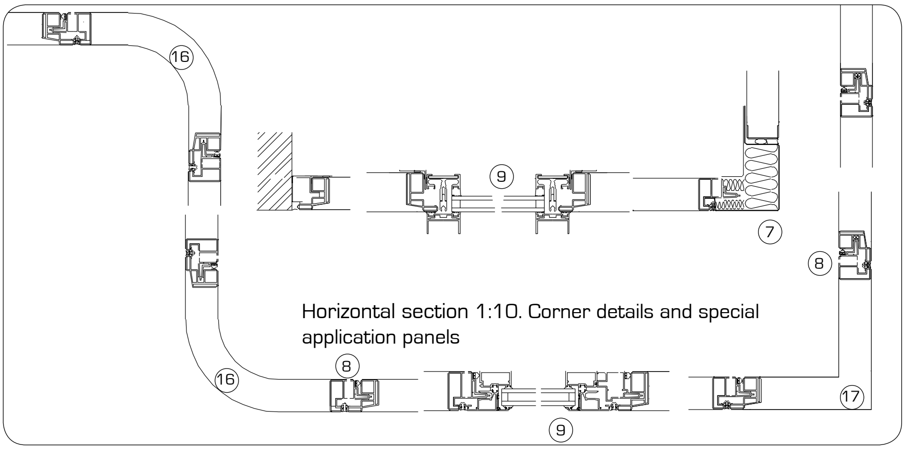
3D view showing vertical section through typical wall system



Vertical section 1:10. Wall build-up showing typical details



Vertical section 1:10. Corner details and special application panels



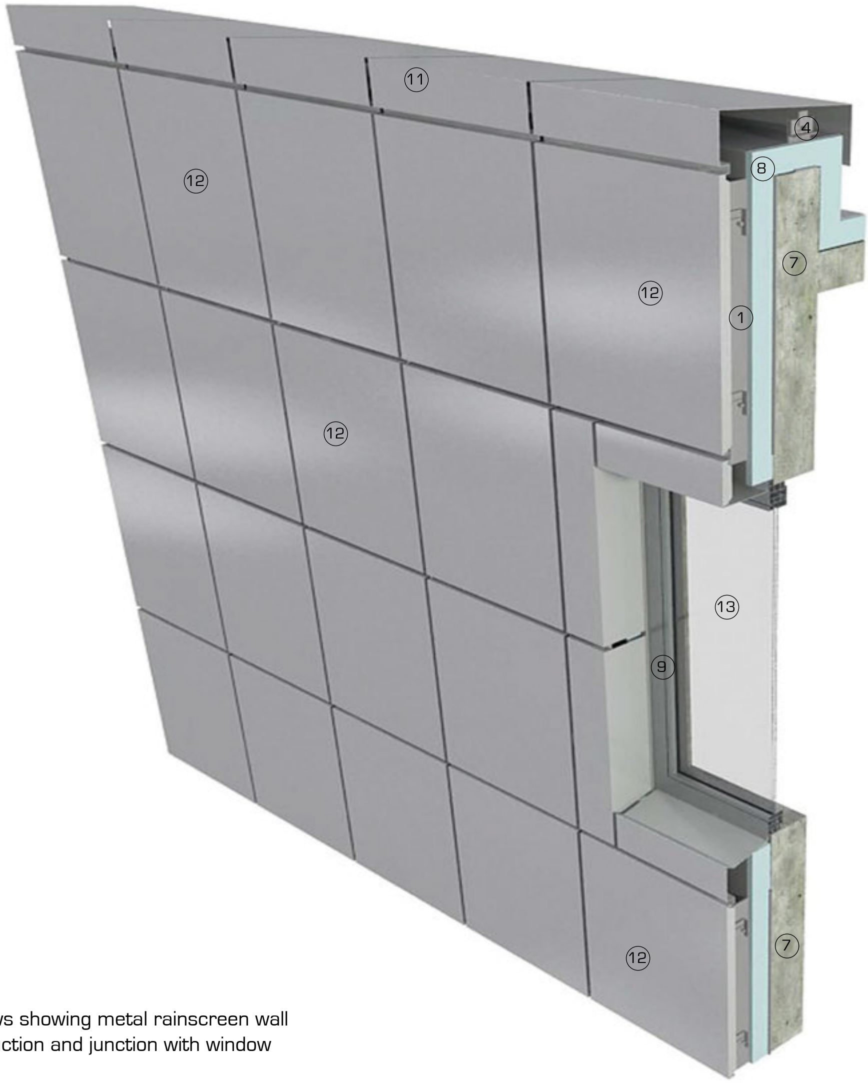
Horizontal section 1:10. Corner details and special application panels

3D view showing special corner panels

and are of a depth equal to that of the composite panels. Interlocking joints are usually made sufficiently rigid to allow two or three panels to be used in a storey height without visible supporting structure. For both vertical and horizontal orientation of panels, this material system requires a supporting metal frame, typically in mild steel, but sometimes in aluminium. This frame is arranged in a way that will support the edges of the composite panels, and is fixed back to the primary structure of the building. The visual characteristics of the supporting frame are usually secondary as they are often concealed behind the interior finishes of the building. Where visible, they form an essential part of the material system, and are often formed from rectangular hollow sections.

System details

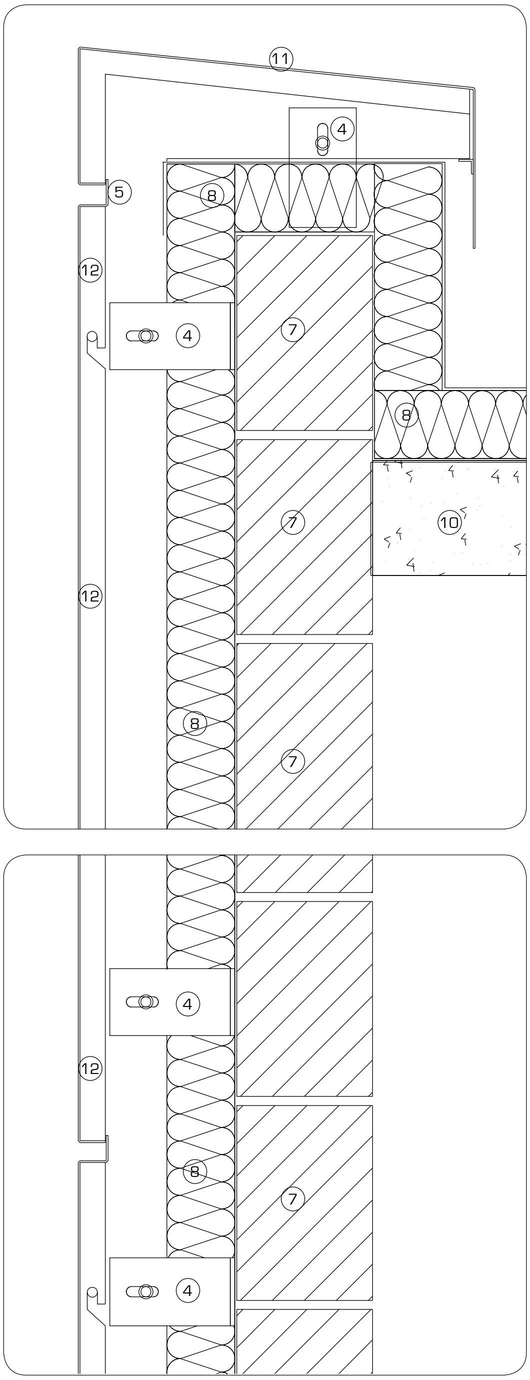
Both two-sided and four-sided interlocking panels have windows and doors as separate components which are coordinated with the material system to varying degrees, with four-sided interlocking systems being the more closely integrated. Windows and doors are fitted in a way that they are either flush with the external face of the composite panels in order that the same panel to panel flashings can be used to seal the door/window, or alternatively windows/doors are recessed. In recessed window and door openings, flat metal panels are used to close the gap between the face of the composite panels and the window or door frame. Some manufacturers of composite panels offer special corner panels for window reveals which are also used at internal and external corners of the facade, and others have a range of preformed panels for cills, corners and parapet copings as part of their systems. This avoids the need for visible metal flashings which lap down over the face of adjacent composite panels to provide a lapped joint, and have a flatter, smoother appearance when compared to pressed metal flashing panels. A wider range of interface components are usually available on four-edge interlocking panels to add to the seamless clipped-together appearance of these systems. Parapets are typically formed with a pressed metal flashing that folds down the face of the facade but can also be created with a parapet panel which can be flat or curved to suit the design. Where a pressed metal flashing is used, a layer of thermal insulation is set beneath, with a vapour barrier on the internal (warm in winter) face of the insulation in order to provide continuity of insulation between wall and roof. Colour matching between metal flashing and composite panel is essential to the success of this method, unless a completely different colour is used for folded metal items. Four-edge interlocking systems allow the possibility of a thin parapet coping of around 100mm that forms a visual continuity with the panels beneath. Any water that penetrates the outer seal is drained away to the base of the wall within the drained and ventilated framing to the panels. Windows are often given the same colour and finish in order to provide a visual continuity between window frame and composite panel, giving the facade the visual crispness previously associated with fully glazed walls.



3D views showing metal rainscreen wall construction and junction with window

This material system uses the rainscreen principle of allowing rainwater to pass through open joints, or partially open joints, where the water is drained away back to the outside of the building. Panels are set typically forward of a waterproofed and thermally insulated backing wall. Wind driven rain that passes through the outer open joints is drained away down the cavity between the back of the rainscreen panel and the outer face of the backing wall. The backing wall is typically of economic type as it is not visible if interior finishes are applied within the building. Metal rainscreen panels are given typically either a completely open joint with framing behind positioned to close views into the void behind, or have folded edges on the panel to close the joint visually, but not to seal it. Small amounts of rainwater that pass through the outer joint are drained away in the ventilated void behind. Visually, this material system provides visually crisp joints with strong shadow lines to the metal panels. The use of narrow joints between panels can give the metal panels a more monolithic appearance as the joints are less visible. Rainscreen panels can provide a flatness or consistency of texture across a facade that is independent of the backing wall behind. Most panels are fixed so as to avoid visible fixings. Face fixings on the metal sheet are usually not preferred since, at around 3mm thick, point fixings on a thin sheet can produce visible distortions across the panel surface. Panels are usually formed as trays or 'cassettes' with folded edges that provide rigidity to the panel as well as a depth to the joint that both reduces rainwater penetration and obscures views into the void behind. Most panels are fixed with either a hook-on fixing or with slotted grooves in the manner of composite metal panels that avoid the need for any visible fixings. With hook-on supports, panels have brackets that are fixed to the sides of the panels that form the tray. Panels are fixed onto vertical rails which are usually aligned with the joints where they serve as a screen to the void behind. Continuous rails are preferred to individual fixings, except in small-scale applications, since rails are much faster to fix than individual brackets.

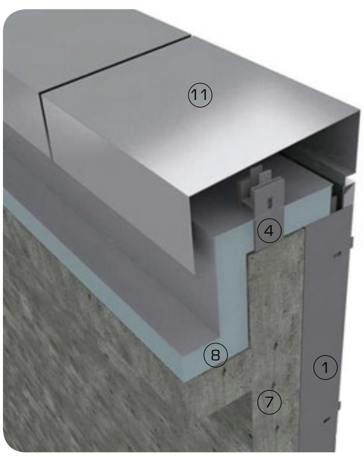
Sizes of rainscreen panels are determined by available metal sheet sizes. Metal coil is supplied typically in 1200mm and 1500mm widths, with metal plate in greater widths and in varying lengths. Metal-faced composite materials are also used, comprising either a thin metal sheet, such as aluminium, bonded to both sides of a rigid plastic core or, alternatively, a single sheet of metal bonded to one side of a honeycomb panel. Composite materials that use a thin (3-5mm thick) inner plastic-based core can be folded to form trays, but honeycomb panels require either an edge strip to conceal the joints, or are set close enough together for the inner core not to be visible. An alternative method of fixing panels is to form a folded tongue and groove joint on the long edges of the panel where panels slot together. An advantage of this method is that the support framing behind can be simplified with vertically-set or horizontally-set rails to suit the pressed metal panels where concealed fixings can be used.



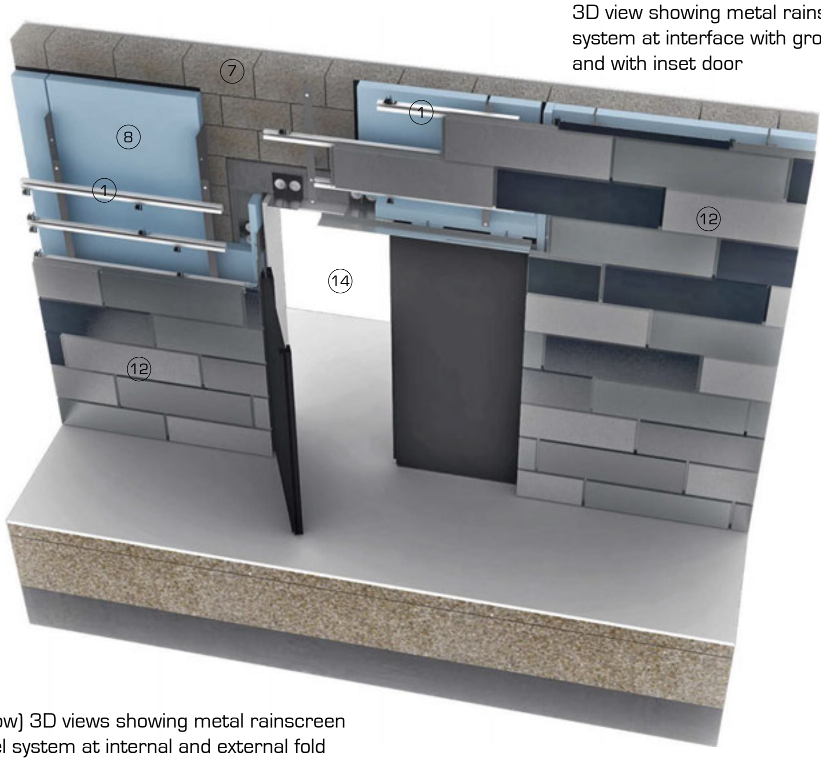
Vertical section 1:10. Parapet showing typical details

3D detail views showing window and parapet detail in rainscreen wall system

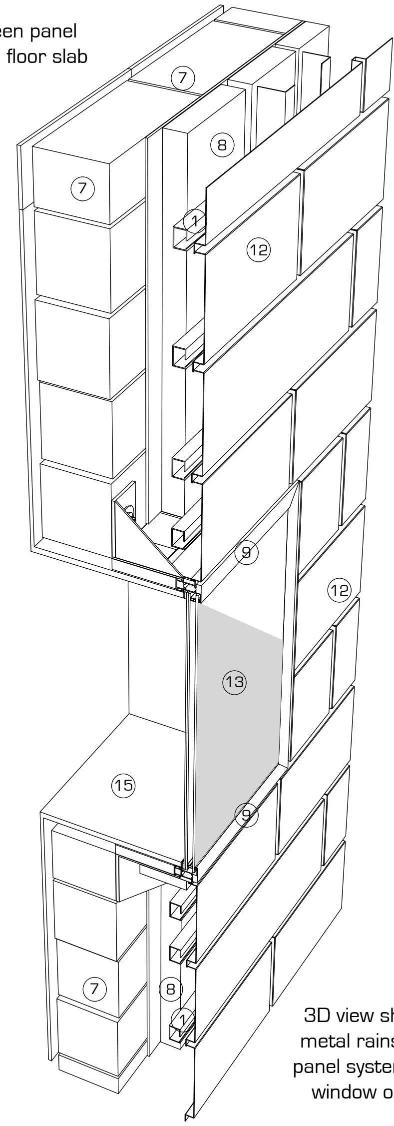
Details
1. Metal support frame
2. Stainless steel mesh
3. Stainless steel spring
4. Metal fixing bracket
5. Fixing bolt
6. Framed perforated metal sheet
7. Backing wall
8. Insulation
9. Window frame
10. Floor slab
11. Pressed metal parapet coping
12. Metal rainscreen cladding panel
13. Double glazing



3D detail view showing typical parapet details

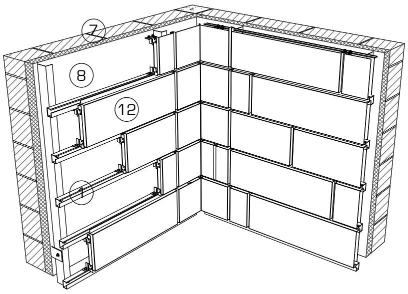


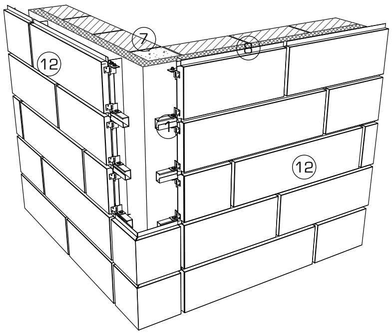
3D view showing metal rainscreen panel system at interface with ground floor slab and with inset door



3D view showing metal rainscreen panel system with window opening

(Below) 3D views showing metal rainscreen panel system at internal and external fold in facade



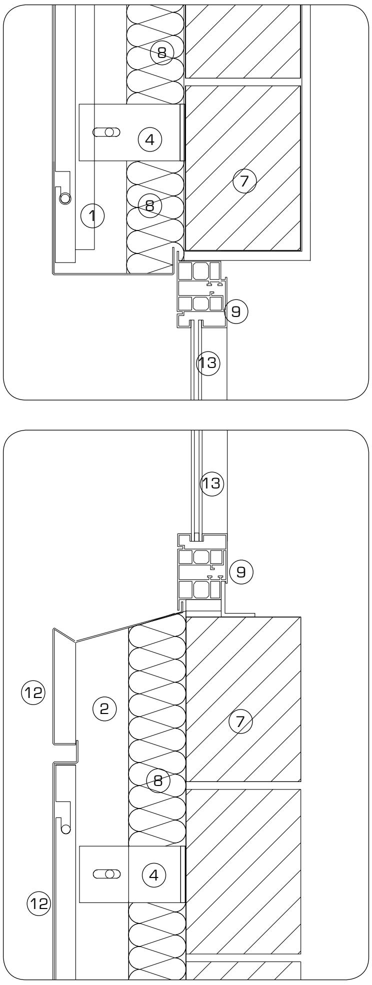


System details

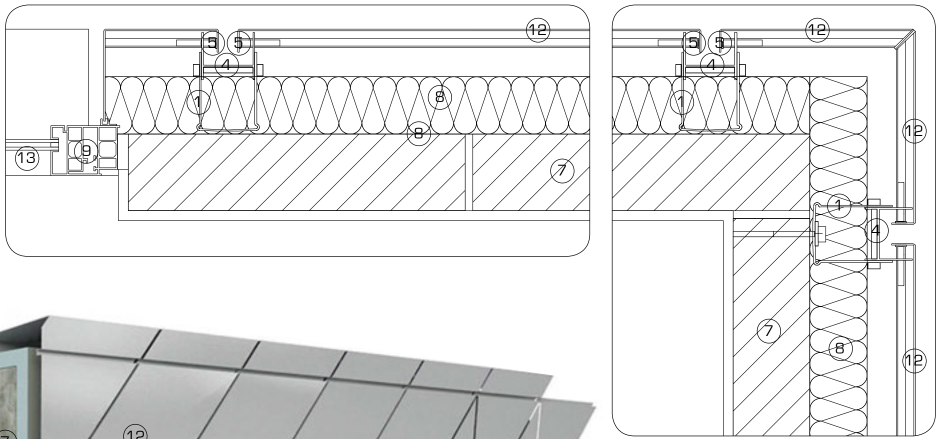
An essential aspect in the design of metal rainscreen systems is the layout and fixing of the framing that supports the rainscreen cladding. Although panels can be set out independently of the backing wall behind, which is one of their primary advantages, the need to fix panels economically makes it essential to engage with the idea of their fixing during the detailed design stage. This is of particular importance where rainscreen panels are set out to coordinate visually with window openings. The open jointed nature of the rainscreen panels allows the junction with windows to be straightforward and visually driven, as windows and doors are sealed to the backing wall, with which they form a continuity. At facade corners, panels are formed typically either from folded sheet or thin composite sheet, or alternatively with mitred panels that meet at the corner, particularly where honeycomb panels are used. Internal corners are formed in the same way, but their geometry allows panels to meet without any special panels with two panels butting up to one another. The corner condition is an important junction, from a visual point of view, as the thin nature of rainscreen panels can be either exposed or concealed at this point. Butting panels together with an open joint on the corner can make it difficult to create a visually sharp edge to the facade, with any imperfections in the setting out of panels being apparent.

Parapets are formed in a similar way to corners, with panels fabricated to suit particular project conditions as a part of manufactured systems. Since the coping is sealed between panels on its horizontal face to avoid rainwater falling directly through the joint between panels, the joint is often recessed to match with the open joint on its external vertical face. The coping usually has a little gap between the coping panel and the inner face of the parapet upstand in order to ventilate the cavity, where the joints between the facade panels do not admit sufficient air for ventilation.

Because windows in openings are sealed directly against the waterproof layer of the backing wall, the visual treatment of the junction of panel and window requires attention during design to avoid an uncoordinated alignment. The rainscreen panels are terminated adjacent to the window in order to conceal the seal between window and backing wall. In order to avoid staining from dust and dirt, cills are usually formed in a way that directs rainwater to the sides of the opening and down joints between panels rather than directly down the face of the panels below. Drips at ground level are formed as pressed metal flashings, with the gap between the panels and the backing wall being closed with metal mesh that allows the passage of air for ventilation but avoids the ingress of insects into the ventilated void. Although manufacturers offer metal rainscreen panel systems, they can be modified designed to suit individual projects and fabricated economically.



Vertical section 1:10. Typical window details

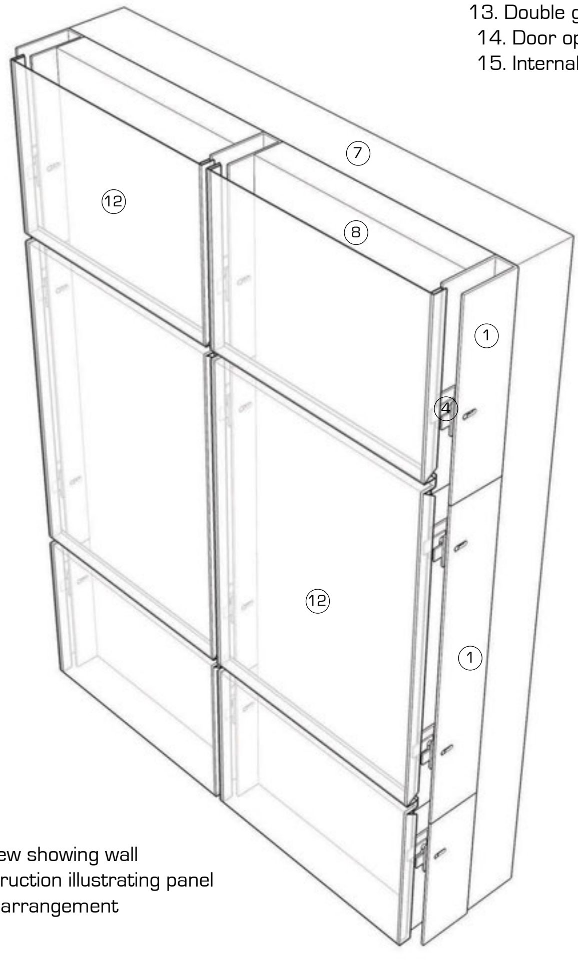


Horizontal section 1:10. Typical details through wall and junction with window

3D view showing basic rainscreen panel system

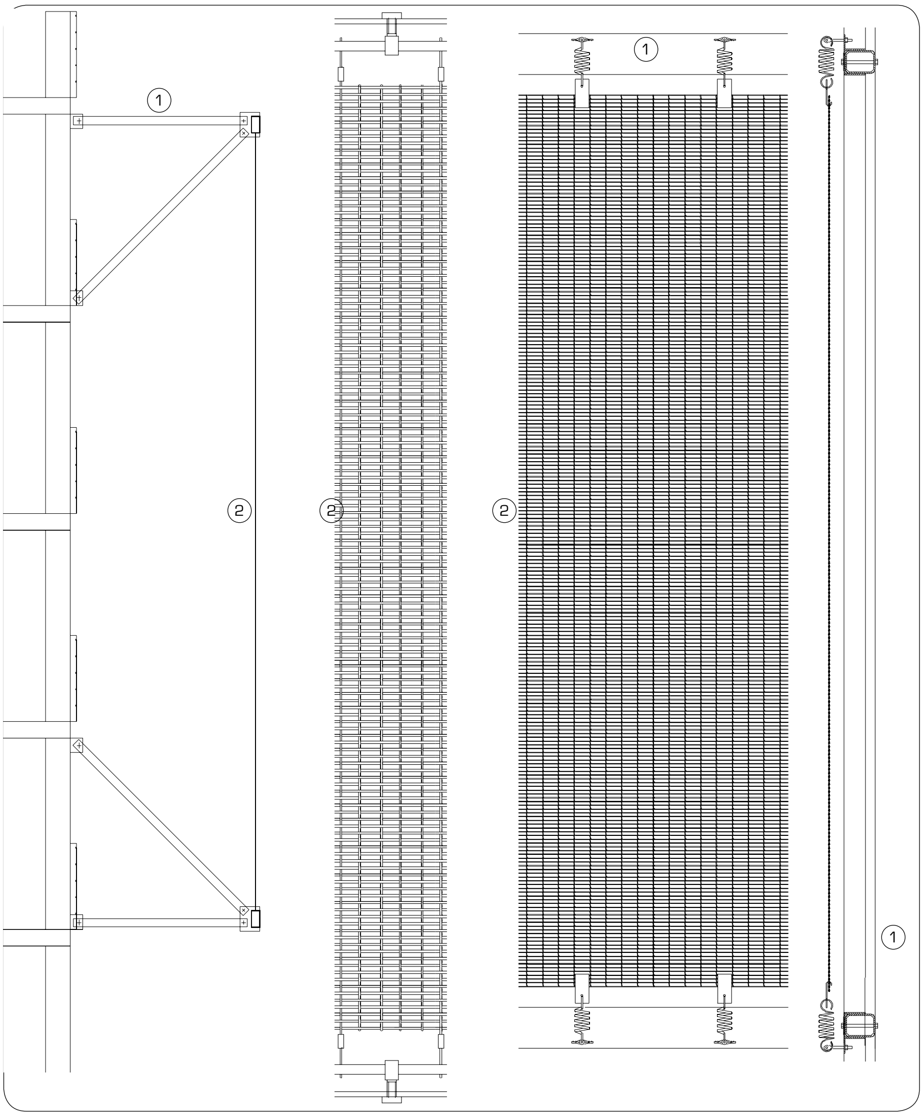
Details
1. Metal support frame
2. Stainless steel mesh
3. Stainless steel spring
4. Metal fixing bracket
5. Fixing bolt
6. Framed perforated metal sheet
7. Backing wall
8. Insulation
9. Window frame
10. Floor slab
11. Pressed metal parapet coping
12. Metal rainscreen cladding panel
13. Double glazing
14. Door opening
15. Internal finish

3D view showing basic rainscreen panel system at window opening

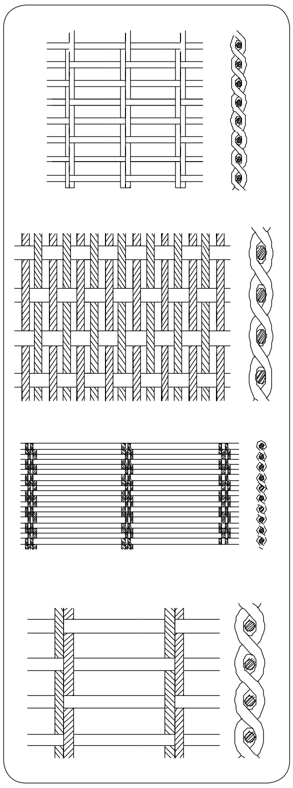


3D view showing wall construction illustrating panel fixing arrangement

3D views showing various mesh screens

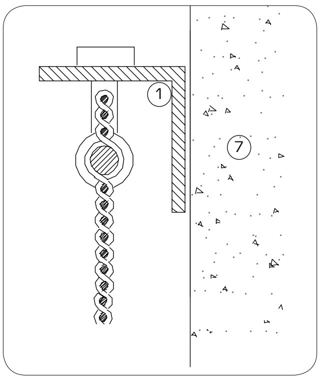


Elevation and vertical section 1:25. Typical screen arrangement

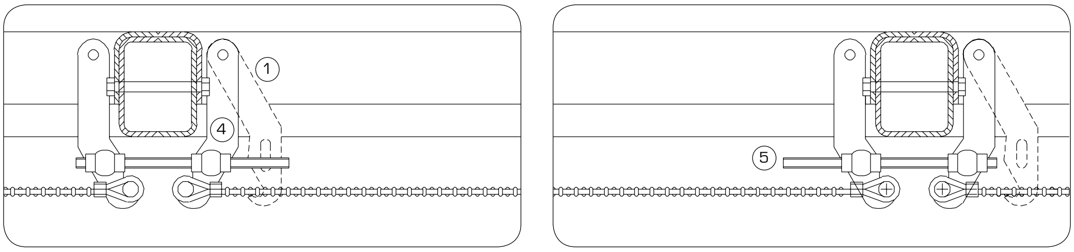


Examples of mesh weave patterns

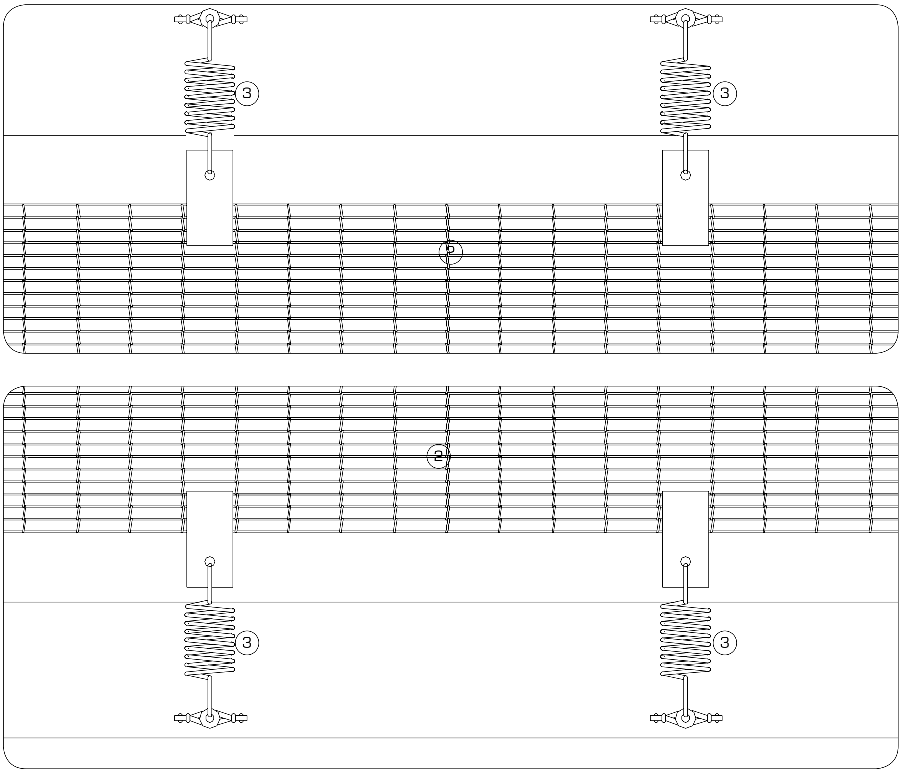
Details
1. Metal support frame
2. Stainless steel mesh
3. Stainless steel spring
4. Metal fixing bracket
5. Fixing bolt
6. Framed perforated metal sheet
7. Backing wall
8. Insulation
9. Window frame
10. Floor slab
11. Pressed metal parapet coping



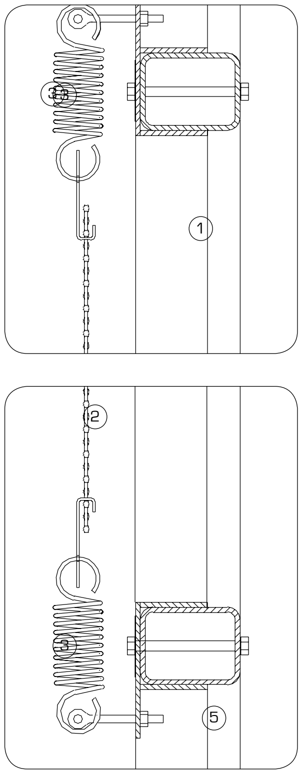
Vertical section 1:2. Woven mesh fixed to wall



Horizontal section 1:2



Elevation 1:2



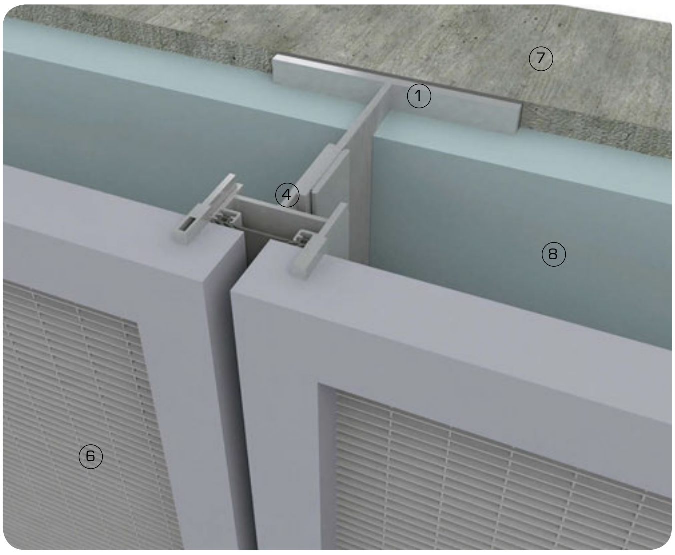
Vertical section 1:2

System design

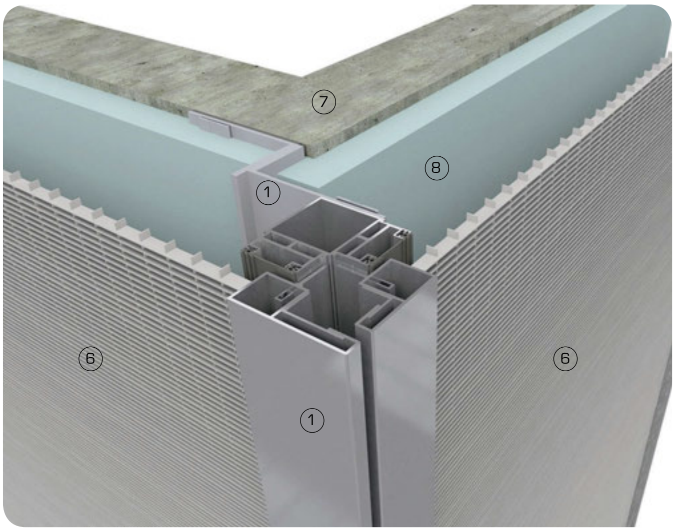
Metal mesh in facades has developed as a material system from the early 1990s with the introduction of woven stainless steel and woven copper to provide lightweight screens, typically as screens. From its origins in industrial applications, such as woven metal conveyor belts, stainless steel mesh is used in facades for a variety of functions: solar shading to glass walls, guarding to full height balustrades, and as visual screen to backing walls. Woven stainless steel has cables set in one direction, which can be tensioned at points or along its edges to provide a rigid, lightweight screen that has little visible supporting structure, while metal rods set perpendicular to the direction of the cables provide rigidity in one direction. Stainless steel is preferred to mild steel for its greater durability and resistance to corrosion. Copper and bronze are being introduced, but the lower tensile strength of these materials currently limits their use to smaller scale applications. Because the cables require tensioning, their supporting structure can be visually prominent, which has led to a greater interest in using more rigid meshes made from rod woven in both directions, where the material is set into a frame at its edges. Consequently, there are three generic types of varying rigidity: rigid mesh, mesh flexible in one direction and fully flexible mesh.

Rigid mesh is made from rods which are woven in two directions that can use very similar patterns to those where cable is used in one direction. The material is made in relatively small panels of around 1800mm x 1500mm, and is fixed by clamping the materials into a continuous edge frame or by point fixing, since the material cannot be tensioned. The diameter of the rod is typically around 2mm set into a grid of 6mm x 2mm. They are joined to form a continuous wall of mesh panels where the grid of the frame can dominate visually. Because no cable is used, the material can be colour coated or etched to create specific visual effects. Where aluminium is used (which is not as rigid as stainless steel), the material can be anodised in addition to these finishes, though panels are made from either greater diameter rod or smaller panel sizes.

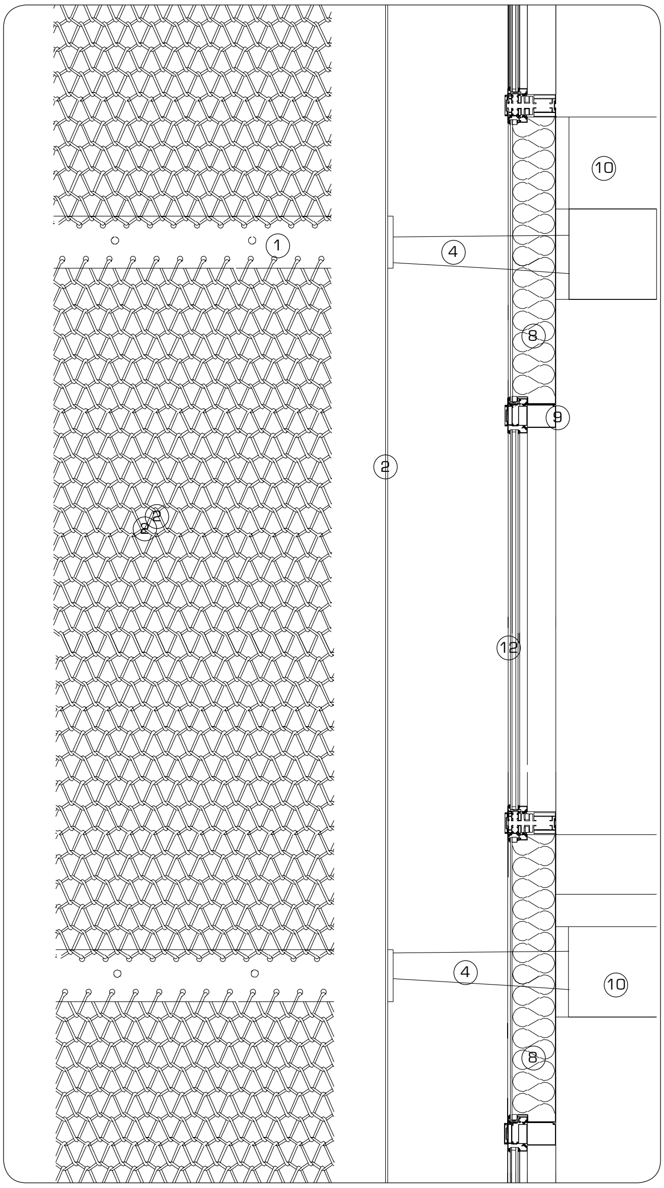
Mesh which is flexible in one direction is sometimes woven in groups of cable, running the length of the material, with thin rods woven into these cables in the opposite direction, across the width of the material, creating a visually textured surface. The material is manufactured in long lengths, allowing it to be used as a continuous facade ‘wrapping’ material, either tensioned horizontally across the facade or hung from top to bottom. Meshes are typically hung to reduce the sagging that could occur when used horizontally, but cables beginning to be set at different angles, even 45° from the vertical direction. These meshes are usually made in widths up to around 7500mm but they require restraint at close centres if used as guarding, as their deflections can be high. A wide variety of weave pattern is used to suit different amounts of transparency, rigidity and weave. Light transmissions ranging from 25% to 65%, making them very suitable for solar shading where a specific percentage of shading is required. Light transmission can be reduced



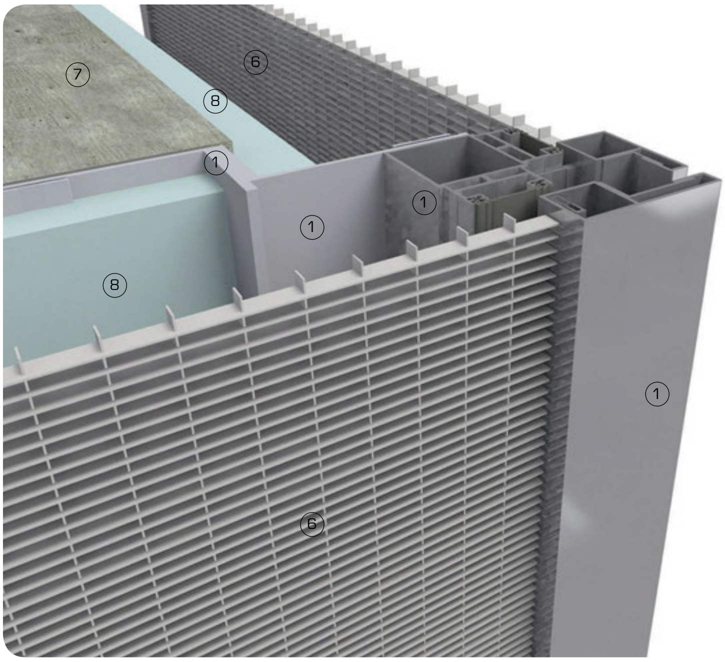
3D detail view showing panel junction of perforated metal screen



3D detail view showing external corner of perforated metal screen

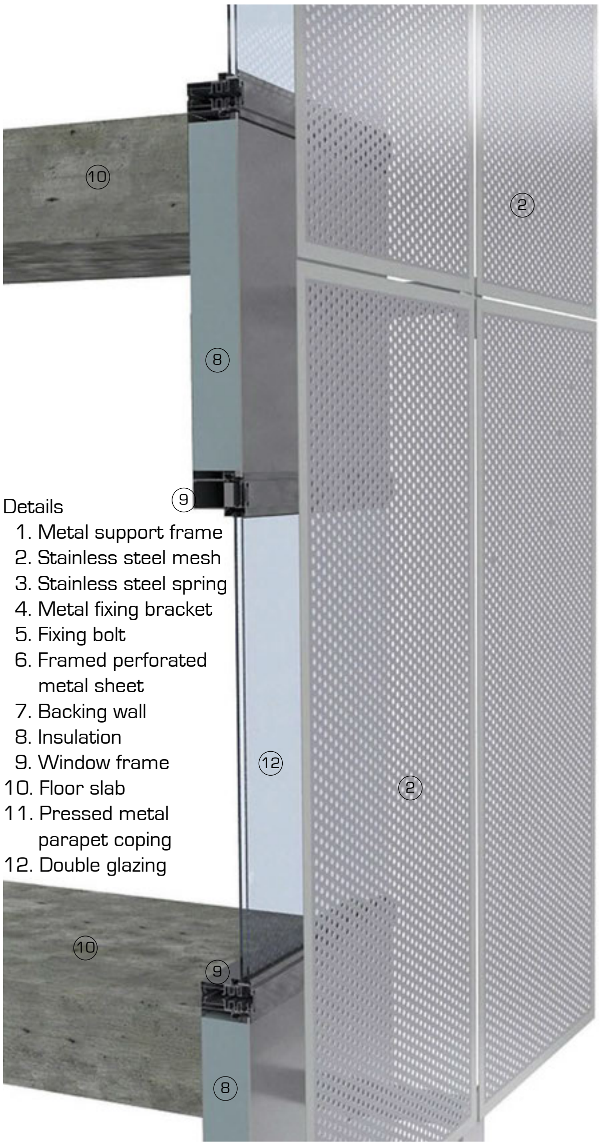


Vertical section and elevation 1:25. Mesh flexible in one direction fixed to brackets supported on adjacent wall

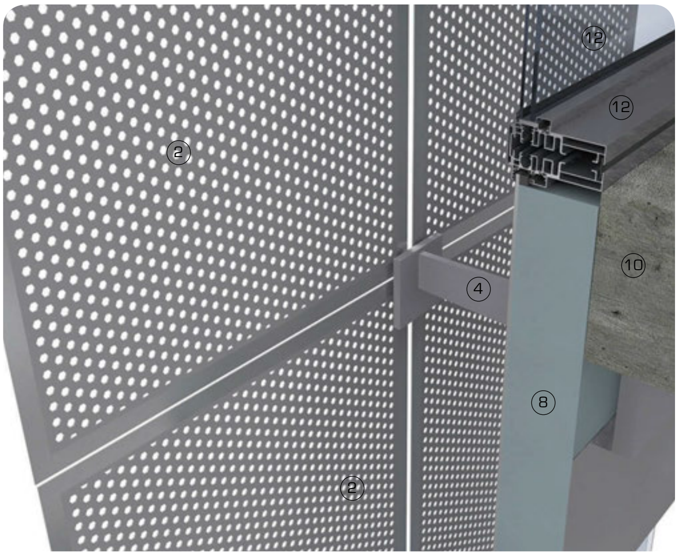


3D detail view showing external corner of perforated metal screen

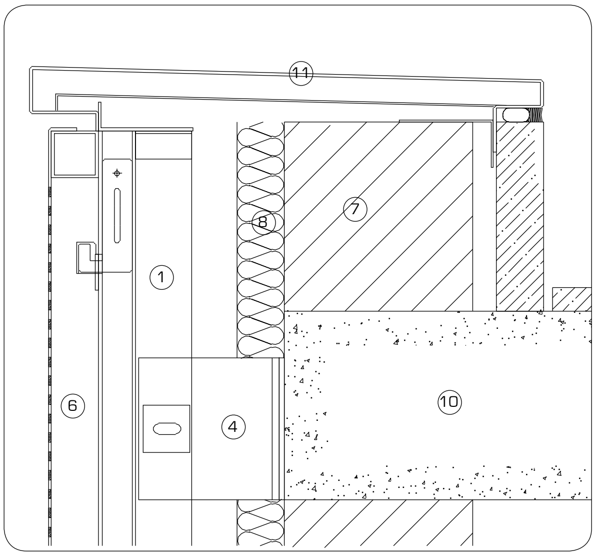
3D detail view showing mesh panel in front of curtain wall glazing



3D detail view showing mesh panel in front of curtain wall glazing



3D detail view showing mesh panel in front of curtain wall glazing



Vertical section 1:10. Parapet of perforated metal screen

by reducing the distance between cables, between rods, or a combination of both, depending on the visual effect required. Cable thicknesses vary from 2mm to 6mm with rod diameters ranging from around 2mm to 4mm. Weave patterns can be as dense as 4mm x 10mm for low light transmission to 4mm x 10mm for high light transmission. Meshes can also incorporate a varying weave within a single length of material to suit varying light transmission requirements.

Fully flexible mesh is less commonly used in facades, but has a visually rich appearance as a result of its non-rectilinear open weave. Metal widths range from around 1800mm to 2400mm and are manufactured in long lengths. More open weave versions are available, which resemble thin cable woven in two directions. These are manufactured in widths of around 6000mm, requiring restraint at around 1500mm centres. The material is held in place by tensioning the material in two directions, typically in an edge frame, but where panels can be as wide as the material as manufactured, subject to its deflections being within the limits of its prescribed use.

System details

Where rigid mesh is fixed into a frame around its edge, the material is usually clamped between flat bars, or angles of the same material. The plates are clamped with bolts, which can be countersunk to avoid highly visible fixing bolts. The frames are then fixed back to the facade on support brackets. An alternative edge frame is to use a C-shaped folded section into which the rigid mesh is fixed. Rigid mesh can be curved in either one direction or two directions to give a highly modelled surface. The form of the curves is typically influenced by its supporting structure, which needs to be a balanced blend of structure and mesh to avoid the supporting structure from becoming visually dominant.

Mesh which is flexible in one direction avoids the need for a highly visible supporting frame, but typically requires substantial mild steel brackets projecting from the facade that can absorb the tension in the cables at each end. Panels can be set side by side to create a continuous texture of material across a facade, which is one of its preferred visual characteristics. Whether the material is set vertically or horizontally, a similar variety of support methods can be used at the ends of the cable. Cables can be turned over a continuous rod at its ends to form a loop, with the rod being supported on individual brackets to suit the design rather than being aligned with each cable. Alternatively, the continuous rod can be woven into the mesh, usually during manufacture, with the rod being supported in the same way.

Details
1. Extruded aluminium frame
2. Curtain wall carrier system
3. Extruded aluminium louvre blades
4. Floor slab

3D view showing metal louvre screen in front of curtain wall system

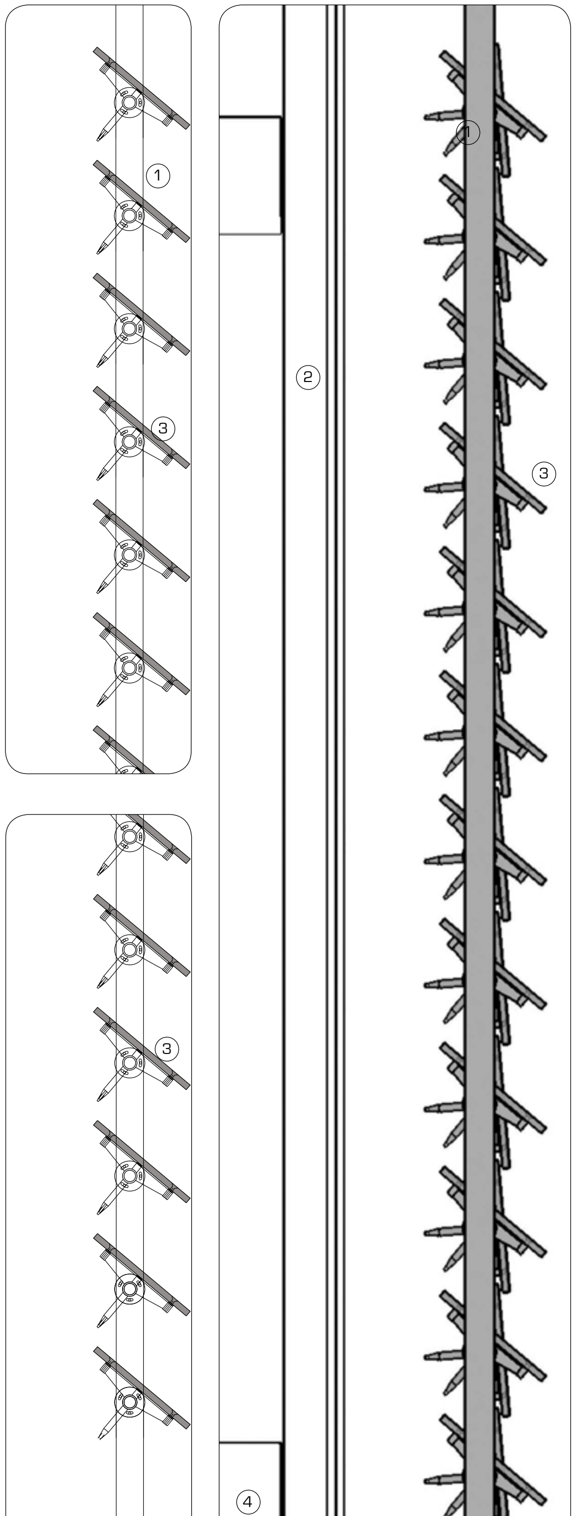
System design

Metal louvres are used typically in facades either to provide weather resistance to the ends of ducts for mechanical equipments or as acoustic screens. Glass blade louvres with metal frames are used to provide ventilation to daylit spaces such as semi-open circulation spaces where high levels of thermal insulation are not required. The orientation of metal louvres is as much a visual consideration as one of technical performance, with the blades used to conceal views through as well as to allow the free passage of air through the panel. For this reason metal louvre blades can be set either vertically or horizontally with an orientation that avoids views through the blades. At ground/street level, horizontal blades usually conceal views through the void behind, but above ground floor level, the 45° orientation of the blades allows views through unless an additional bank of blades is added, which both improves weather protection and conceals views through the panel. Vertically set blades provide a screen that conceals views through when seen at an oblique angle, but allows views through a small part of the facade when directly facing the facade. Deeper vertically-set blades increase the screening effect for views at close proximity to the louvres. Where more than a single row of inclined blades is needed in horizontally-set louvres, typically to improve their weather resistance, rainwater is drained by forming a groove along the bottom edge of each blade to drain away water through the sides of the louvre frame, then down the base of the frame and back to the outside. The perimeter of the frame is sealed against the surrounding waterproofed wall where a different material is used for the surrounding area of facade.

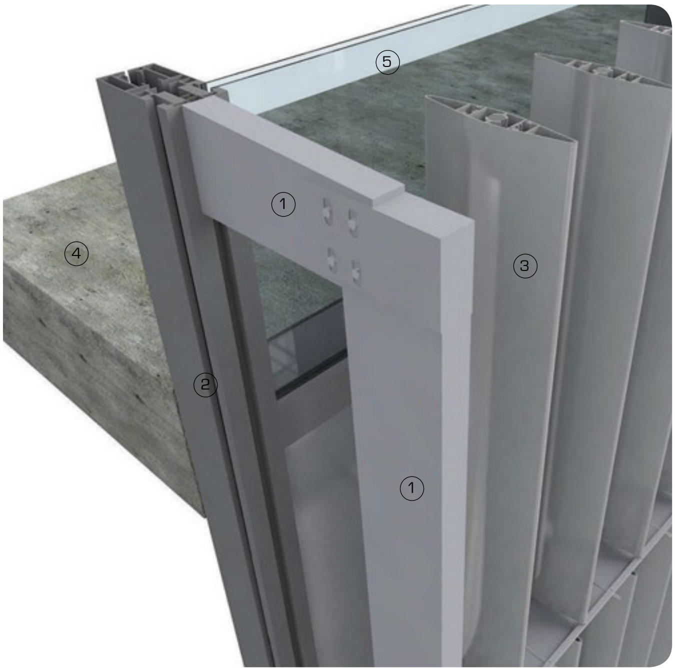
Where metal louvres are set into a curtain walling system, blades are placed in a perimeter frame to form a complete panel which is then fixed into curtain walling framing in the same manner as a glazed unit or metal panel would be fixed. This is particularly useful where a glazed wall has a few louvre panels that form part of the facade. The louvres can be introduced without the need for changing the system to accommodate the louvres, simplifying the interfaces between glass/metal units and the open louvre panels. Water that penetrates the glazing system is drained away through the drained and ventilated cavity of the curtain walling system. Metal louvre blades are usually made from extruded aluminium or mild steel. Aluminium is typically polyester powder coated, while mild steel is galvanised and painted. The use of aluminium provides precisely formed sections that can both encourage the passage of air through the panel and minimise rainwater penetration. The blades are fixed into a perimeter frame also formed from extrusions or angle sections to suit the frame size and method of drainage. Mild steel is often used where greater resistance to accidental damage is needed, as the material better withstands the effects of local impacts than aluminium, and can also be accommodated within curtain walling systems.

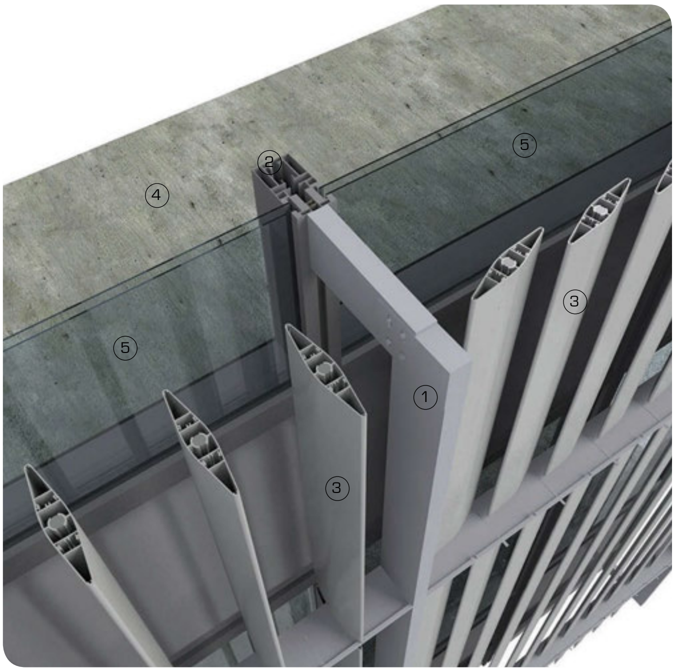
3D detail views showing louvre panel fixing details

3D view showing metal louvre screen in front of curtain wall system



Vertical section 1:25. Metal louvre system and fixing elements



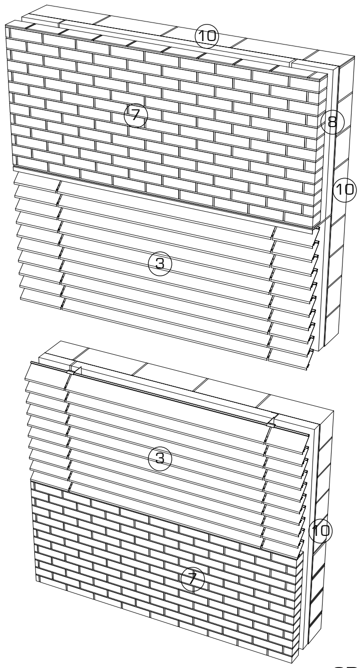


3D detail views showing profiled aluminium louvres and fixing system

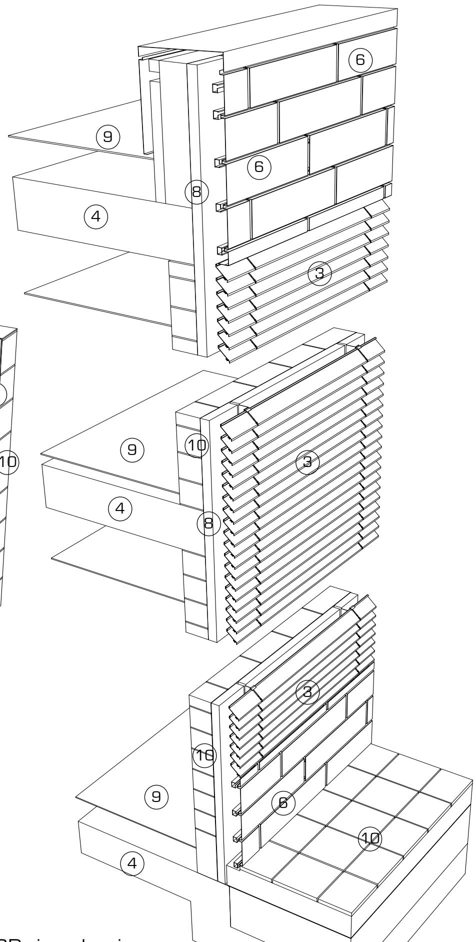
3D view showing profiled aluminium
louvres and fixing system overview

3D detail views showing profiled aluminium louvres and fixing system

Details
1. Extruded aluminium frame
2. Curtain wall carrier system
3. Extruded aluminium louvre blades
4. Floor slab
5. Glazing
6. Masonry rainscreen cladding
7. Brickwork outer leaf
8. Thermal insulation
9. Floor finish
10. Blockwork backing wall



3D view showing horizontal louvres set within loadbearing masonry facade system



3D view showing horizontal louvres set within rainscreen cladding facade system

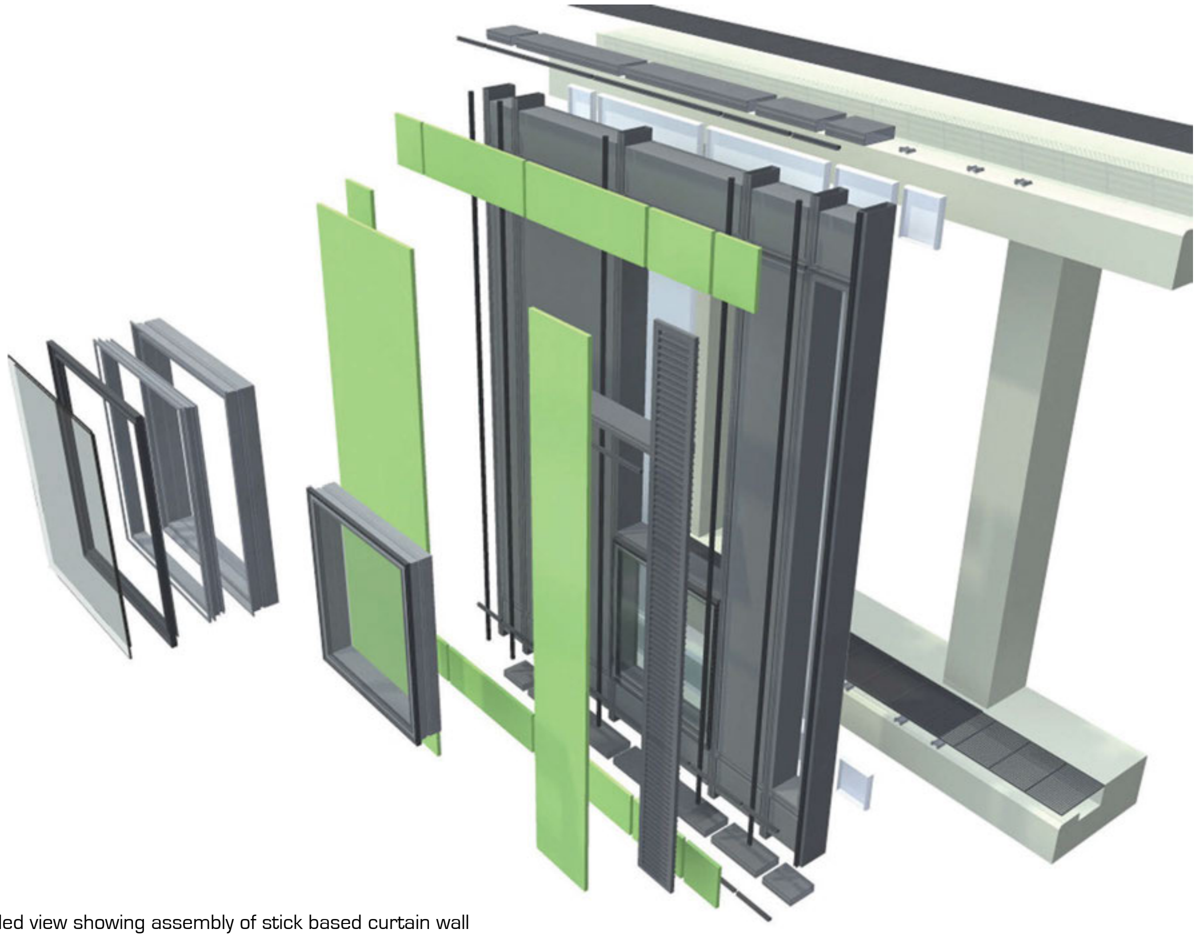
3D view showing horizontal louvres set within rainscreen cladding facade system

System details

Metal louvre panels are made in widths of 1500mm to around 3000mm to suit the facades into which they are set. Individual blades are supported by vertical or horizontal framing members along the length of the blades in order to provide the required stiffness in addition to the perimeter frame required for each panel. Because of the required technical performance and visual criteria required of louvres, they are made as proprietary systems which are adapted to the requirements of individual projects. Doors in louvre panels are usually formed in a similar way to fixed panels to avoid them being highly visible, but usually have larger frames to provide the required door panel stiffness.

Metal louvres are also used for solar shading as part of double skin facades, typically set 750mm to 1000mm in front of a glazed outer wall. This application of metal louvres has led to them being required in much larger sizes set vertically or horizontally to suit the incident sun angles for which shading is provided. Since aluminium is extruded economically in widths up to around 300mm, depending on the profile design, metal louvres used for solar shading are often made in combinations of curved sheet and extrusions linked together to form a complete shape. The resulting forms of these blades are also finding an application as regular louvre blades in facades where the increase in scale makes them a more integrated part of the language of metal panel facade design. Larger scale louvre panels allow them to be used as both fixed or adjustable types on a single facade, where the louvres are a less visually obvious part of the design. Mechanisms for moving louvres typically comprise pivots set on top and bottom with a sliding arm at the bottom, to which the blades are connected to provide louvre movement. These can be hand or electrically operated. Aerofoil-type sections can span up to around 3000mm.

Glass louvre blades are held by metal clips, usually made in cast or extruded aluminium, that provide structural support to the blades. Clips are linked to rods that form part of the supporting frame to the louvres. The rods move up and down, allowing the louvre blades to be moved to opened and closed positions to suit both ventilation and solar shading requirements. Movement of the blades is controlled either manually with a winding mechanism, or electrically, with louvres operated in groups of panels. Panel sizes are around a maximum of 1500mm high x 1200mm wide. Glass blade louvres provide around 70% free area when fully open. Thermal insulation and lower rates of air infiltration can be achieved with double glazed units. The maximum length of panel is also 1200mm, with blade widths of around 150mm to 200mm. The high air infiltration rates associated with glass blade louvres have been improved in many years, but do not significantly affect their performance for semi external applications, with which they are usually associated.



Exploded view showing assembly of stick based curtain wall

System design

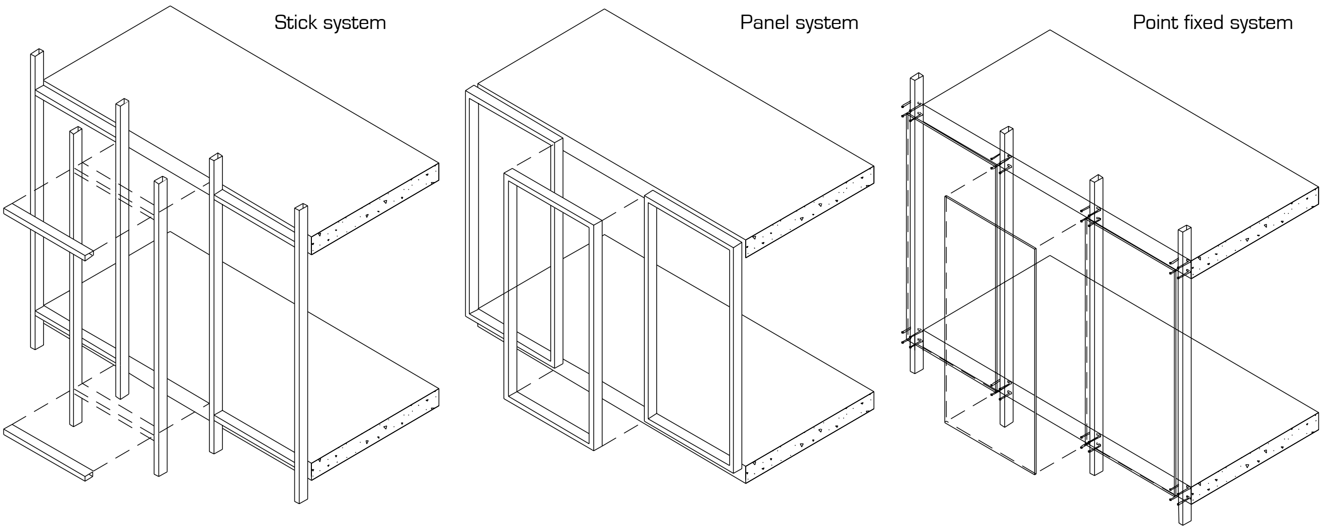
An essential difference between glazed walls and those built in other materials is that the seals in glass construction form a continuity that usually requires the installation to be continuous starting at one point in the wall and setting glazed panels next to each other to continue the assembly. This is different from other material systems, which often allow for much more flexibility in their methods of construction, and which do not have any significant influence on the design of the building.

The main types of glazing system that use primarily double glazed units are stick glazing, unitised panels, point fixed glazing and window walls. In addition, the principles of these systems can be made as small-scale windows set into openings of walls made in a different material. Glass blocks can also be considered to be a glazed wall, but follows none of these principles, using a stack bonded version of masonry construction. All these types are set out in this chapter.

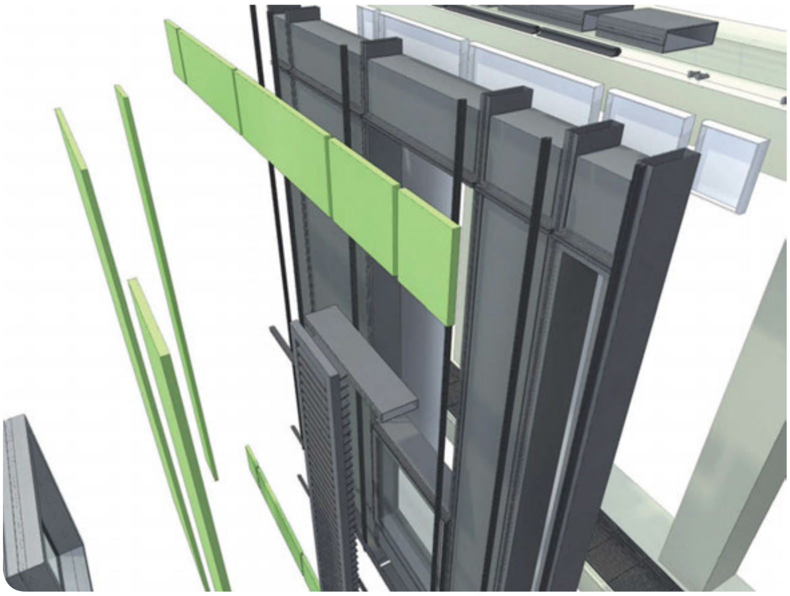
For all glazed wall types the first operation on site is usually to fix the brackets that will carry the façade system to the floor slabs. These are usually made in stainless steel, though mild steel and aluminium can be used depending on the specific application. Brackets are fixed either onto the floor itself, or onto the vertical face of the slab at its edge. Fixing brackets directly onto the floor slab suits situations in taller buildings, where access to the edge would require scaffolding or moving platforms called 'mast climbers' which can be slow to use and suit straight facades in simple arrangements. Floor mounted brackets are sometimes set into a pocket in the floor slab in order that they can be covered by screed and floor finishes. Office buildings typically have raised floors, so the brackets can be fixed directly on the floor slab. If brackets are set on the side of the slab, then this done usually to avoid conflicting requirements at floor level, such as a thin floor build-up, or where brackets cannot be accommodated in pockets set into the slab. It can also be easier to fix brackets on the edge of the slab if scaffolding is used.

Once brackets are in place, framing members or panels are fixed to them. In the case of stick glazing, mullions (verticals) are fixed first, then transoms (horizontals), then glazing and capping. The glass is fixed with temporary short clamps fist, until it is all properly aligned, then the full pressure plates are applied with their rubber-based seals. This makes stick glazing slower to install than unitised types, but has the advantage of flexibility of installation on site. Some glazed walls, such as those used for full height glazed walls, may be fixed back to full height steel frame rather than floor slabs. If the steel frame is designed as a single structure that does not have the structural movements associated with slab edge deflections, this provides the opportunity to omit the aluminium structural box section on the back of the glazed wall assembly, and fix the glazing assembly directly to the supporting steelwork.

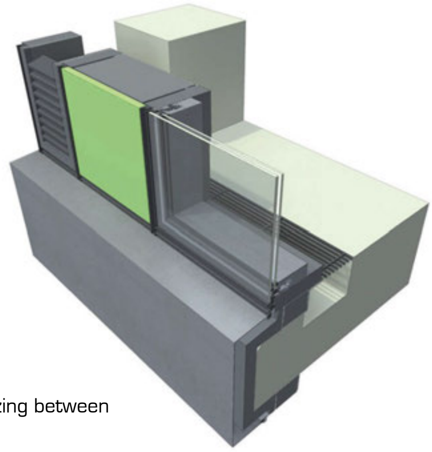
With unitised glazing, panels are typically hung from brackets and are fixed side by side on a single floor, until the floor is complete, or as much of it as can be closed off. Sometimes gaps are left in glazed wall installations on site in order to allow



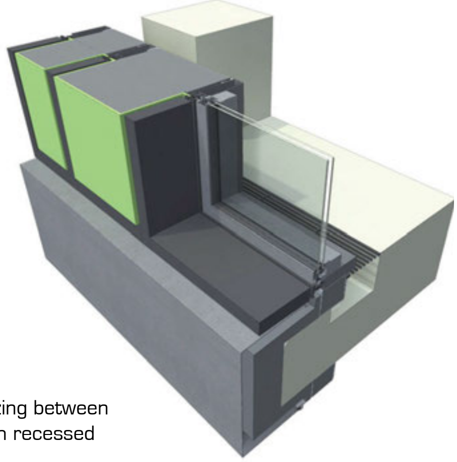
Glass assembly systems



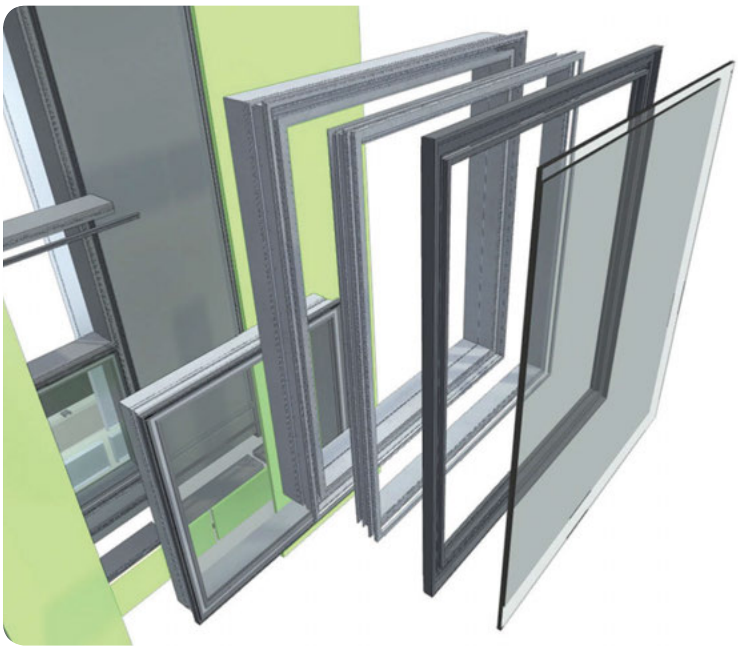
Exploded view showing arrangement of opaque infill panel within stick based curtain wall



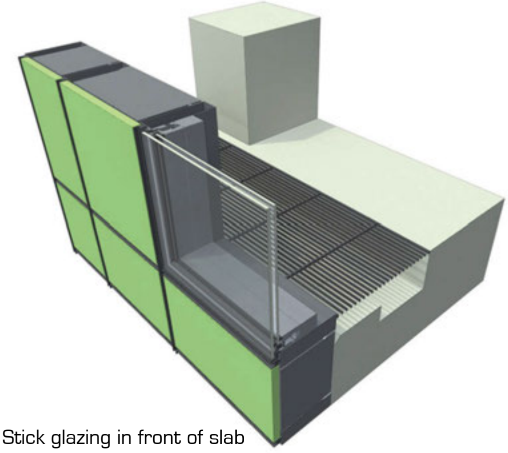
Stick glazing between slabs



Stick glazing between slabs with recessed window

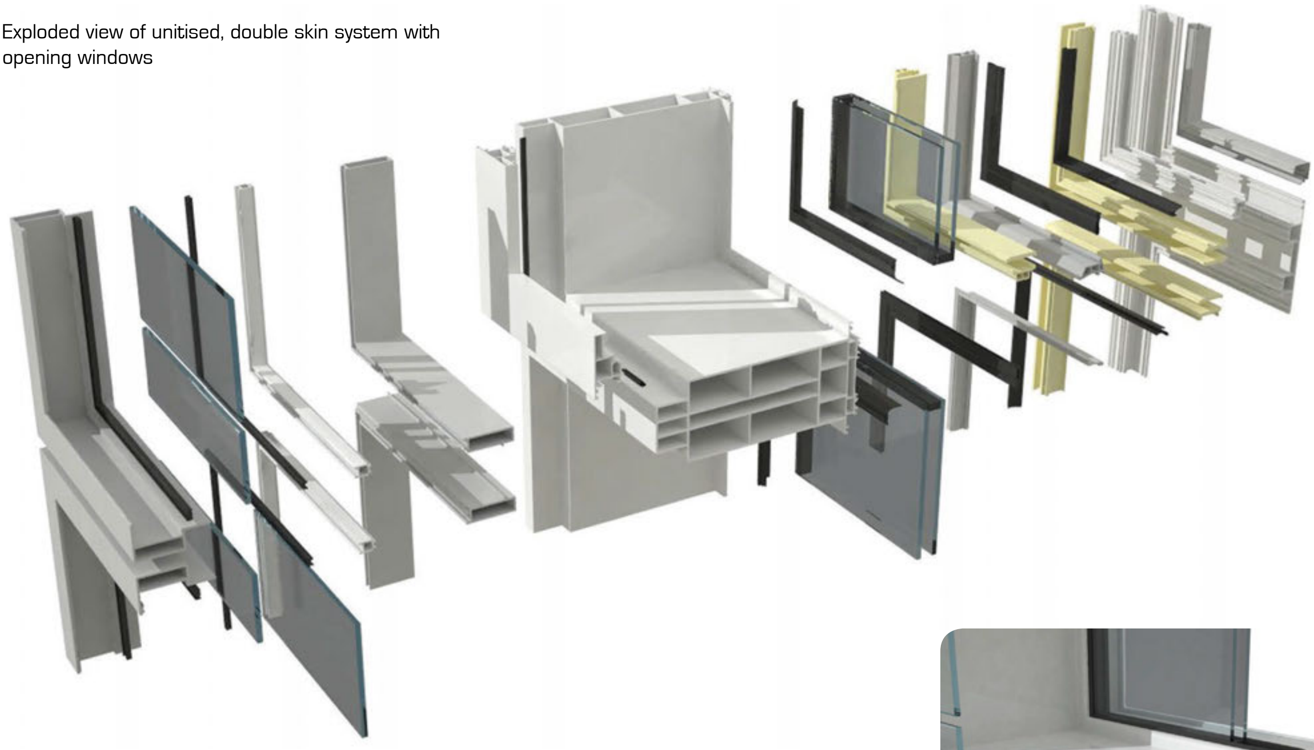


Exploded view showing window assembly within stick based curtain wall

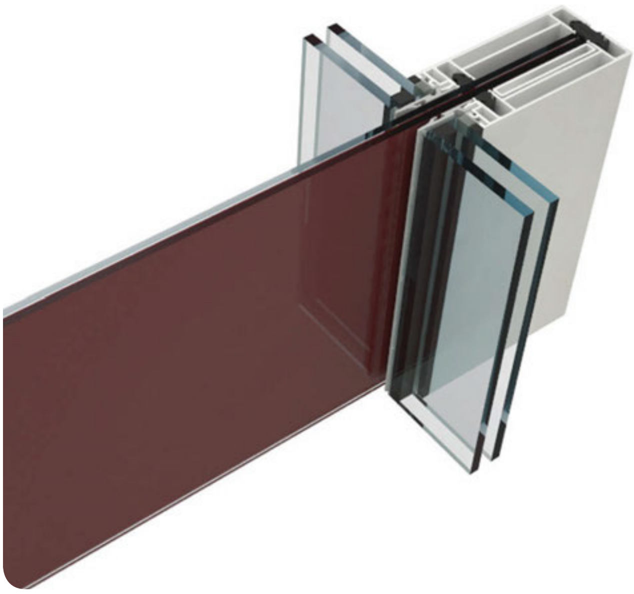


Stick glazing in front of slab

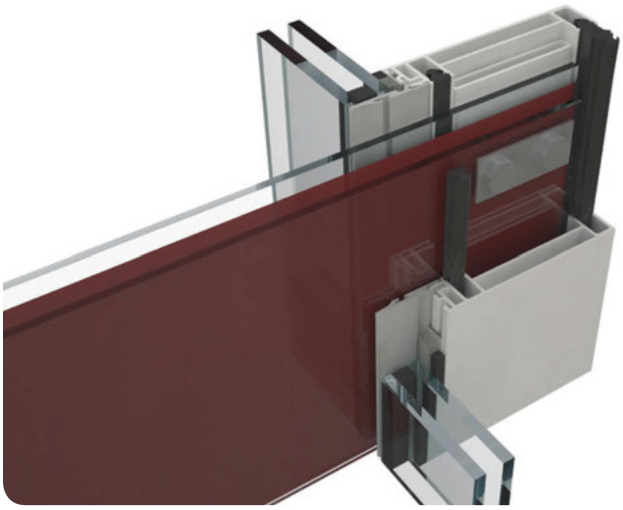
Exploded view of unitised, double skin system with opening windows



Detail of unitised connection for double skin mullion



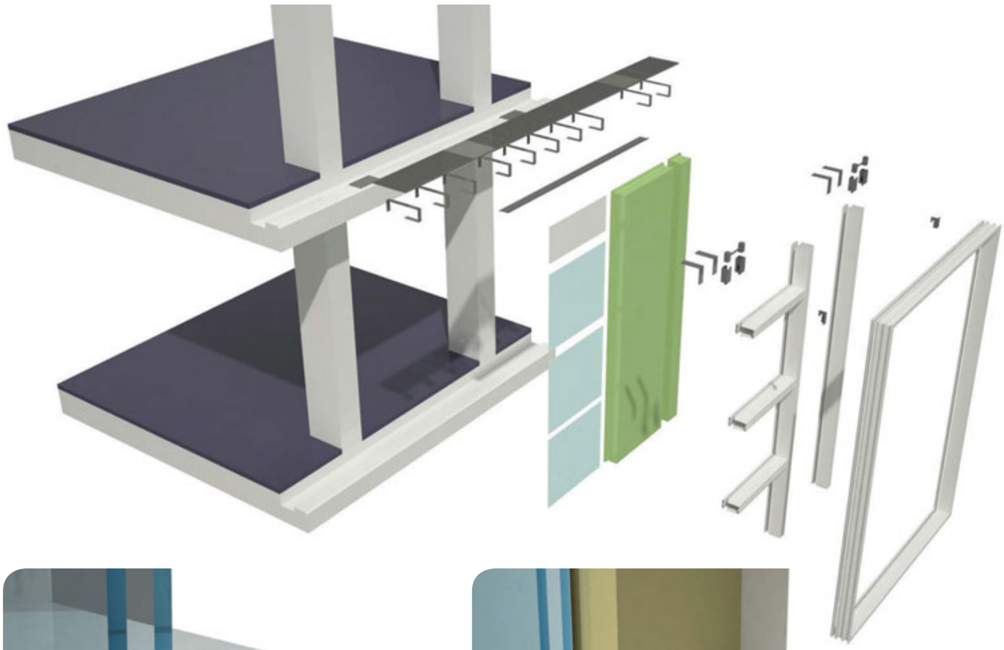
Unitised, double skin glazed panel

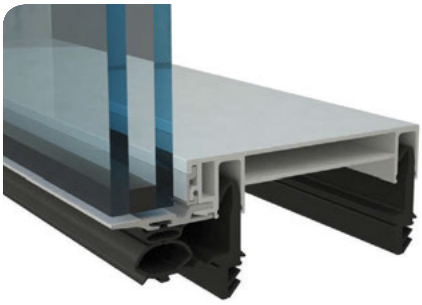


3D view of glazed vertical louvre set into unitised glazing system

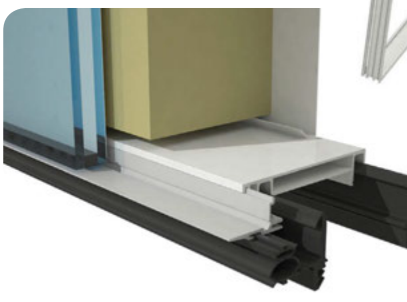
Unitised, double skin panel with opaque infill

Exploded view of unitised glazing panel with framing for additional opaque inserts





Frame detail for unitised system



Frame detail for unitised system with opaque glazing

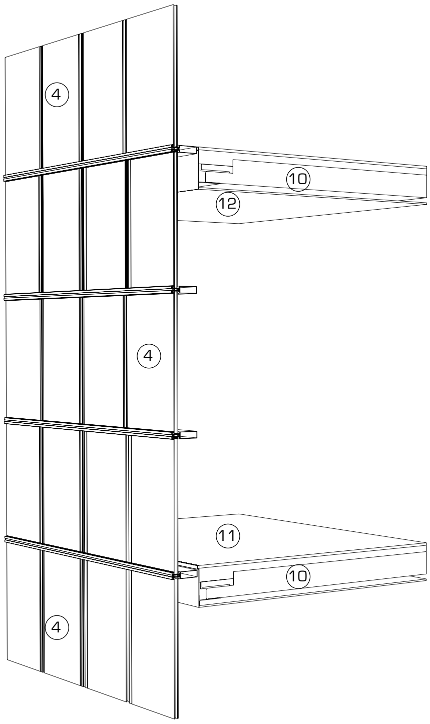
3D section showing unitised panel hung from floor slab

access directly from outside for building materials used for work inside the building, depending on climate and site location. Unitised installations typically start at the bottom of the building and work upwards, slotting panels in one above the other, lifted in place by crane. This makes it a fast method of closing the external wall, allowing work to progress inside the building at earlier stage than would be possible with a comparable stick glazed installation.

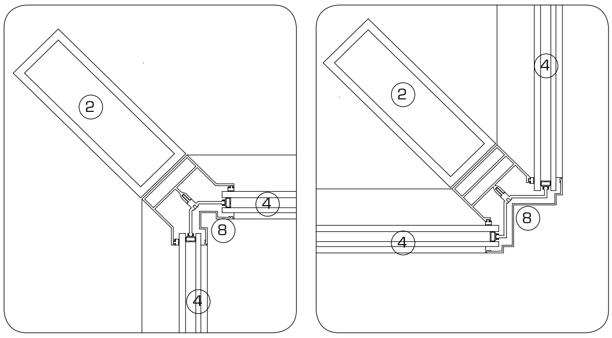
Point fixed glazing is fixed in a variety of ways, depending on size of installation and the method of support. Small scale clamped glazing over one or two floors may be supported at its base, with clamps used to transmit loads down from the top panel to the floor below. This method of installation starts by fixing clamps at floor level and setting the glass in place from the bottom upward, with either scaffolding or temporary supports to hold the glass in place. If glass mullions are used rather than a steel frame, then the glass mullions are installed along with the glass panels. If a steel frame is used, then this is installed before the glazing. Larger scale bolt fixed glazing is installed with glass panels being craned into place with bolts or clamps often already fixed to the glass, making it easier to install. These larger installations are typically supported from a steel frame which is built either by installing large prefabricated sections, sometimes pre-finished, or by using steel sections which are first set in place and levelled, then have prefabricated supports for the glazing fixed in place, which may also be pre-painted. Clamped glazing is used typically for glazed walls which do not need to interface with internal walls, as an edge frame to the glazing is typically needed in such situations.

Where a glazed roof forms part of the same design, the roof elements are sometimes installed before the glazed wall in order to provide a shelter to spaces below, allowing the work to proceed from the top down, away from materials and equipment being moved in and out of the building below. The sequence of installation can influence the detailed design of glazed walls and enclosures, so this should be taken into account during the stages of design development.

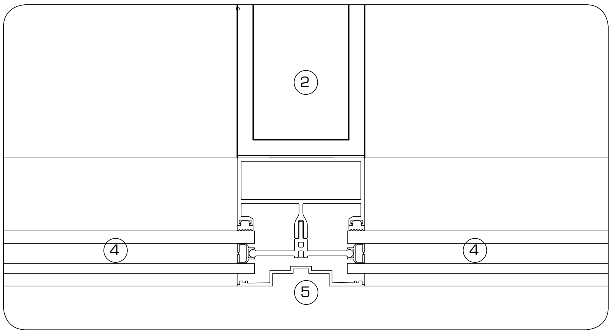
Window walls are installed either as independent sets of windows and fixed panels fixed together to form a single frame, or are fixed back to a structural backing wall. Where installed as large-scale window assemblies, the glazing can be installed as complete window panels, sometimes of considerable size. This makes the system surprisingly quick to install, though the weight associated with large panels requires the use of a substantial crane. Windows fitted to a backing wall often have the brackets fixed to the wall in advance, either at the sides for narrow windows, or on the bottom of the window assembly for wider assemblies. The windows are then sealed against adjoining construction in order to provide a weathertight envelope. The infill glass panels are then installed afterwards, allowing work to proceed inside the building, while this installation work is conducted in parallel.



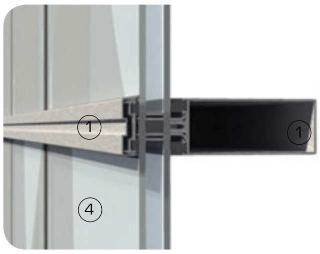
3D overview of basic stick system



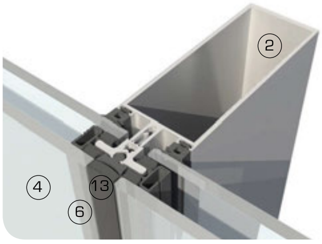
Horizontal sections 1:10. Toggle-fixed unitised glazing system frame at internal and external corners



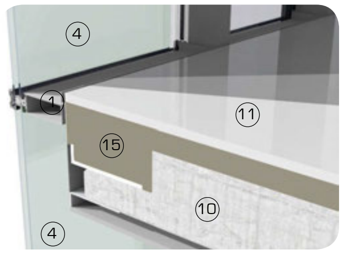
Horizontal section 1:2. Unitised glazing system



3D detail views showing basic stick glazing systems



3D detail view showing uncapped unitised glazing detail



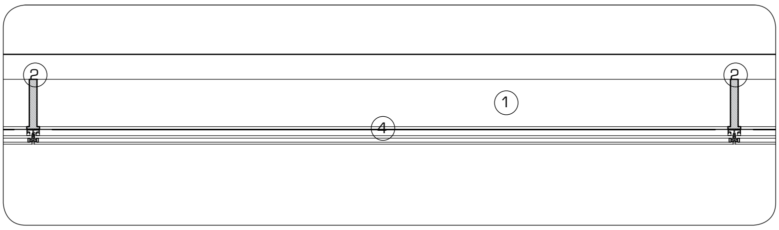
3D detail view showing unitised glazing connection to slab

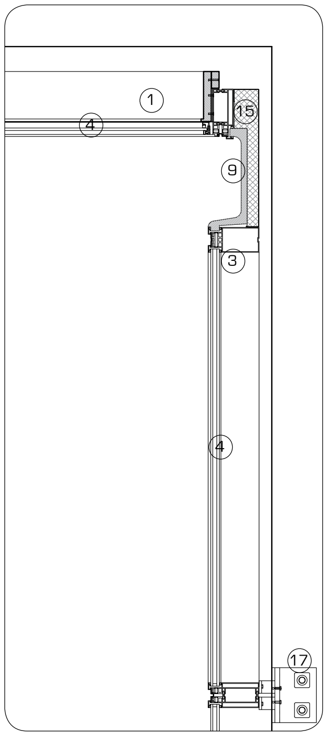
System design

This material system is essentially a site-based method of forming glazed walls, with mullions (vertical framing members) and transoms (horizontal framing members) prepared in the factory with the slots and holes required for assembly and installation on site. Stick systems are suitable for glazed walls with either a wide variety of conditions or complex geometry which makes the use of prefabricated glazed panels uneconomic. This method also has the advantage of permitting a discontinuity of mullion and transom to give an ungridded appearance, while maintaining the internally drained and ventilated principles of the system, an essential aspect of this form of glazed wall. This principle accepts that small amounts of water will penetrate the outer seal of the curtain wall, but this water is drained away in a chamber immediately behind this seal, and returned to the outside at the base of the wall. The overall continuity of framing required in stick glazing ensures that the internal chamber in the transom can drain into an adjacent mullion and that any moisture is drained, typically immediately above movement joints.

Stick glazing systems comprise extruded aluminium sections onto which glazed panels are set, held in place with extruded aluminium pressure plates which secure the panel to the carrier frame with screw type fixings. A synthetic rubber-based outer seal is set between the glass and the pressure plate. A gasket in the same material is also set between the inner face of the panel and the carrier frame to provide an inner air seal. The pressure plate is secured with visible fixings at around 300mm centres, which are usually concealed with a continuous cover capping in extruded aluminium clips onto the pressure plate. The cover cap is sometimes omitted where a more utilitarian appearance is required, but the installation of the fixing screws needs to be done with additional care, and holes need to be planned to avoid visually unexpected results. The capping profile can be made in a variety of flat, projecting or recessed profiles to suit visual requirements. Similarly, the supporting aluminium grid of mullions and transoms can be formed in a variety of structural-based sections that can vary from a rectangular box section to an I-section to a T-section with a blade-like appearance.

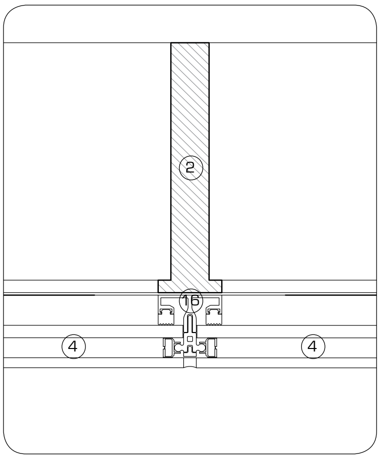
In terms of panels set into the framing, double glazed units are the most typical panel used, though insulated opaque panels are used for spandrel conditions at floor level, typically faced in metal or opaque glass. Spandrel panels are made either as single sealed panels or as panels with a separate decorative front panel. Single panels have the insulation bonded to the inner face of the glass, with a vapour barrier set on the inside face of the panel. Alternatively, the spandrel panel is formed with an air gap between the outer panel and an insulated panel behind. The insulated panel is typically faced in metal on both sides. Where opaque glass is used as the outer panel, care must be taken to avoid dust entering the air gap from becoming visible on the outer face, if the outer panel is required to be ventilated to avoid a build-up of heat in the cavity.



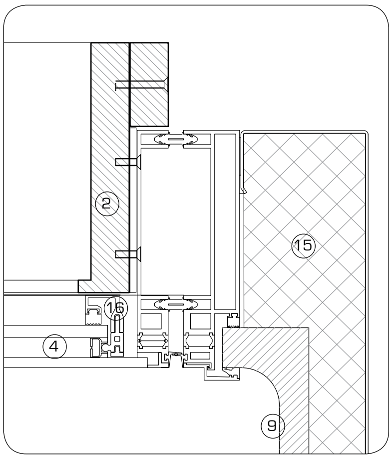


Horizontal section 1:10. Unitised glazing system and typical unitised glazing system corner condition

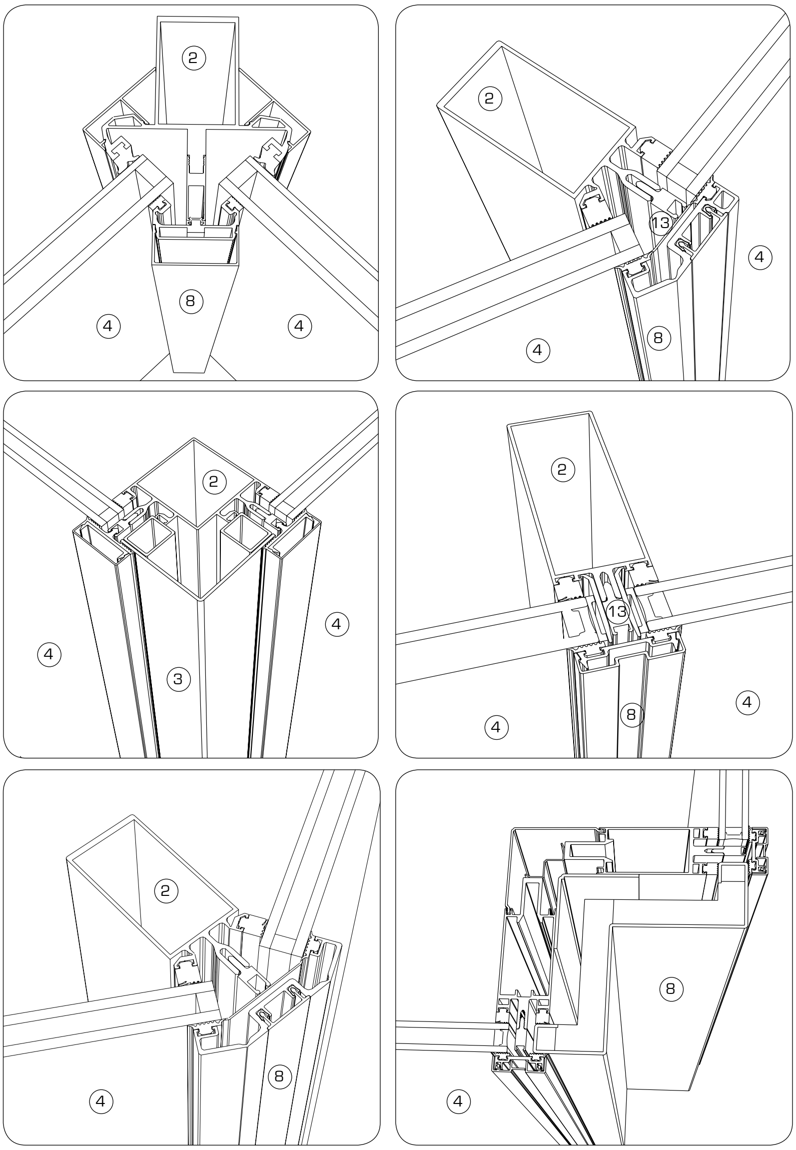
Details
1. Extruded aluminium transom
2. Extruded aluminium mullion
3. Extruded aluminium section
4. Single glazed or double glazed unit
5. Pressure plate
6. Rubber-based seal
7. Metal honeycomb panel
8. Capping piece
9. Metal-faced or opaque glass-faced insulated panel
10. Floor slab
11. Floor finish
12. Ceiling finish
13. Thermal break
14. Projecting bracket to support external screen
15. Thermal insulation
16. Toggle-fixing
17. Fixing bracket



Horizontal section 1:2. Unitised glazing system frame



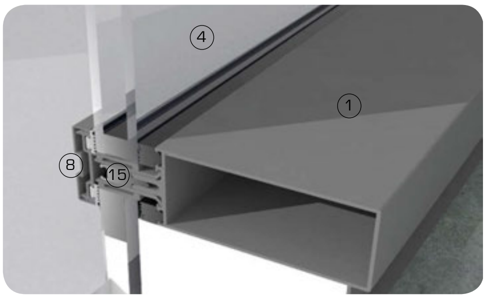
Horizontal section 1:2. Unitised glazing system at junction with insulated panel



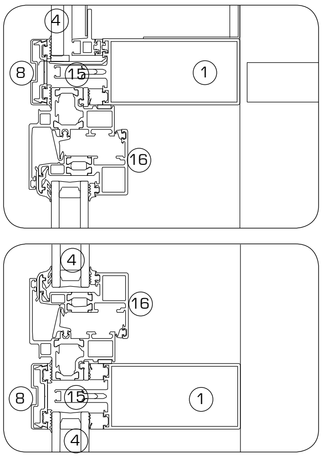
3D views showing corner and angled glazing panel connections

3D views showing flexibility of stick glazing to allow discontinuity of capping pieces

3D view of stick glazed wall with outer glazed screen

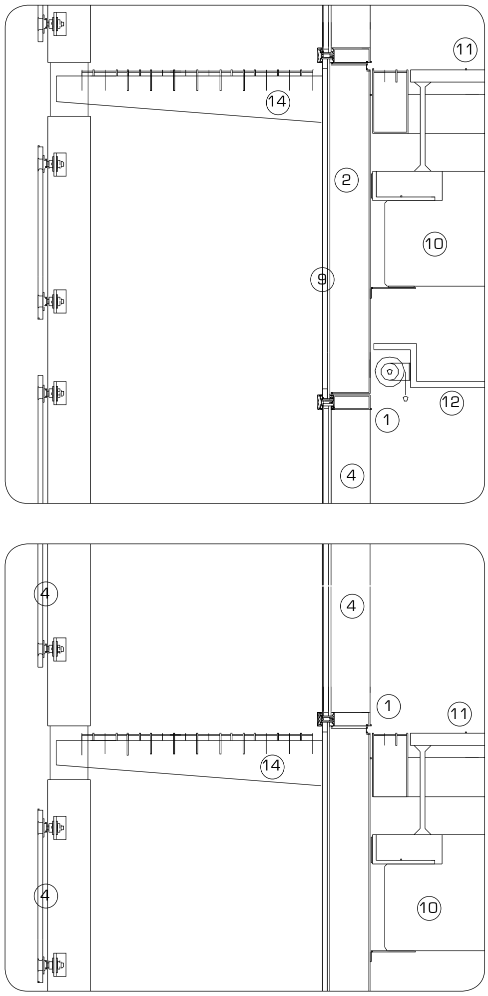


3D view of stick glazed wall with outer glazed screen



Vertical section 1:5. Opening window within stick glazed wall

Details
1. Extruded aluminium transom
2. Extruded aluminium mullion
3. Extruded aluminium section
4. Single glazed or double glazed unit
5. Pressure plate
6. Rubber-based seal
7. Metal honeycomb panel
8. Capping piece
9. Metal-faced or opaque glass-faced insulated panel
10. Floor slab
11. Floor finish
12. Ceiling finish
13. Thermal break
14. Projecting bracket to support external screen
15. Toggle fixing
16. Glazing frame



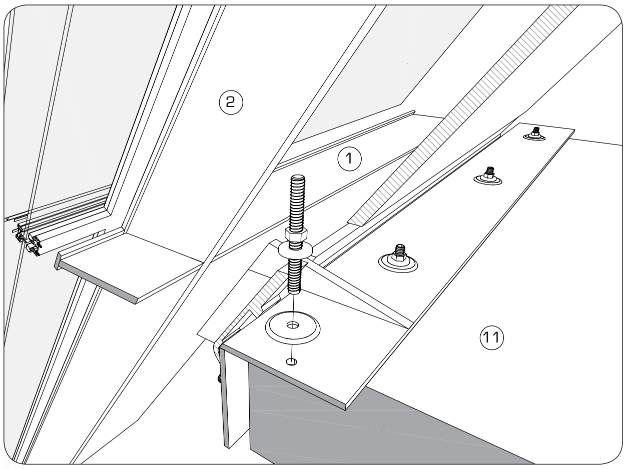
Vertical section 1:5. Stick glazing system with additional outer glazed screen to provide solar shading or as part of a twin face wall

Stick curtain walling is constructed by spanning mullions vertically from floor to floor from brackets fixed at each floor level, by either hanging each mullion and restraining it at the floor level below, or by supporting the mullion at floor level and restraining it at the floor slab above. The hanging mullion option usually allows a smaller mullion to be used, but this depends on the specific application. Mullion sections are joined from floor to floor with a sliding connection that allows the glazing between each floor level to move independently, while maintaining the overall continuity of the system. The movement joint is visible in the facade and is accommodated either at the junction of the mullion and the transom above, or within the length of the transom, usually within the spandrel panel. Brackets supporting the framing are fixed either onto the floor at the edge of the slab, or on the vertical edge of the slab.

System details
Interfaces with openings, edges and different adjacent materials are formed either by the use of metal flashings or by special components that form part of proprietary systems, such as synthetic rubber strips that are glazed into the system on one side of the strip, and are bonded directly to the face of adjacent concrete or masonry surfaces on their projecting face. This provides a continuity of waterproofing across the interface of two systems, with thermal insulation and vapour barrier set behind to form a continuity of the complete construction.

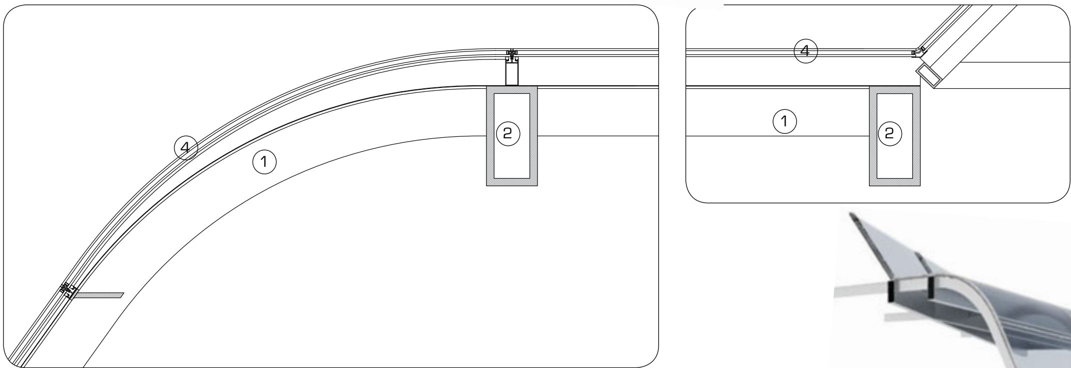
Windows are fitted into stick glazing by applying an additional sub frame within the main framing against which the opening light is closed. The overall width of the window frame is usually of similar width to that of the main framing of mullions and transoms. Both outward or inward opening windows and doors are used, with some with their frames silicone bonded to the glass to reduce their visual impact externally, though the frames look similar from within the building. Electrically operated windows, such as those at high level, usually have a motor in a box that fits within the height of the window frame. With the wiring concealed within the framing, the visual impact of motors and window opening arms has been reduced significantly in recent years. Junctions at floors are closed by bringing floor finishes up to the transom, which is also set at floor level to close off the gap between floors. The spandrel panel has a smoke seal between separated floors, but a full fire barrier is required in some countries where the spandrel panel is required to be fire resisting and to provide a barrier that stops flames from passing from floor to floor. Corners are formed, typically, either with a special extrusion that allows a glass-to-glass junction at the corner, or has two mullions meeting at a corner and an insulated metal flashing turning the corner. Parapet copings are formed by glazing the bottom edge of the metal flashing into the top transom and folding the flashing over the top of the parapet. Junctions between mullions and adjacent areas of wall in a different material are made in the same way.

3D view of inclined and curved stick glazing system

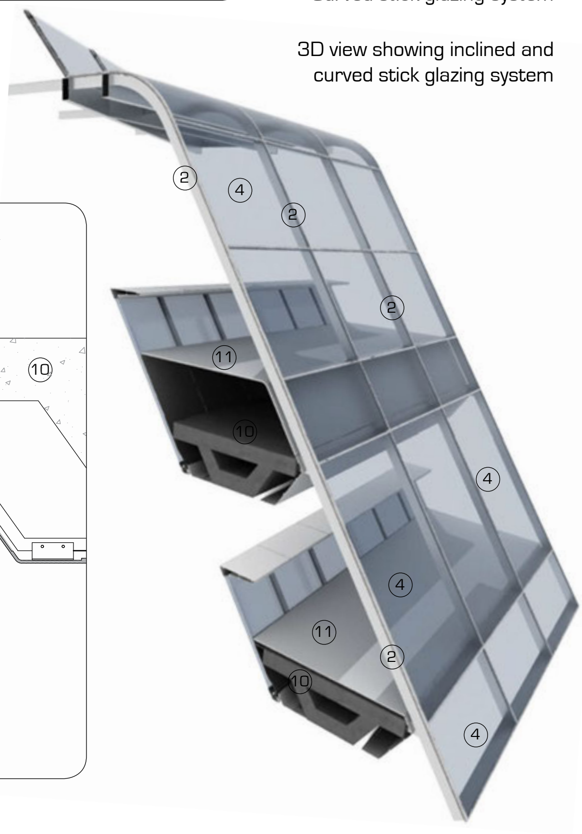


3D exploded view of typical restrained connection to steel

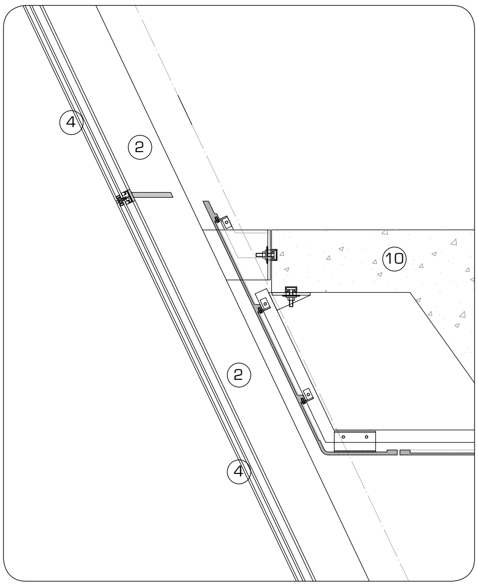
3D detail view showing inclined stick glazing system connection to floor slab



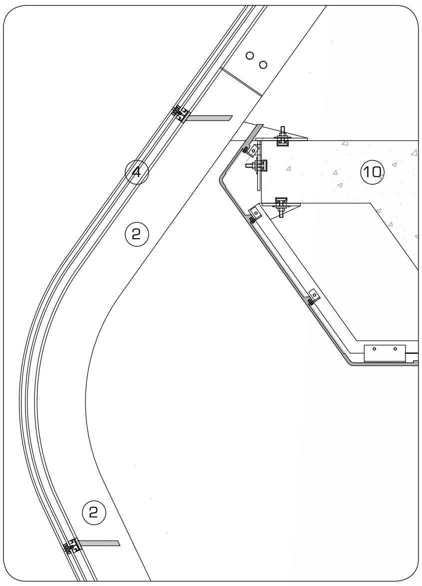
(Left) Horizontal section 1:10. Curved stick glazing system



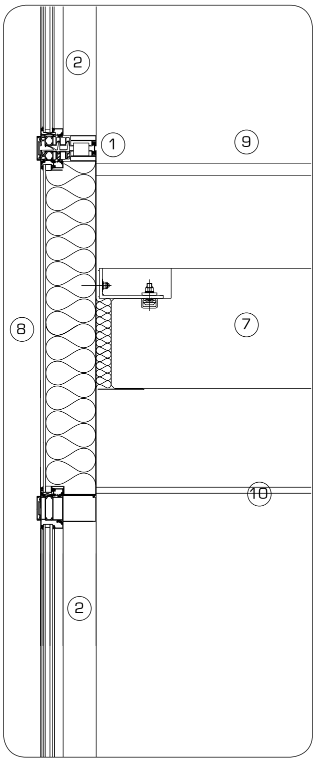
3D view showing inclined and curved stick glazing system

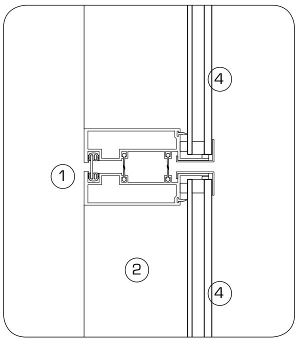


Vertical section 1:10. Inclined stick glazing system at floor junction

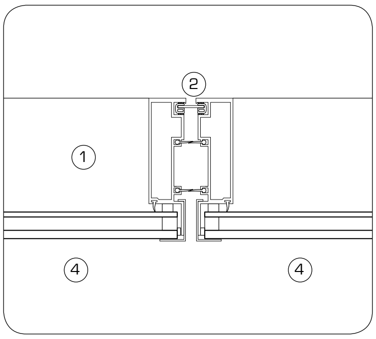


Vertical section 1:10. Curved stick glazing system

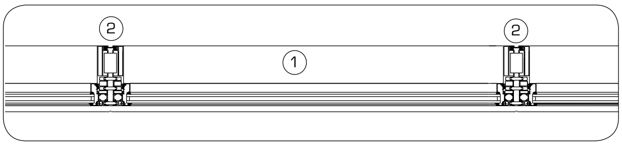




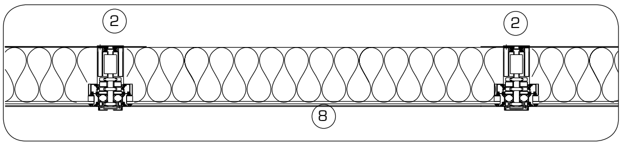
Vertical section 1:5. Unitised transom



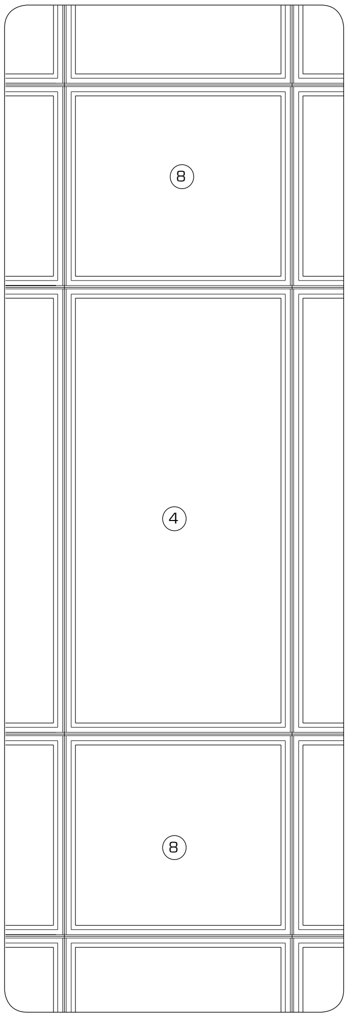
Horizontal section 1:5. Unitised mullion



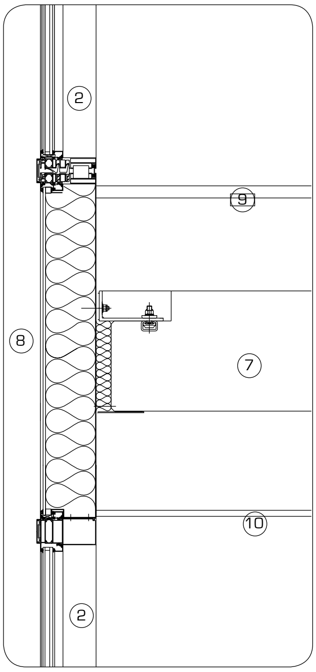
Vertical section 1:25. Transparent unitised panel



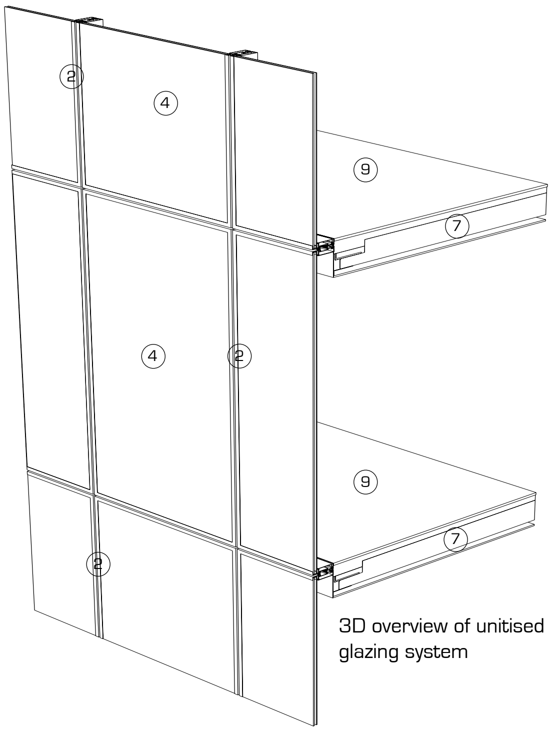
Vertical section 1:25. Opaque unitised panel



Elevation of typical unitised glazing system



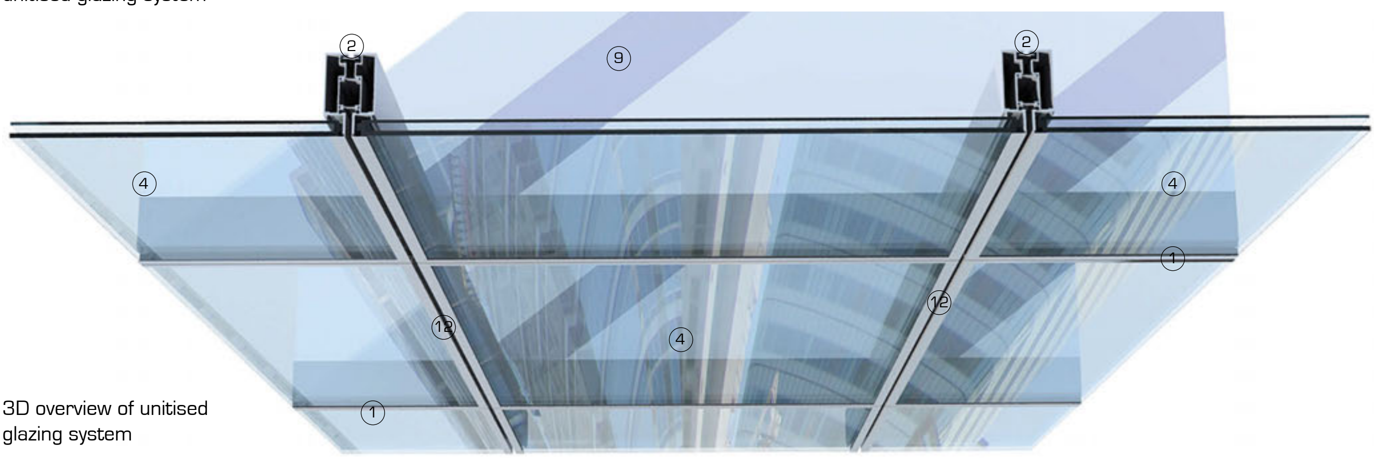
Vertical section 1:25. Typical unitised glazing system



3D overview of unitised glazing system

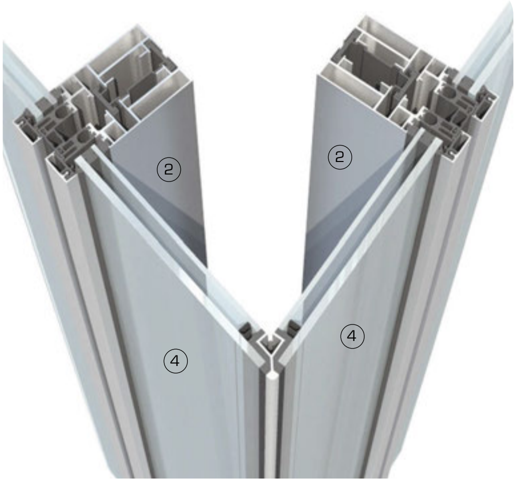
Details

1. Extruded aluminium transom
2. Extruded aluminium mullion
3. Extruded aluminium section
4. Single glazed or double glazed unit
5. Rubber-based weather seal
6. Rubber-based air seal
7. Floor slab
8. Metal-faced or opaque glass-faced insulated panel
9. Floor finish
10. Ceiling finish
11. Silicone seal with optional aluminium corner extrusion
12. Capping piece

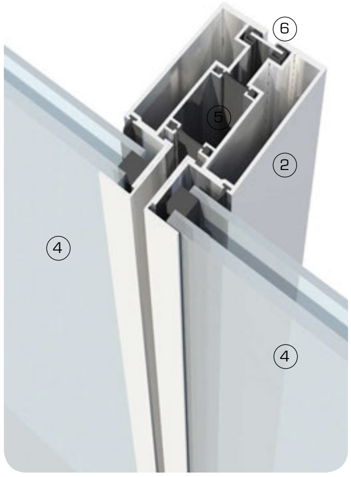


3D overview of unitised glazing system

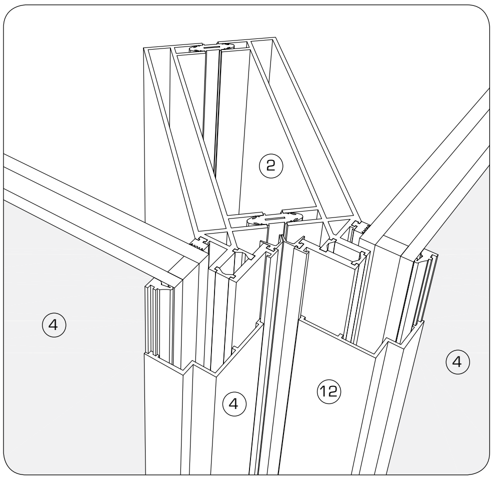
3D detail view showing framed corner connection



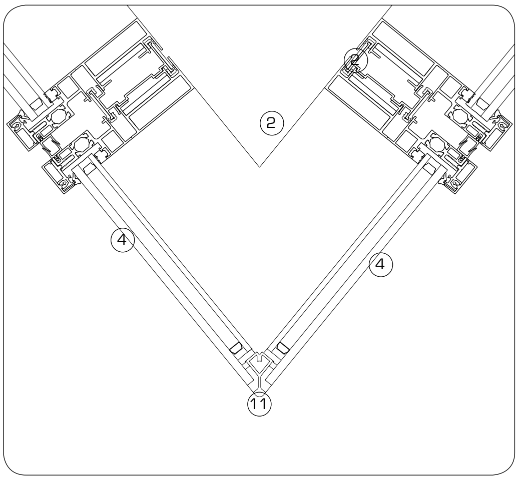
3D detail view showing unframed corner connection



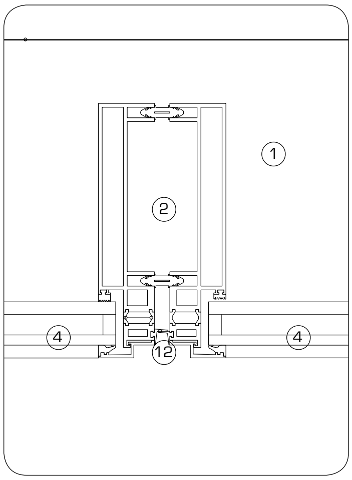
3D detail view showing frame assembly



3D detail view showing framed corner connection



Horizontal section 1:5. Unframed corner connection



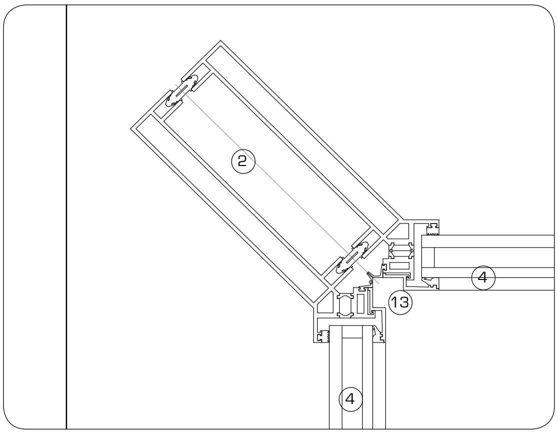
Horizontal section 1:5. Unitised mullion

System design

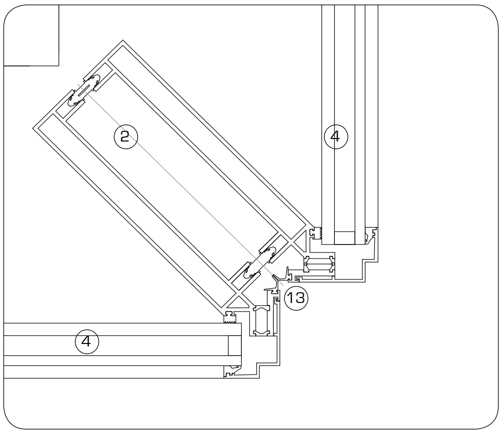
Unitised glazing is essentially a method of using prefabricated panels which are fixed together on site to form a complete glazed wall. Like stick glazing, unitised glazing uses aluminium framing to support the glazing, but where stick glazing is secured to a continuous supporting frame, all of which is fixed on site, unitised glazing is put together in the factory. Panels are delivered to site and lifted into place and set next to one another, the gaps between each panel being sealed with synthetic rubber gaskets. These gaskets interlock from panel to panel vertically, but typically are separated at each floor level with a continuous horizontal gasket that follows the horizontal joint between panels. Some systems have panels which are completely separate structurally from the adjacent panels, allowing a damaged panel to be removed if damages occur, either during construction or later, but the junction between vertical and horizontal joints requires special attention. Other systems are semi-interlocking on horizontal joints in order to combine the structural capacity of members as well as assist in internal drainage. The term semi-interlocking is also used for stick systems where large-scale frames, covering several bays both vertically and horizontally, are pre-assembled in the factory and then lifted in place on site. The glass units and pressure plates are then fixed on site as per regular stick glazing methods.

The double glazed units in unitised glazing are fixed to the supporting frame either from the outside of the panel or the inside, to suit the strategy for glass replacement in the event of accidental damage. The double glazed units are secured with pressure plates which are either mechanically fixed to the main frame, or form part of the frame itself. An alternative method of fixing glass is to bond the glass units to a sub frame which is then mechanically fixed to the aluminium frame. This method provides an all-glass appearance on the outside, usually with a recessed joint between panels giving a shadow gap appearance between panels.

Vertical joints between panels have an outer seal which is usually formed by two gaskets which are pressed together, either in the form of 'flipper' gaskets or as compressible hollow seals. These are made from synthetic rubber, typically EPDM. Behind this outer seal is a drained and pressure equalised chamber closed off by an inner seal, also formed typically in EPDM. At the internal face of the panel is an air seal. In hot and humid climates, typically in South East Asia, it is assumed that moisture will find its way to the back of the supporting aluminium frame. Consequently, seals are in horizontal joints to drain moisture from the back of the system to the front face of the panel, where it is released to the outside. In more temperate climates, unitised panels are sealed in the mid-depth of the framing, with the inner joint, visible from within the building, serving as an air seal only. Any rainwater that penetrates the outer seal is drained down through the inner chamber and is expelled at the base of each unitised panel, typically at floor level. Horizontal joints between the transoms formed by the top of one panel and the bottom of the panel above are formed in the same way, with seals aligned with those

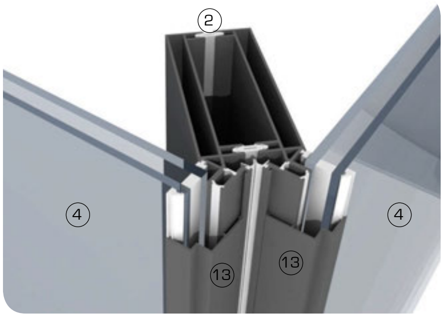


Horizontal section 1:2. Unitised glazing internal corner connection

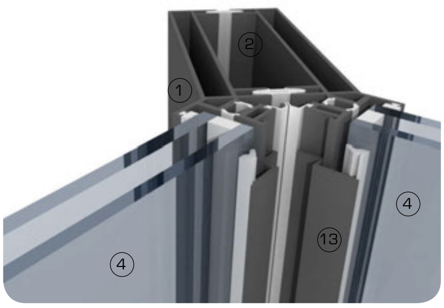


Horizontal section 1:2. Unitised glazing external corner connection

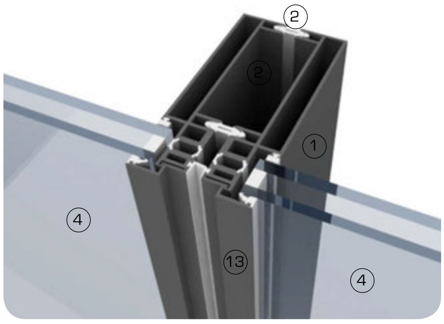
Details
1. Extruded aluminium transom
2. Extruded aluminium mullion
3. Extruded aluminium section
4. Single glazed or double glazed unit
5. Rubber-based weather seal
6. Rubber-based air seal
7. Floor slab
8. Metal-faced or opaque glass-faced insulated panel
9. Floor finish
10. Ceiling finish
11. Silicone seal with optional aluminium corner extrusion
12. Thermal insulation
13. Capping piece
14. Concrete structure



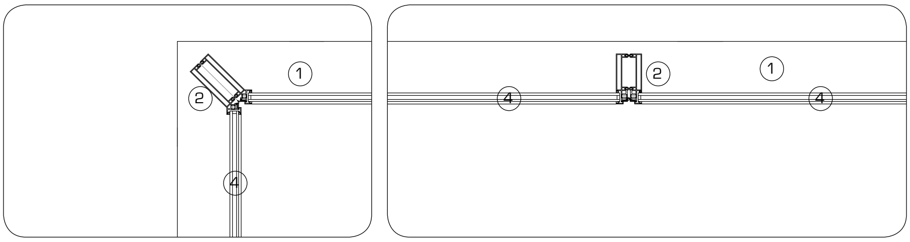
3D detail view showing unitised glazing frame

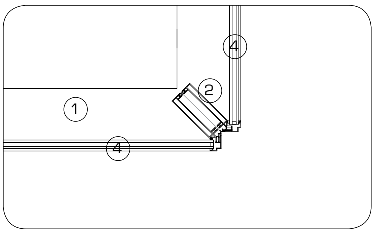


3D detail view showing unitised glazing frame



3D detail view showing unitised glazing frame

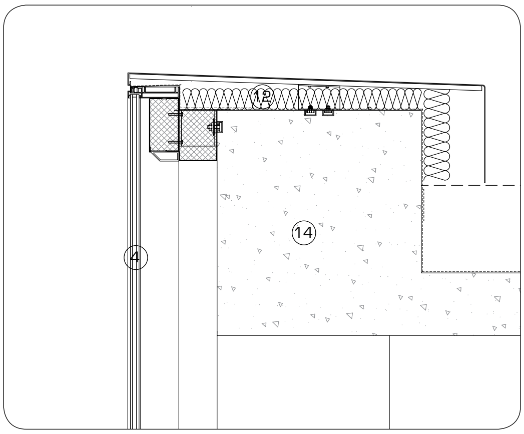


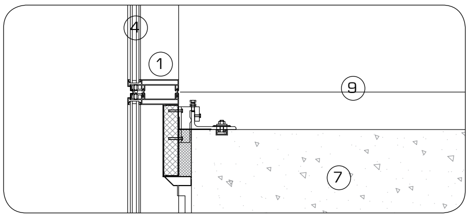


Horizontal section 1:10. Unitised glazing system at internal and external facade folds

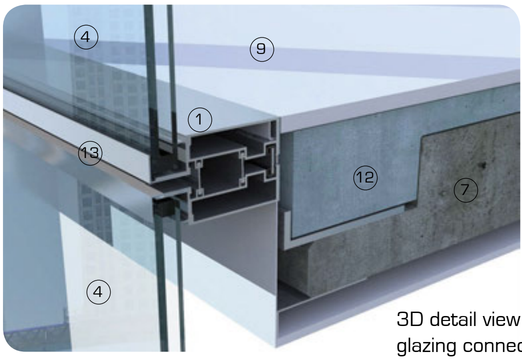
3D view showing folded unitised glazing system

(Right) 3D view showing folded unitised glazing system





Vertical section 1:10. Unitised glazing at parapet level and floor-slab level and (below) 3D view of typical floor-level connection



3D detail view showing unitised glazing connection to floor slab

3D overview showing unitised glazing connection to floor slab

in the vertical joints to ensure that rainwater is drained to the outside. Unitised panels typically include at least one additional transom to provide a spandrel zone at floor level, for example, though some systems incorporate an additional transom set against the inside face of the glass only, so that it is not visible externally, but provides a horizontal edge against which internal ceiling finishes can be set.

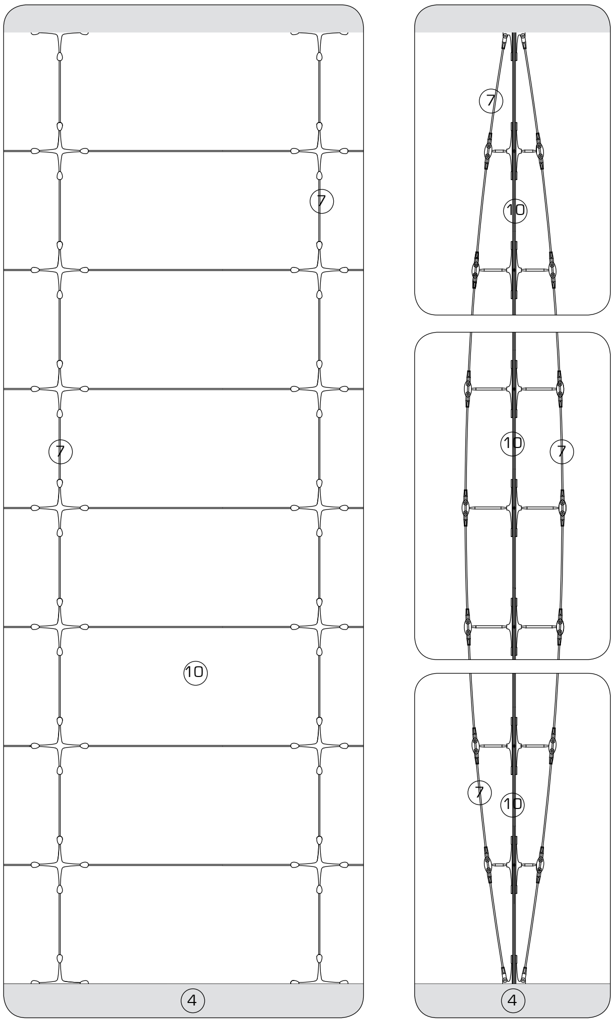
Panels are set so that they span from floor slab to floor slab, and like stick glazing, are either hung from a floor slab and restrained on the floor below, or are supported on a floor slab and are restrained on the floor above. Like stick glazing, movement between panels is provided by a sliding spigot joint set into the vertical joint between mullions. This movement is taken out horizontally in the horizontal joint, typically at floor level.

In common with stick glazing, unitised panels have thermal breaks set within the framing in order to reduce the transmission of heat or cold from the outside of the frame to the inside, or vice versa. Since the inner ventilated chamber is typically deeper than that used in stick glazing, the thermal break is positioned accordingly in order that the thermal break and double glazed unit are aligned. The overall width, or sight line, of the unitised panels is greater than those used for stick glazing, from around 80mm to 120mm depending on the application. The greater width often suits the needs of internal partitions which are required to intersect with the framing members of the facade.

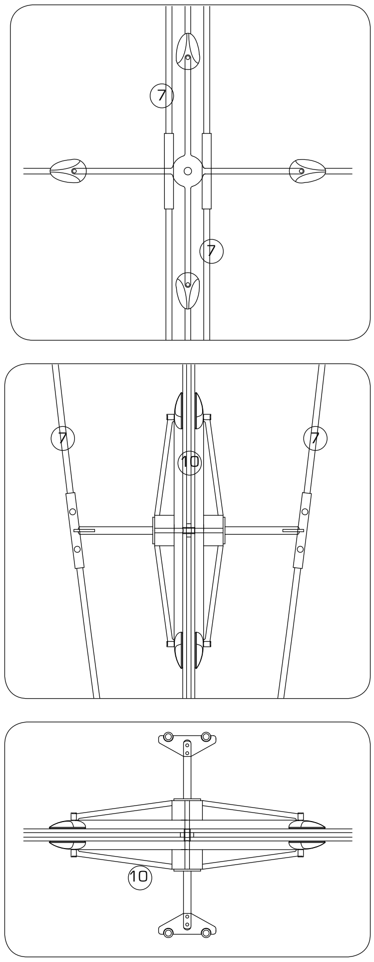
System details

An essential aspect of unitised glazing is that the panels use the same perimeter framing, which can however be of different shape and have different materials set within them. Corner panels are the most common of the atypical panels, and are often the most complex to construct in the factory. In common with stick glazing, unitised panels can have vertical glass-to-glass joints rather than setting a mullion at the corner, providing a visual crispness of the frameless corner. The unitised frame is stiffened internally to compensate for the loss of structural stability of the corner. Regular framed corners are made usually with a 45° angled mullion to reduce the visual impact and sight lines of the mullion.

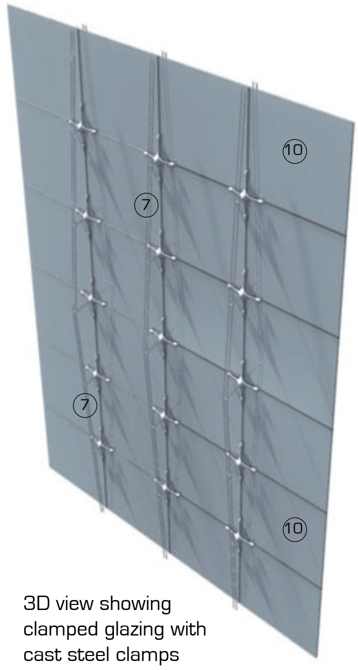
Parapet copings are formed by sealing and waterproofing the gap between the top of the panel and the parapet wall behind with a synthetic rubber seal that is integral with the panel. Thermal insulation is used to provide a complete continuity of insulation from wall to roof. A metal coping is set on top of the panel to provide protection to the membrane beneath. Elsewhere, most interfaces follow the principles of stick glazing, with an integral EPDM strip that can be fixed to project out beyond the edges of the panels, allowing the strip to be bonded to adjacent construction.



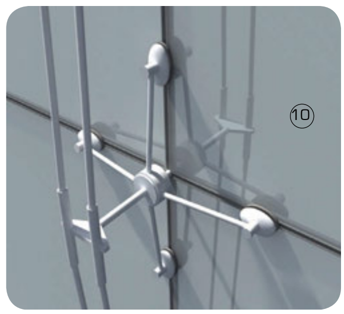
Elevation and vertical section 1:40. Clamped glazing with cast steel clamps held in place by forming part of a continuous truss



Elevation, vertical and horizontal sections 1:5. Spider clamp hung from cable truss supporting glass panels



3D view showing clamped glazing with cast steel clamps



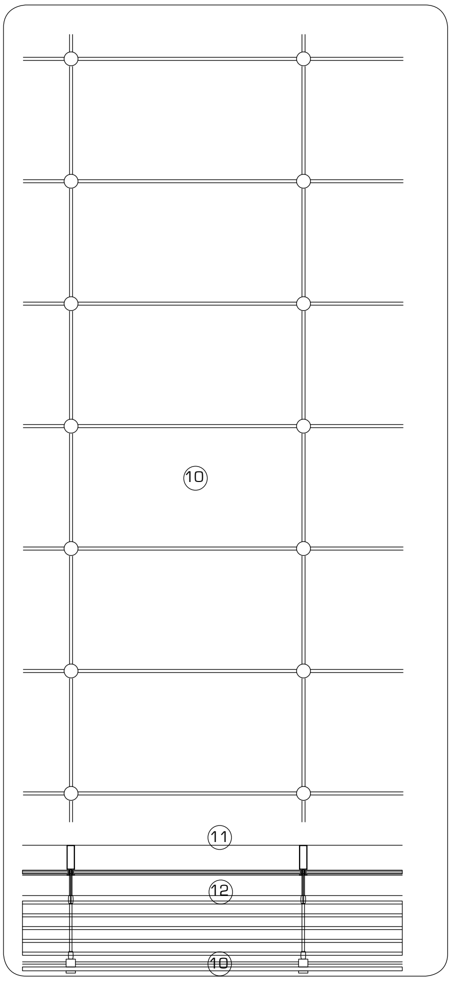
3D detail view showing clamped glazing fixing method

System design

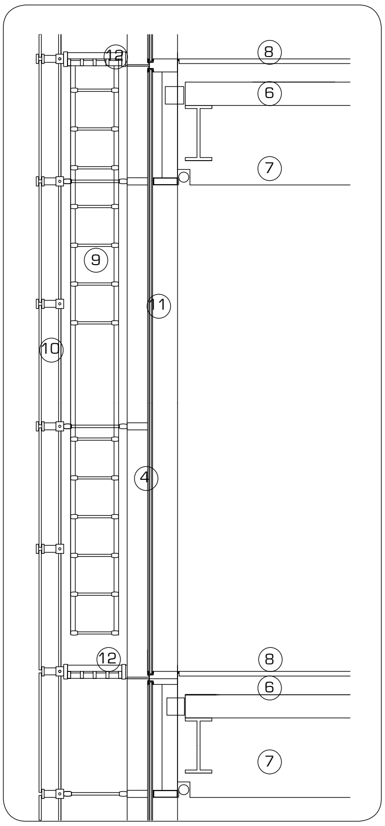
There are two types of 'point fixed' glazing used for facades: clamped glazing and bolt fixed glazing. Both systems are used to increase the transparency of a facade, and this is particularly successful in open jointed single glazing as used in double skin facades. Where double glazed units are used with their black edge band and joints between units, the width is usually equal to that of framed glazing, but the omission of framing provides a visual continuity of glass where transparency is required. The all-glass appearance has visual benefits to oblique views across a facade, where the double glazed units are seen as a continuous uninterrupted surface, made all the more dramatic by changes in direction provided by corners, as well as increasingly by folds in the glass surface. Where a sealed facade is required, joints are sealed with silicone through the full thickness of the joint, typically with a polymer-based backing rod in the mid depth of the joint. Clamped glazing was the first point fixed glazing system used commercially and developed in the 1960s, using metal plates called 'patch plates' set on either side of glass sheets at their corners. This technique is still used, though with increasing geometric complexity.

The clamped glazing system positions the fixings holding the plates in place such that they pass through the joints between the glass to avoid the additional complexity and cost of drilling the glass. Because fixings are positioned at the glass edges, rather than within the glass itself, the span between fixings is higher than for an equivalent bolt fixed solution and glass thicknesses may be higher for a clamped glazing solution as a result. When used in a single glazed configuration in double skin facades, the glass is joined with clamps, plates and brackets, the preferred material is stainless steel due to its resistance to corrosion. The use of plates allows a more complex geometry of glass to be used, such as in a shingled arrangement of lapped glass panels, where air can pass up through gaps between lapped glass sheets, while admitting only small amounts of rainwater into the buffer zone behind. Glass can be supported either at the corners, or along its edges to suit the supporting structure for the glass, which is usually visually lightweight in order to maximise transparency. Clamps are formed by setting a synthetic rubber gasket, typically EPDM, between the stainless steel plate and the glass sheet. A bolt is passed through one side of the plate and is secured into the other plate, usually with a countersunk type.

Clamped glazing often uses glass fins to provide structural stability, set at 90º to the plane of the glass, typically supported at its base on the floor slab. Glass fins are usually in lengths equal to the height of each panel, with a patch plate connection occurring at each horizontal joint of the glass, to form a single structural section, with the dead load of each panel transferred to the glass panel below, in the case of single glazing, or alternatively to the glass fin behind. Installations have reached up to around 15 metres in height, though these are flat glass walls or those forming vertical walls which are curved in plan. Glass panels and fins are joined with cleats and

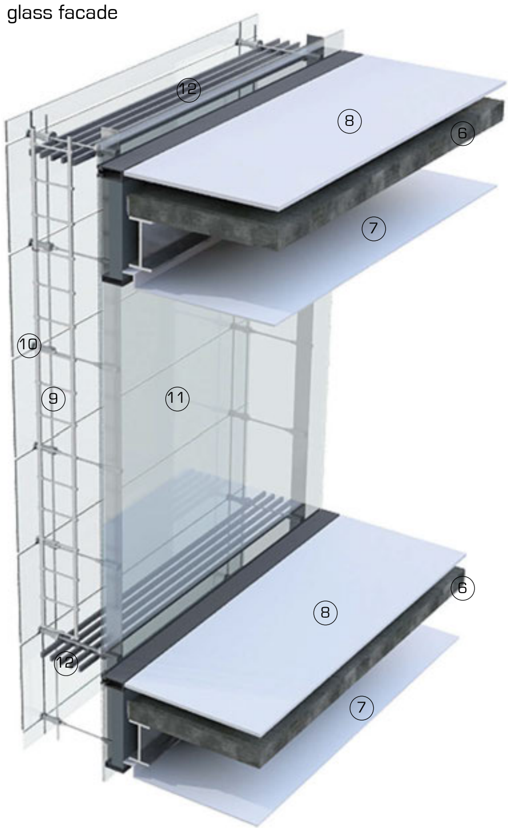


Horizontal section 1:100. Cable hung clamped glass facade



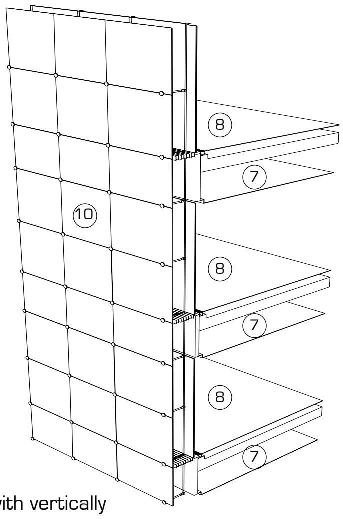
Vertical section 1:100. Cable hung clamped glass facade

3D views showing cable hung clamped glass facade

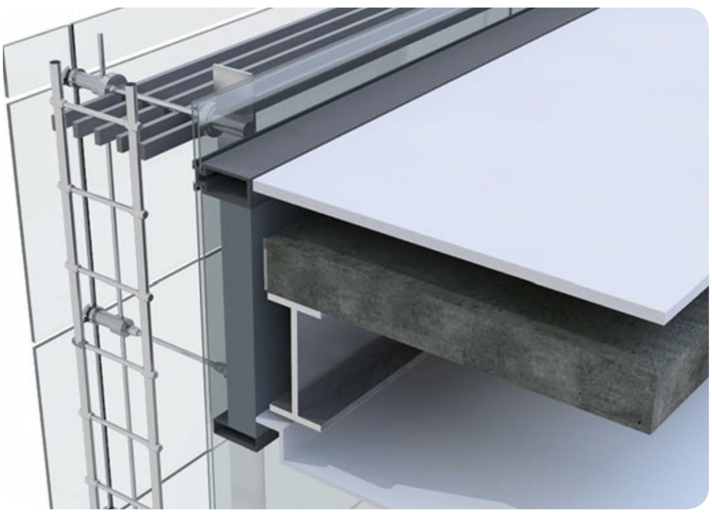


Details

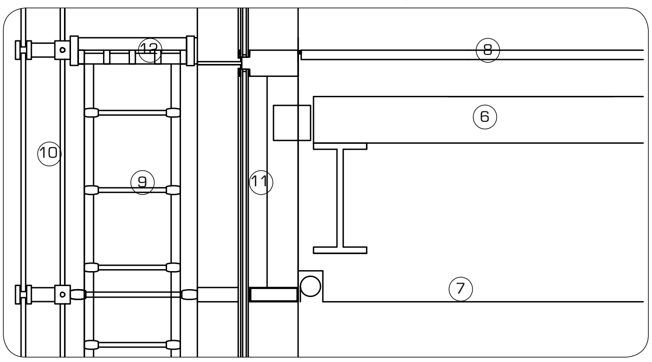
1. Stainless steel patch plate
2. Single glazed or double glazed unit to suit application
3. Silicone seal
4. Glass fin
5. Support bracket
6. Floor slab
7. Ceiling finish
8. Floor finish
9. Access ladder
10. Clamped glazed wall
11. Inner curtain walling
12. Maintenance access deck



3D view showing cable hung clamped glass facade with vertically framed supporting system

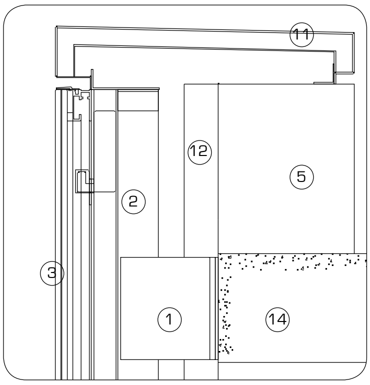


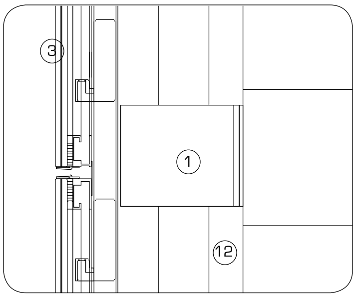
3D detail view showing cable hung clamped glass facade

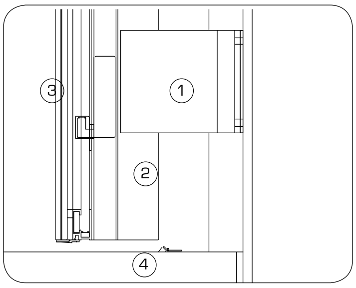


Vertical section 1:50. Cable hung clamped glass facade

Glass systems 3: clamped glazing



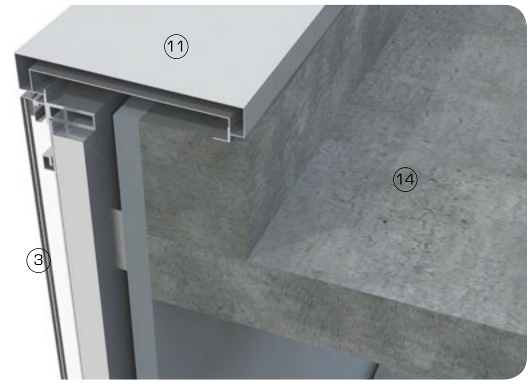




Vertical section 1:10. Opaque clamped glazed panels. Junctions at ground level, movement joint and panel-to-panel conditions

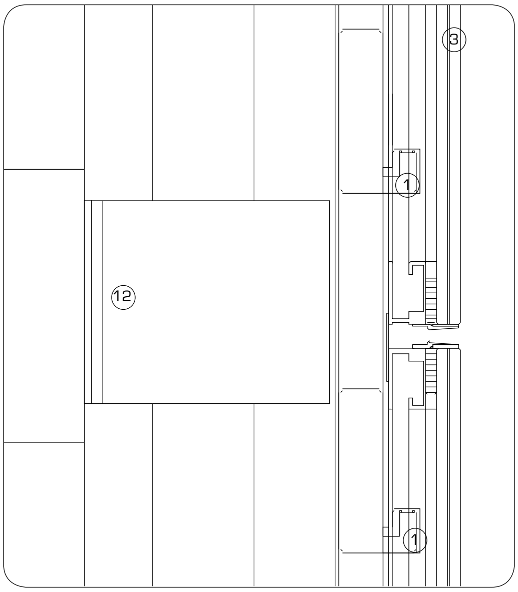
Details

1. Fixing bracket
2. Extruded aluminium mullions
3. Opaque glazing
4. Ground slab
5. Backing wall
6. Inclined and lapped glass
7. Cable support
8. Corner clamp
9. Cast metal fixing bracket
10. Clamp bracket
11. Metal parapet coping
12. Thermal insulation
13. Single or double glazed unit
14. Concrete slab

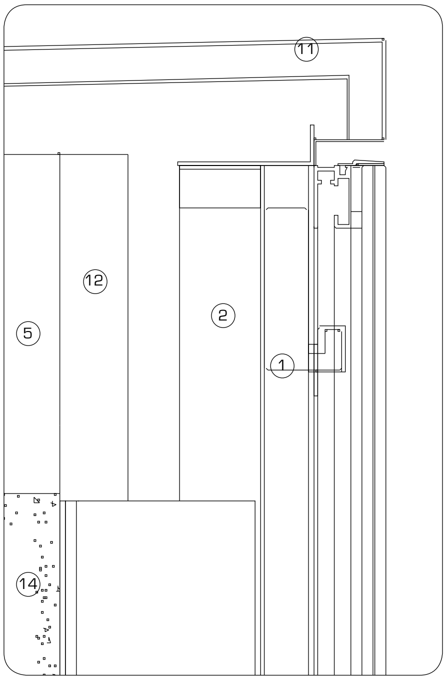


3D views showing opaque clamped glazing panel system at panel-to-panel and movement joint conditions

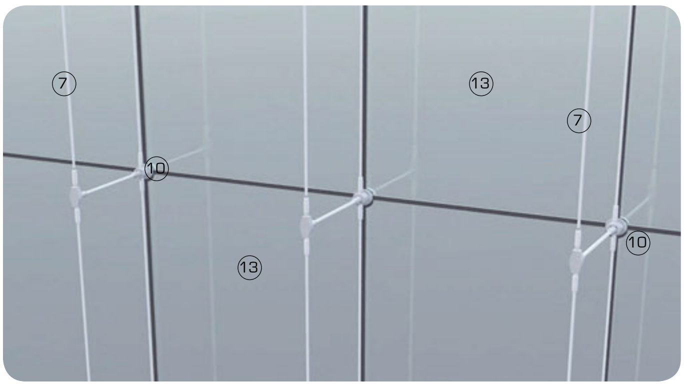
3D overview showing opaque clamped glazing panel system

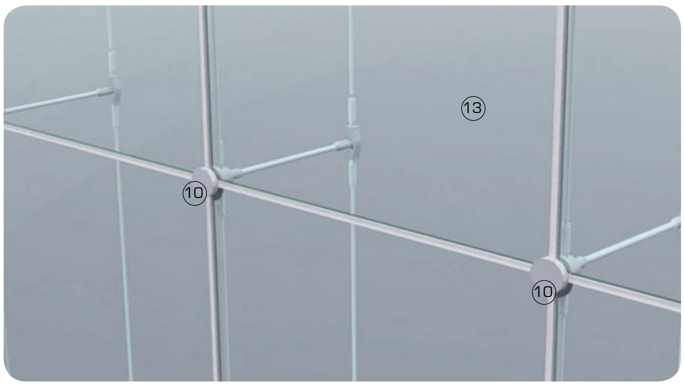


Vertical sections 1:5. Opaque clamped glazed panels. at panel-to-panel junction

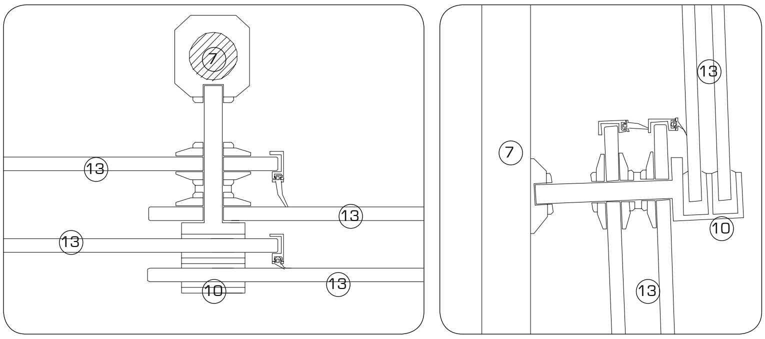


Vertical sections 1:5. Opaque clamped glazed panels. at parapet condition

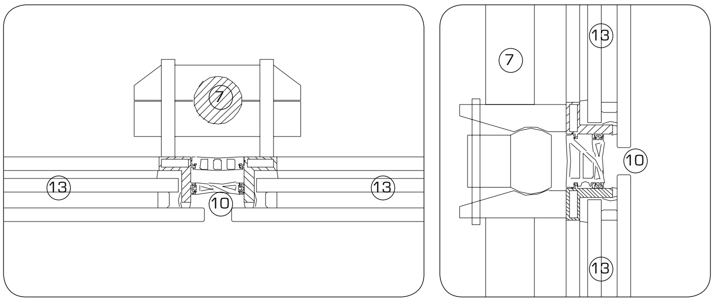




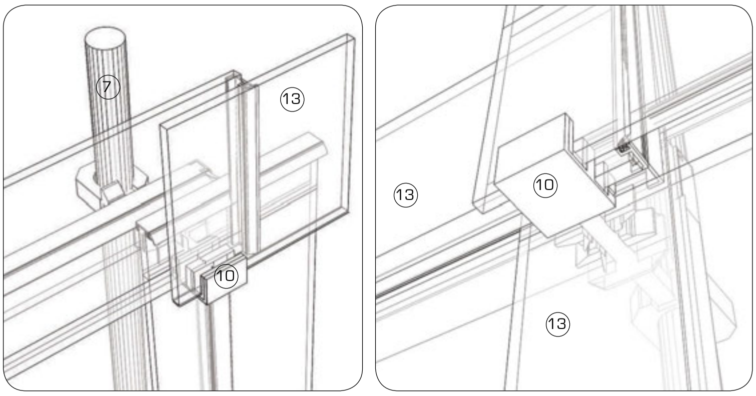
3D detail views showing clamped glazing system fixing method supported on cables



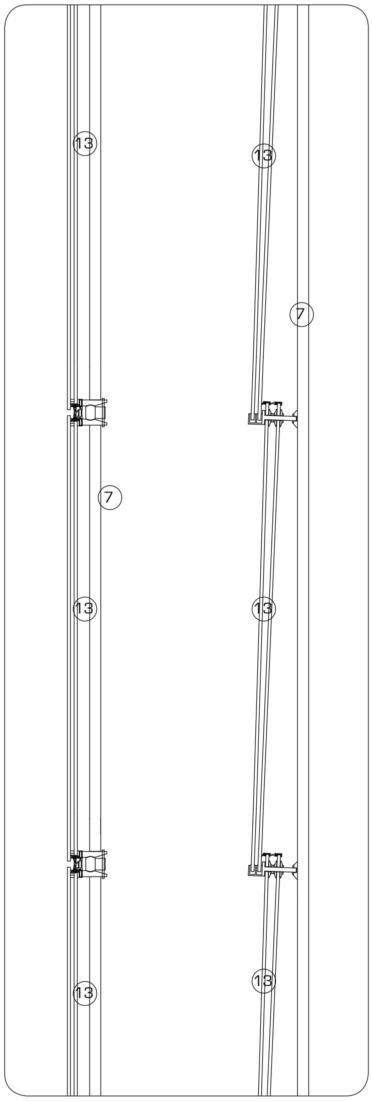
Horizontal and vertical sections 1:2.
Clamping configuration in lapped clamped cable hung system



Horizontal and vertical sections 1:2.
Clamping configuration in adjacent clamped cable hung systems



3D detail views showing lapped clamped glazing system fixing method



Vertical sections 1:10.
Clamping configurations in cable hung systems (lapped and adjacent)

plates at the corner junctions, and are usually fixed through holes in the glass rather than through the joints in order to transfer loads effectively through the plates. Clamping plates usually have a polished finish for ease of cleaning, but brushed finishes are also used.

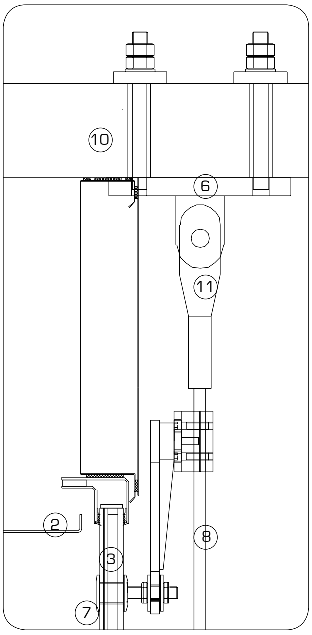
This method of glazing has evolved into an economic method of fixing glass to a continuous supporting frame behind the glass joints, as an alternative to the capped glazing techniques of stick and unitised systems, with silicone seals set between the glazed units. This makes it suitable for facades with complex frame design, particularly when combined with a glazed roof that uses the same system. Triangular framed glazed walls, where the glass is required to have a smooth, continuous surface free of cover caps, allow clamps to be fixed through the joints between the glass directly back to the supporting structure set behind. Clamp fixings can be set at the corners of glass panels, where units intersect, or be set along the length of joints. The choice of fixing position depends on both the geometry and size of the glazing.

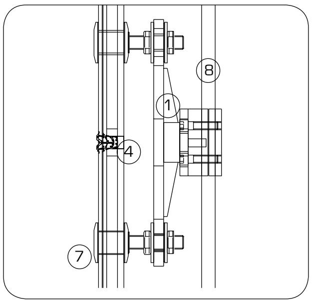
System details

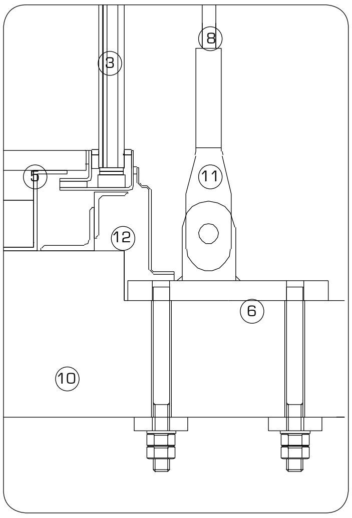
Clamped glazing with glass fins is usually set into a glazing channel at floor level in order to fix the glass in place and support its dead weight. A glazing channel also forms a reliable weather seal with the outside ground level. Supporting glass fins which are supported at floor level rather than ceiling level are usually set below floor level in order to conceal the patch plate brackets, which are usually set either with the floor finishes zone or within a pocket in the floor slab where this zone is insufficiently deep. The same solution is used where the fin is hung from the ceiling. Clamp plates are also used for doors to give a continuous appearance to the facade. Doors are set typically on floor springs, set into the floor, and are supported at the top of the door leaf with a pivot which is clamped to the glass unit above.

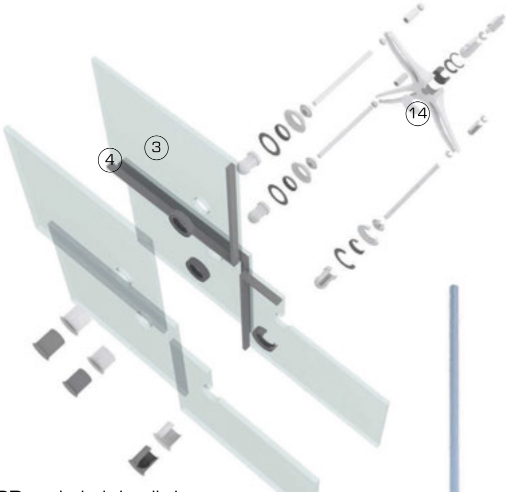
Clamped glazing is usually able to accommodate higher amounts of structural movement than an equivalent framed glazing system, which has encouraged the use of tensioned cables, usually set vertically, to which the glass is fixed. Cables are usually set immediately behind vertical joints to reduce their number and visibility, since plates offset from the vertical joint require either an additional vertically-set cable, or a metal bracket to connect the two patch plates back to a single cable. In supporting cable structures, which allow higher amounts of structural movement, doors are required to be set independently of the glazed wall, usually with a metal frame around the opening which is fixed at floor level only, and is structurally independent of the glazed wall.

Glass systems 4: bolt fixed glazing

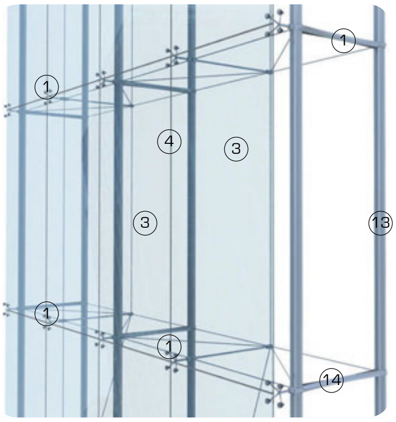


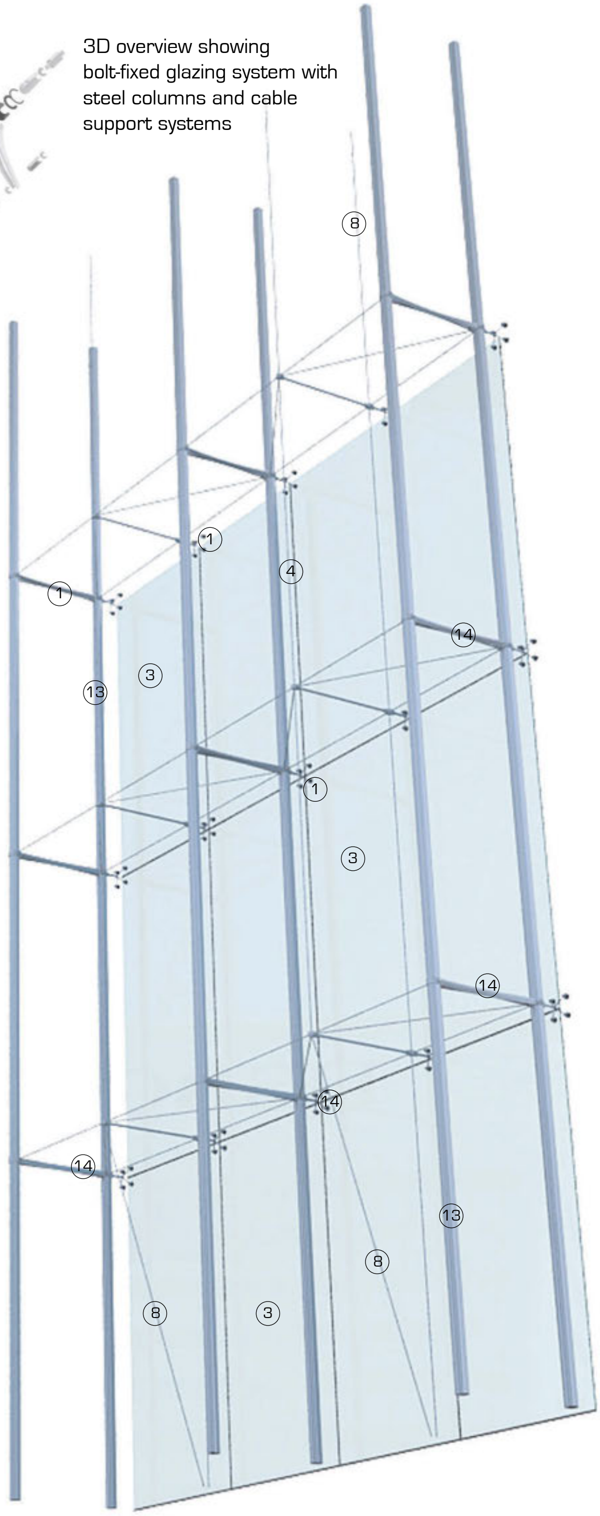






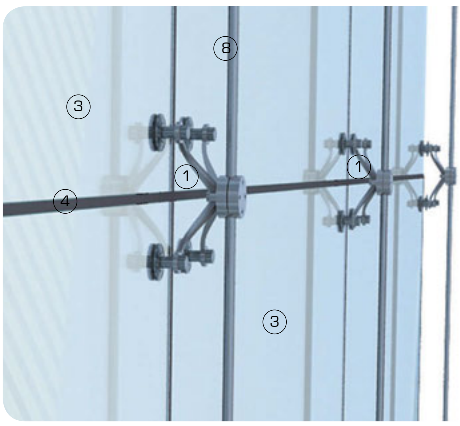
3D exploded detail view showing cast aluminium 4-point spider clamp for bolt-fixed glazing and connection to glazing panels

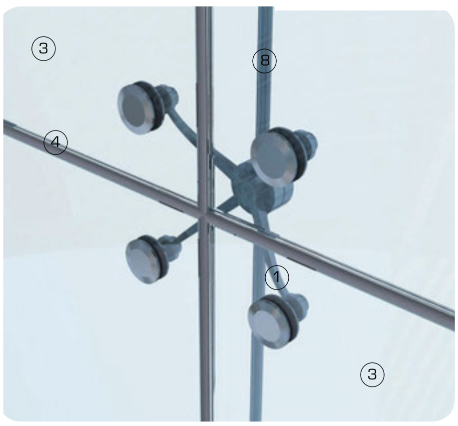


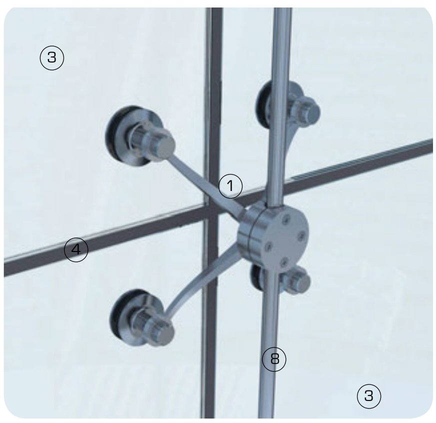


3D overview showing bolt-fixed glazing system with steel columns and cable support systems

Details
1. Cast steel connector
2. Mild steel or stainless steel angle bracket
3. Single glazed or double glazed unit to suit application
4. Silicone seal
5. Floor finish
6. Support bracket
7. Bolt fixing
8. Stainless steel cable
9. Insulated panel
10. Floor slab/structural wall
11. Bolt based cable end
12. Glazing channel at floor level
13. Structural column
14. Steel arm for lateral support

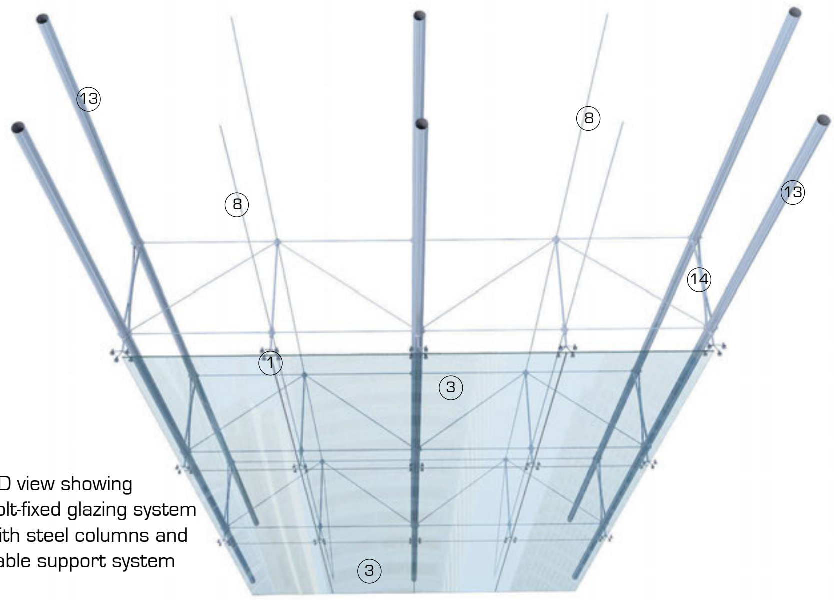




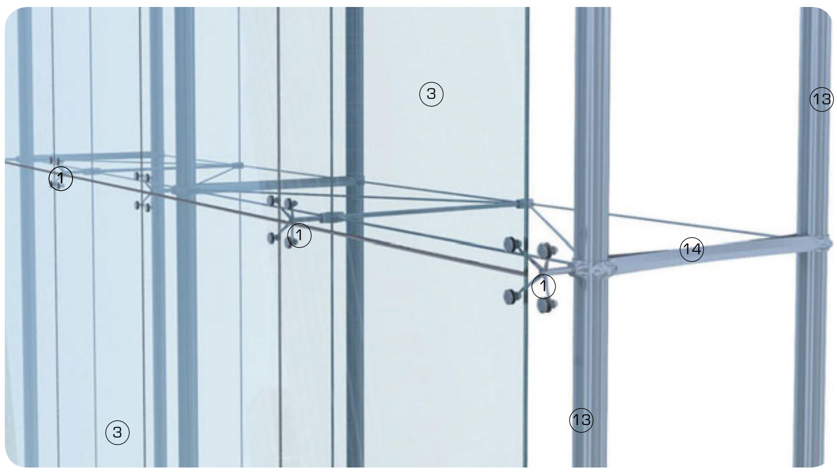


3D views showing blot-fixed glass panels supported on cables

3D overview showing bolt-fixed glazing system with steel columns and cable support systems



3D view showing bolt-fixed glazing system with steel columns and cable support system



3D detail view showing clamped glazing system with steel structural support system

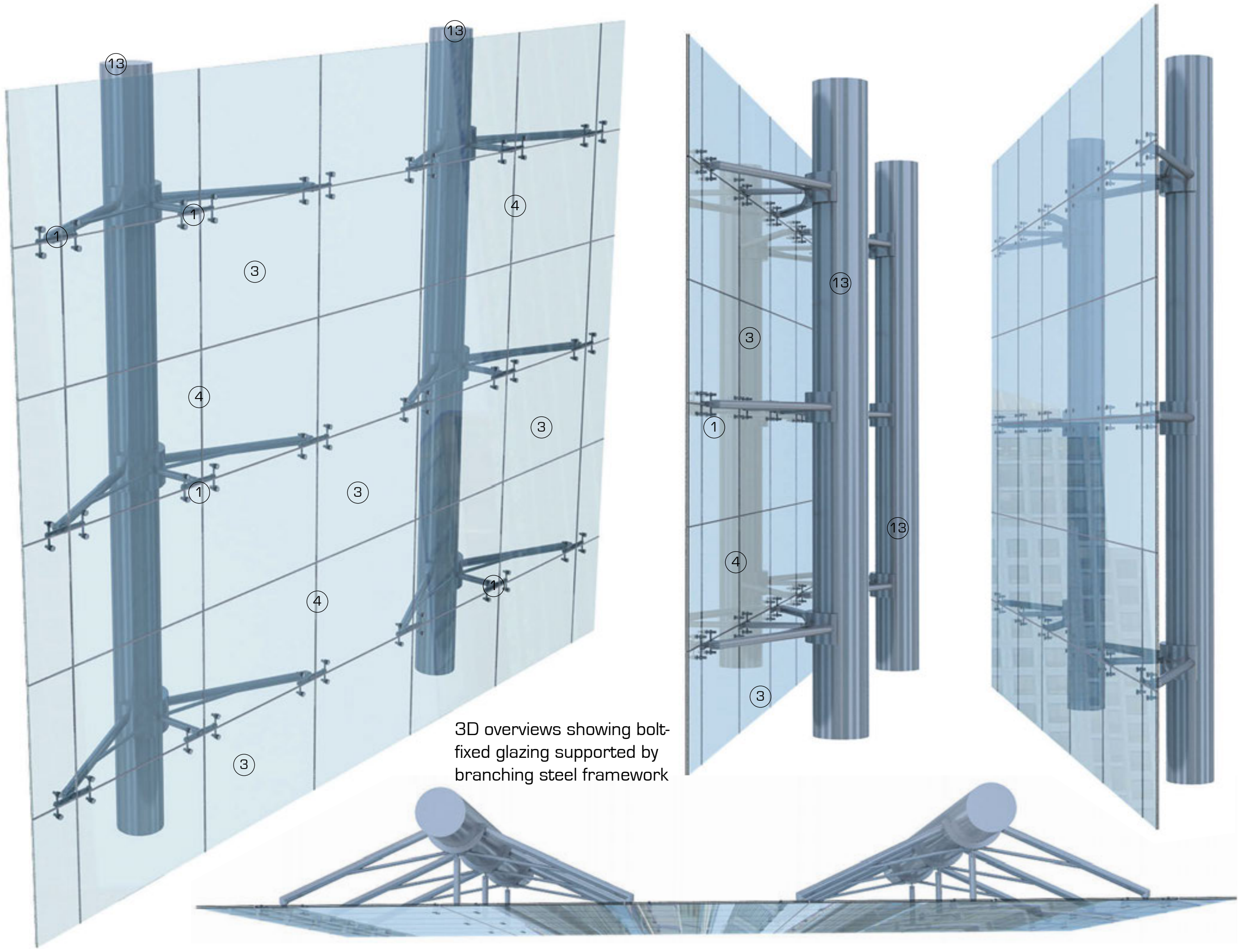
System design

Like clamped glazing, bolt fixed glazing is used for its ability to provide transparency, but usually with fixings set within the glass rather than at their edges. In common with that system, it was originally developed for single glazing, but is more commonly used with double glazed units, with their 50mm joint width which includes the edge of the unit. Despite the overall 50mm black joint width, the absence of framing and continuity of the reflective surface of glass makes this frameless system more visually lightweight than framed glazing. Setting bolt fixings within the glass can have an advantage in reducing the span of the glass between fixings, ensuring that the glass thickness is optimised to a greater extent versus supporting the glass at its edges only.

Where clamped glazing is supported directly onto a supporting structure, bolt fixed glazing can be fixed on brackets which are cantilevered away from the supporting structure, which can be either hung from the top of the wall, or is supported at its base. These cantilevered brackets can also be fixed back to tensioned cables or rods, allowing a visually lightweight supporting structure to be used, but which requires lateral stability to overcome the higher deflections associated with cable structures. Lateral stability is usually provided by forming a vertically-set cable truss from the primary cable supporting the glass units, or by adding horizontal outriggers from structural columns to restrain the horizontal movement of the cables. In common with clamped glazing, glass fins or mild steel posts can be used to support the glazing, typically supported from their base. Glass fins are fixed perpendicular to the vertical joints between glazed units, with an L-shaped bracket with a bolt fixing at each end, with glass panels stacked one above the other, using the glass fins to provide lateral support. Glass fins can also be fixed at the top of the wall or at ceiling level, where they serve as stiffeners in a downstand condition, with the glass still being supported at its base. Glass fins have clamps fixed to them as per the patch plate system described in the previous section.

System details

With both top hung and bottom supported methods of support, bolt fixed glazing uses a similar fixing bolt which is determined by the size of the glass panel, the way it connects to the supporting structure and whether the fixing is countersunk or surface fixed. The bolt fixing is the mechanical connection which is fixed through a hole formed in the glass sheet or double glazed unit. Bolts can have a disc fixed to each external face of the glass, be countersunk to be flush with the outer face of the glass, or penetrate only the inner glass of a double glazed unit. Structural movement and deflections between the supporting structure and the glass are accommodated with a rotating swivel connection at the junction of the bolt fixing that passes through the glass and the end of the threaded rod that projects forward



3D overviews showing bolt-fixed glazing supported by branching steel framework

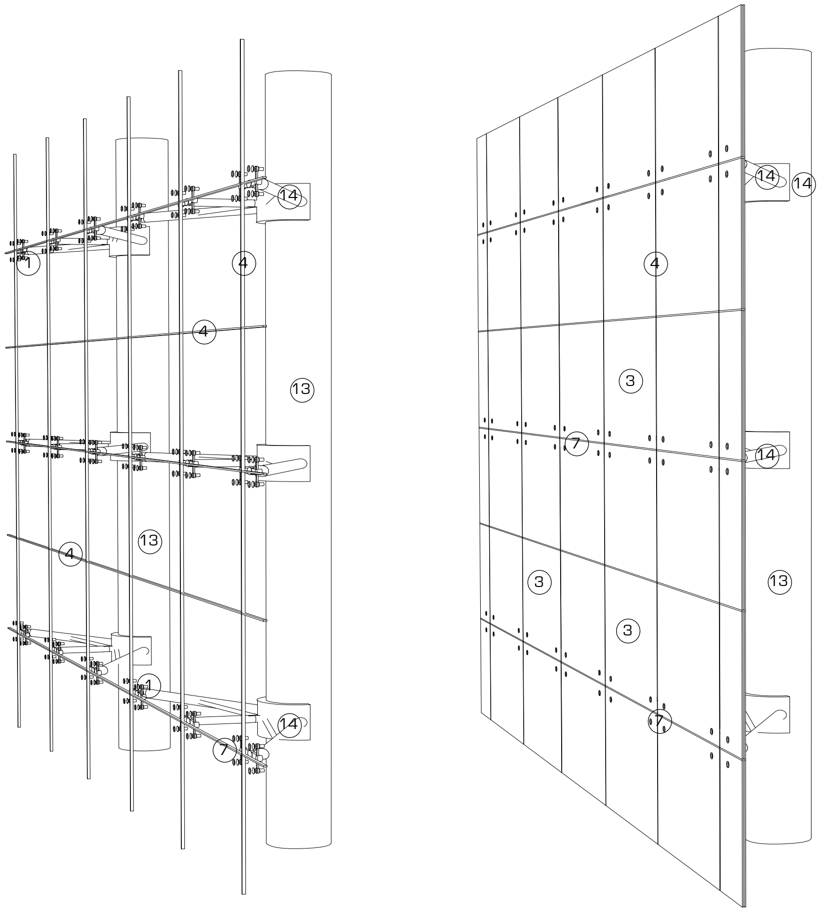
of the glass which is connected to the supporting structure. The rotating joint is allowed to move 12º in all directions away from its regular position. The bolt fixings themselves can vary from those with a fully visible thread and nuts, to a fully integrated type where all these components are concealed in sleeves.

The bolt fixing is secured to fixing brackets whose shape suits the geometry of the intersection of four bolt fixings with the supporting structure. In small-scale applications, fixing brackets can be formed from a simple steel angle, with one side supporting the bolt fixing and the other side fixed to the supporting column, or truss, for example. Larger-scale applications typically use X-shaped or H-shaped connectors to suit the position of bolts set around the intersection of four glass panels. Connectors are made as either castings or machined/welded components depending on the quantity of connectors and their complexity. Where several parts are required to be welded and machined, it is usually more economic and visually preferable to use a casting.

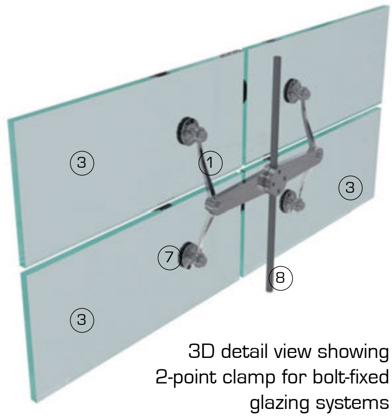
Corner fixings are made either by cantilevering the meeting panels out in each glazed wall forming the corner, and linking the glass panels together with bolt fixings in a pin connection, or by introducing structure at the corner, with bolt fixings being attached to a primary member. Where a corner bracket is used in conjunction with a cantilevered junction, manufacturers increasingly provide a limited range of standard components, though it is not uncommon for special connections to be provided, particularly for junctions where the meeting angle is not a right angle. Like clamped glazing, bolt fixed glazing is sealed between glazed panels with silicone seals, providing a single barrier to water penetration, but one which is reliable if properly undertaken.

The ability of bolt fixings to provide limited rotation at their fixing point has led to their supporting structures being structurally ambitious, with a mixture of steel trusses and cables used to minimise the amount of material needed to support glazed units. Some have horizontally set wind trusses that stiffen an all-cable structure, while others use full height vertical steel trusses with additional vertically set cables to reduce the number of trusses required. They also provide a fixing which is separate from the seals between glazed units, though both bolt fixed and clamped glazing methods have proved to be highly reliable in their weatherproofing performance. Where clamped glazing is used with flat surfaces or glazed walls of single curvature, bolt fixed glazing has the possibility of being set on a surface which curves in two directions, as in those created by cable net structures. Special care is needed to ensure that the angles of incidence at joints provide a reliable weathertight joint. An additional advantage is being able to fix the glass that is visibly forward of the supporting structure, sometimes creating a visual contrast between large structural members and a thin glazed skin set forward of it. This is particularly used if the supporting structure is set in one primary direction, giving the appearance of the glass joints in the opposite direction of spanning freely.

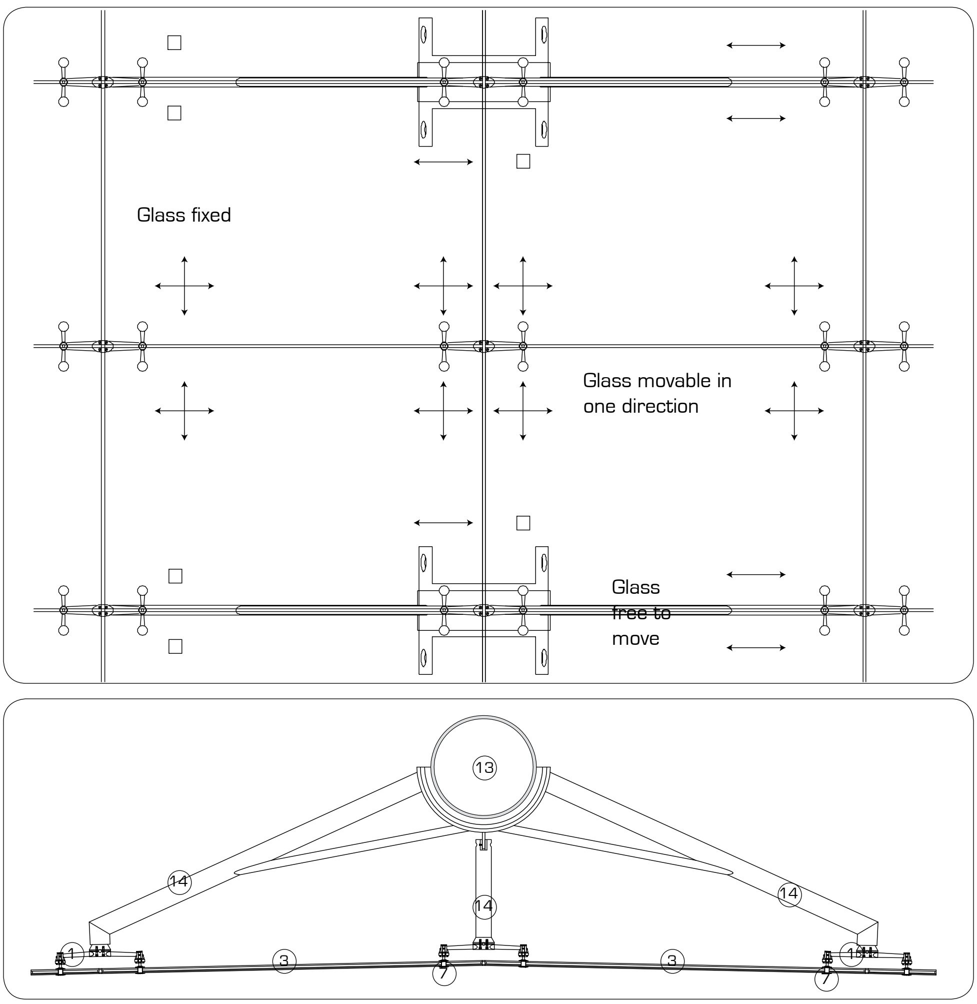
Details
1. Cast steel connector
2. Mild steel or stainless steel angle bracket
3. Single glazed or double glazed unit to suit application
4. Silicone seal
5. Floor finish
6. Support bracket
7. Bolt fixing
8. Stainless steel cable
9. Insulated panel
10. Floor slab/structural wall
11. Bolt based cable end
12. Glazing channel at floor level
13. Structural column
14. Steel arm for lateral support



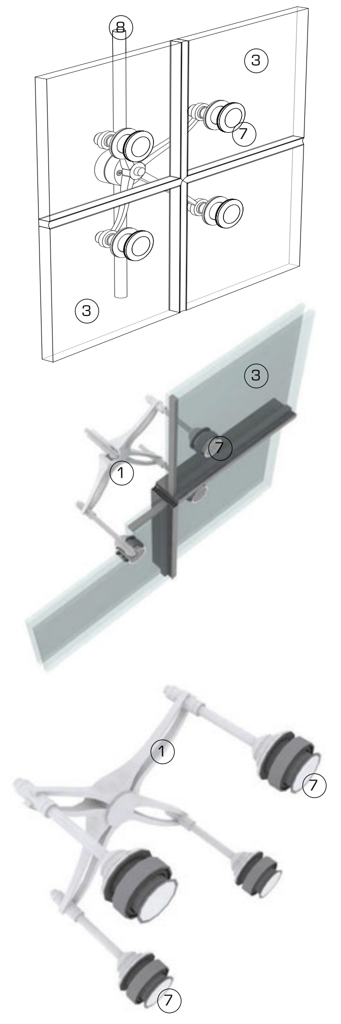
3D views showing bolt-fixed glazing supported by branched steel framework; depicted both with and without glazing panels



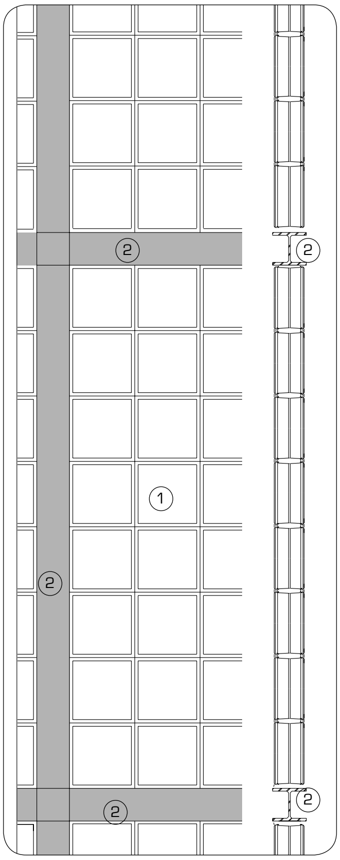
3D detail view showing 2-point clamp for bolt-fixed glazing systems

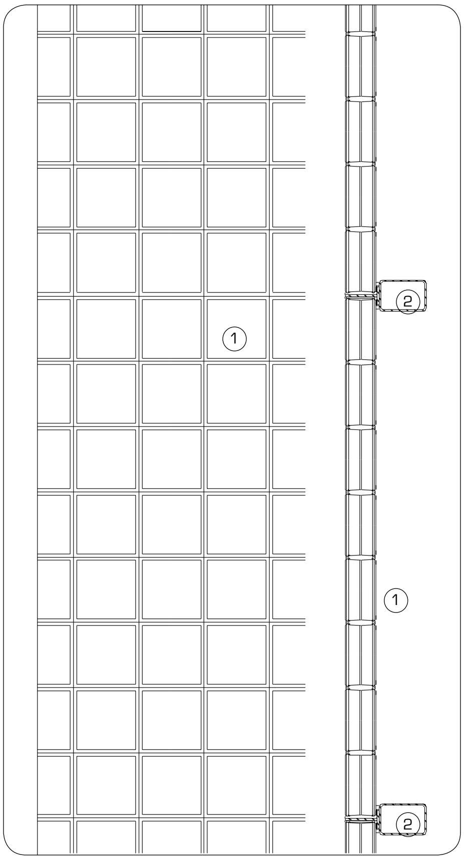


Elevation and horizontal section 1:50. Bolt-fixed glazing supported by branching steel framework



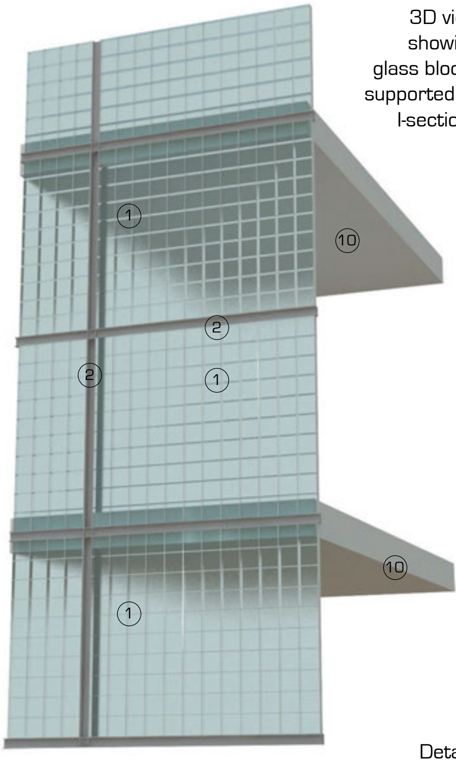
3D view showing various 4-point clamps for bolt-fixed glazing systems



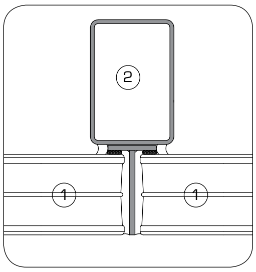


Elevation and vertical section 1:20.
Glass blocks supported by steel I-sections

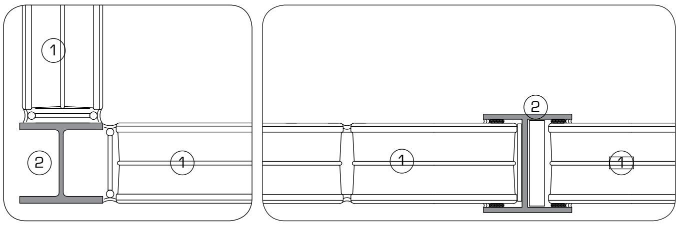
Elevation and vertical section 1:20.
Glass blocks supported by box sections



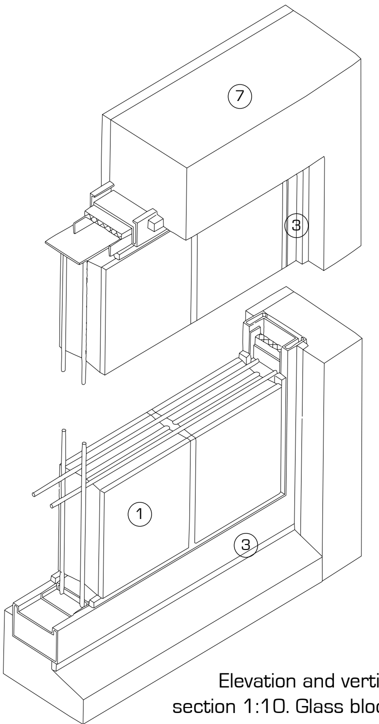
3D view showing glass blocks supported by I-sections

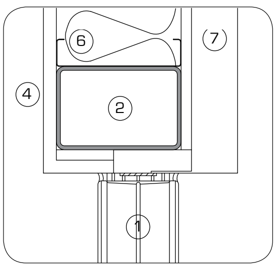


Details
1. Glass block
2. I-section or box section
3. Metal edge frame
4. External cladding
5. Steel flat or T-section
6. Thermal insulation
7. Enclosing wall or adjacent wall
8. Window casement
9. Cast glass channel
10. Floor slab

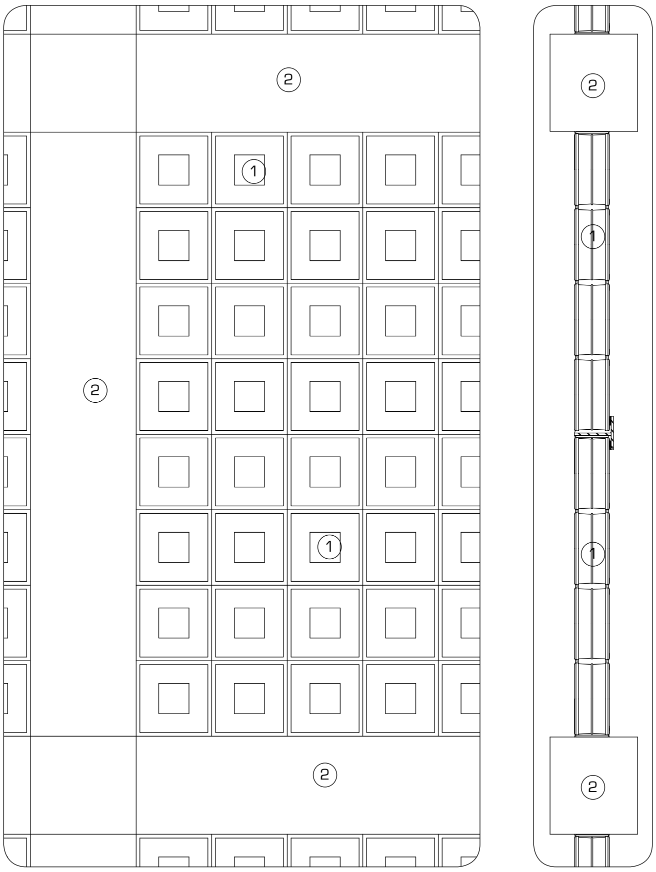


Horizontal section 1:10. Glass blocks supported by box sections



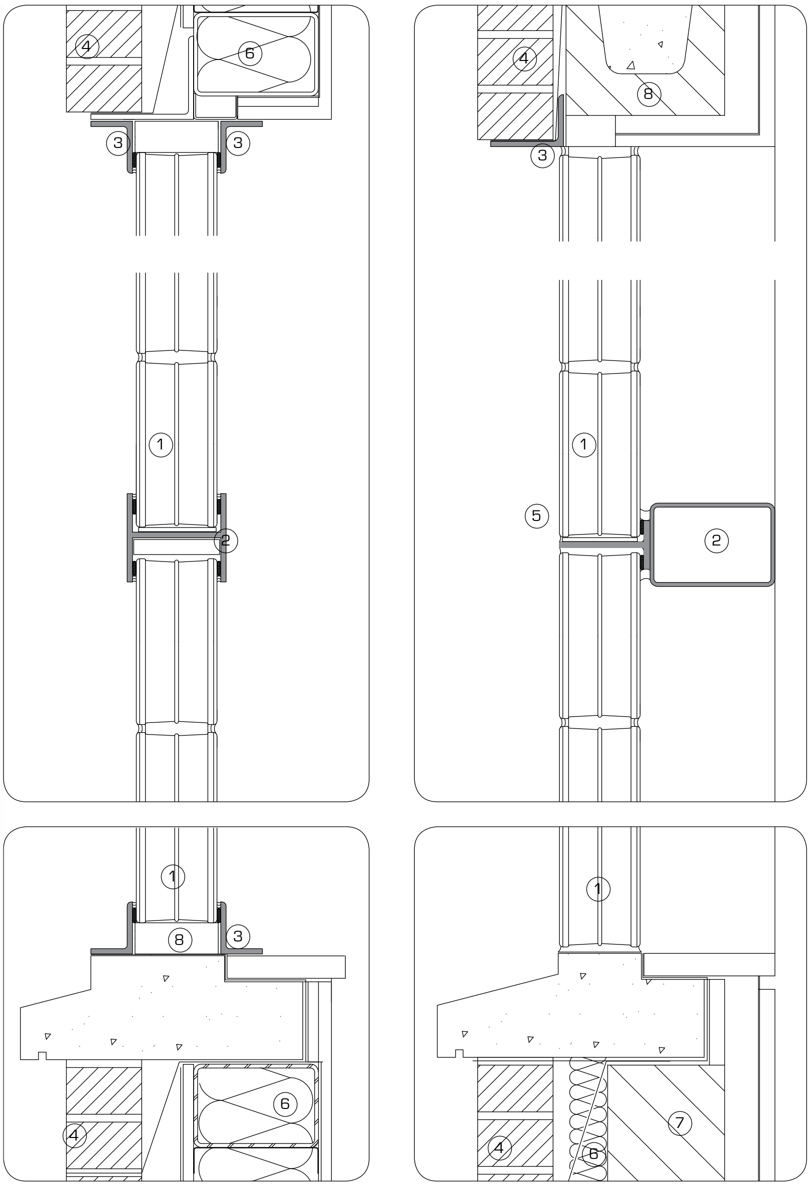


Elevation and vertical section 1:10. Glass blocks supported by box sections



Elevation and vertical section 1:20. Glass blocks supported by box sections

3D view showing glass blocks within masonry wall

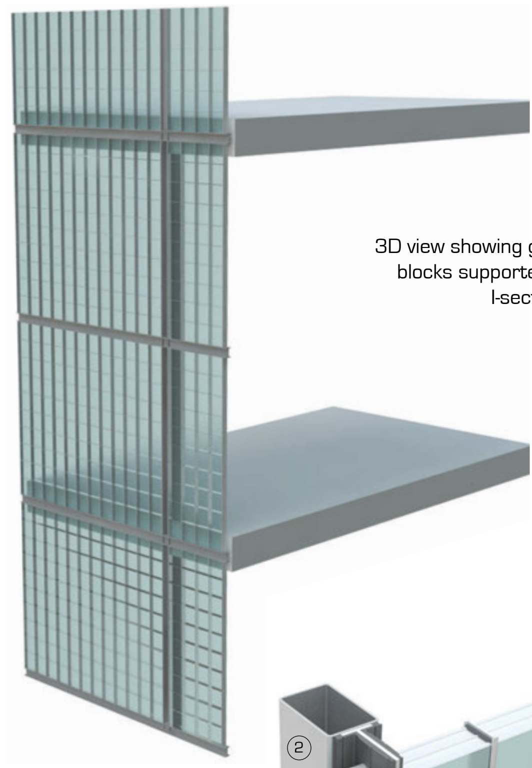


Vertical sections 1:10. Glass blocks fitted into window frames in masonry wall

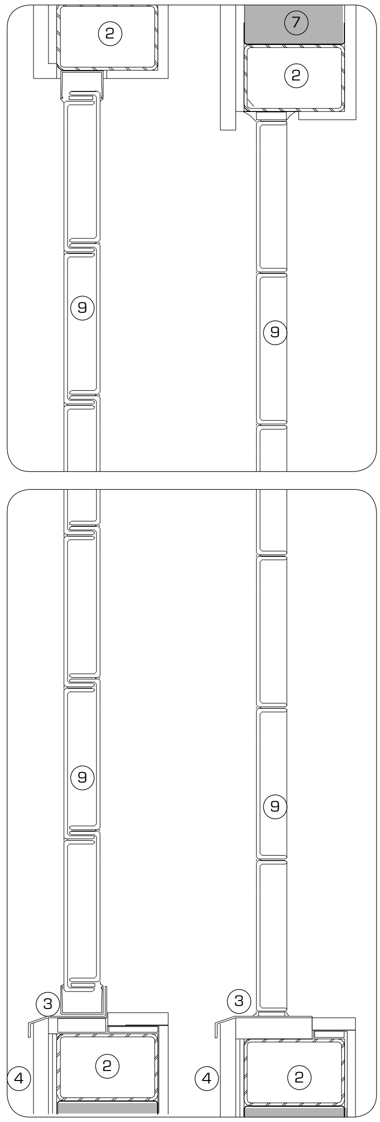
System design

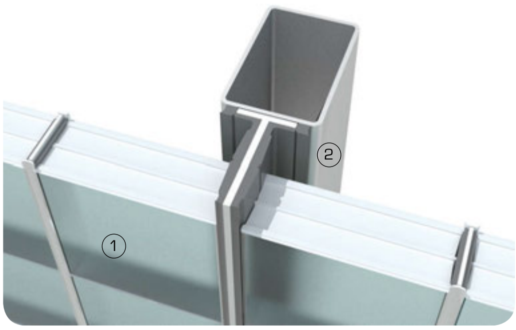
Glass blocks have been used in recent years for their qualities of robustness combined with fire resistance to form economic, translucent, glazed walls. Their translucency varies with the thickness of the wall of the individual glass block, which can range from solid to hollow type. The hollow type has the advantage of slightly greater thermal insulation and acoustic insulation, but the thermal insulation levels are well below those expected from regular double glazed units, so they tend to be used in locations where this is not a design consideration, such as in naturally ventilated spaces. The most common block sizes are a nominal 200mm x 200mm and 300mm x 300mm, generally 100mm thick. Blocks are arranged in stack bonded rectilinear grids that form individual panels, formed either as openings in walls or as bays of a structural frame, typically in reinforced concrete or steel. The continuous vertical and horizontal joints of these non-loadbearing panels give their characteristic gridded appearance, with panel sizes limited from around 3600mm x 3600mm in area, to around 4500mm x 4500mm in area, depending on block thickness. The panel size can be adjusted in proportion to give a maximum height of around 6000mm and a maximum width of around 7500mm. Glass blocks are well suited to providing an economic glazed fire resisting construction. One hour fire resisting panels can be made in panel sizes of around 3000mm x 3000mm in area, with a maximum height or width of 4000mm. Panels providing fire resistance greater than 60 minutes (usually up to 90 minutes) require metal channel restraints at the perimeter of the panel due to their greater reliability than cement mortar or silicone seals.

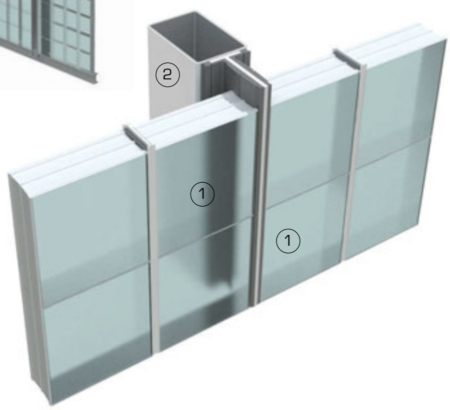
An alternative to glass blocks is cast glass channels, a long spanning material which can reach storey height without intermediary supports. Channels resemble half glass blocks in section, manufactured in lengths up to around 7000mm. Most are made around 250mm wide and 60mm deep. Channels are set either vertically or horizontally in a single layer, or can be interlocked by setting channels facing one another to form a double layer with smooth internal and external appearance. The interlocked version also provides a U-value similar to that of hollow glass blocks. An advantage of glass channels is that they are made either with a patterned surface characteristic of casting, or be made clear, with no pattern or hue. They can be Low-E coated to assist thermal insulation, and when interlocked can be thermally insulated with proprietary gel to significantly improve their thermal performance, though this process can be disproportionate to the cost of the cast glass channels.



3D view showing glass blocks supported by I-sections

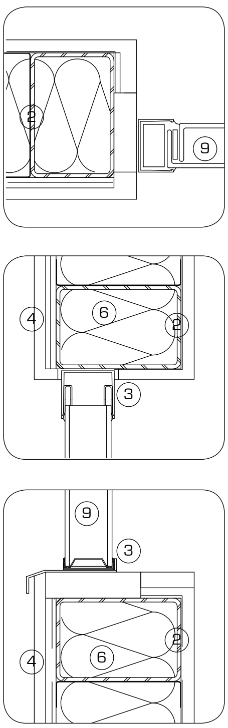




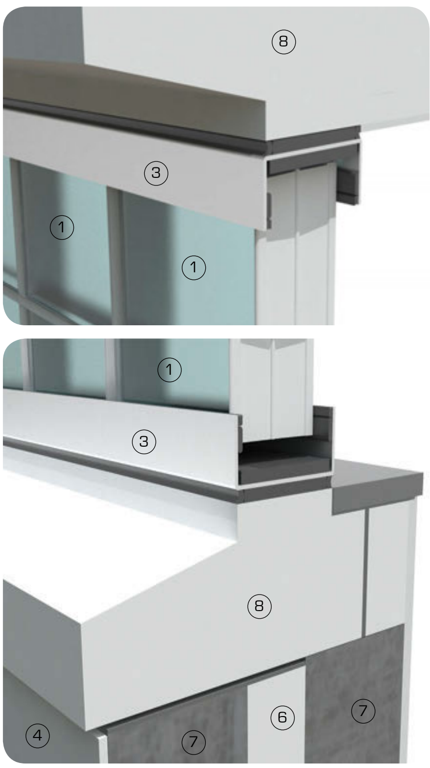


(Above) 3D view showing glass blocks supported by steel box-sections

vertical sections 1:20. (Left) double skin of interlocking glass horizontal channels. (Right) Single skin



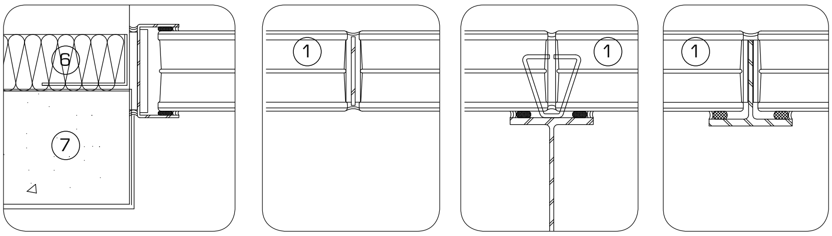
Horizontal and vertical sections 1:20. Vertically-set glass channels used as window



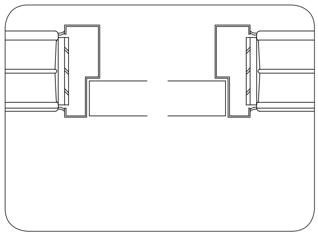
3D view showing glass blocks within masonry wall

Solar protection can also be added. Like glass blocks, cast glass channels are known for their properties of sound insulation combined with robustness. When stacked vertically, channels can be set out to form a curved wall, a characteristic well known with glass block walls.

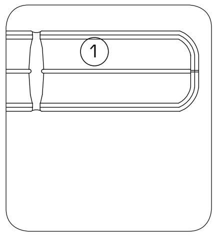
The relatively poor thermal insulation of glass blocks and cast channels, when compared to double glazed units, can lead to condensation occurring on the interior face of the block, and adequate ventilation is required to avoid this. Consequently, their use remains ideally suited to semi-external conditions in temperate climates, such as circulation spaces. Glass block panels fixed into reinforced concrete frames or wall openings are bedded in either mortar or silicone, with flexible joints introduced on the sides and top edge to allow for structural movement. Glass blocks are set within the frame which forms the external wall, or on the edge of reinforced concrete floor slabs. Storey height panels on the edge of floor slabs require metal angle restraints at the top of the opening to accommodate the deflection in the slab. This can be overcome by setting the glass blocks forward of the floor slab on a steel frame in the manner of glazed curtain walling.



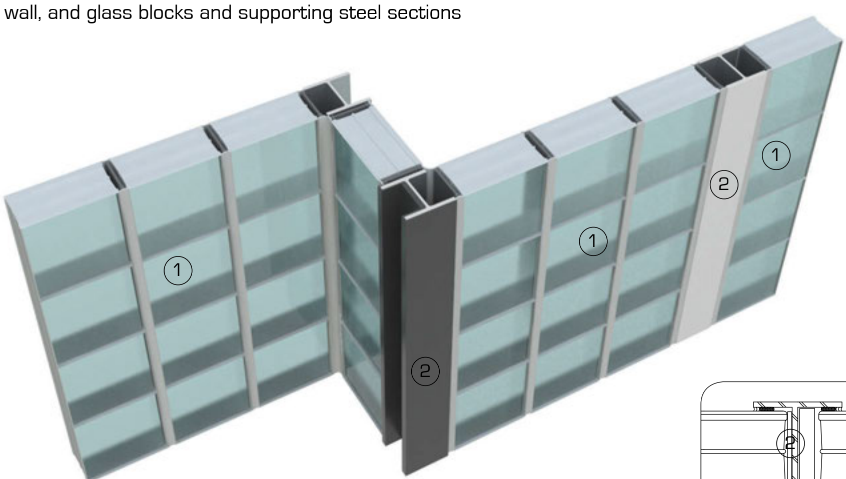
Horizontal section 1:10. Connection between glass blocks and cavity wall, and glass blocks and supporting steel sections



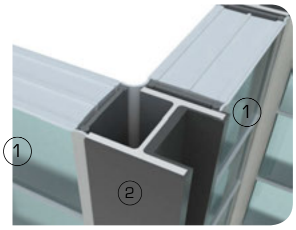
Horizontal section 1:10. Detail of door set into glass block wall



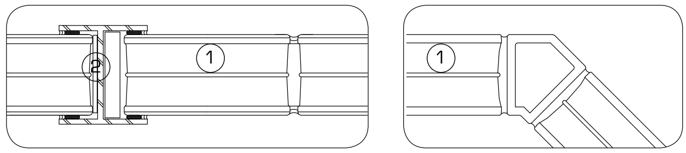
Horizontal section 1:10. Glass end block



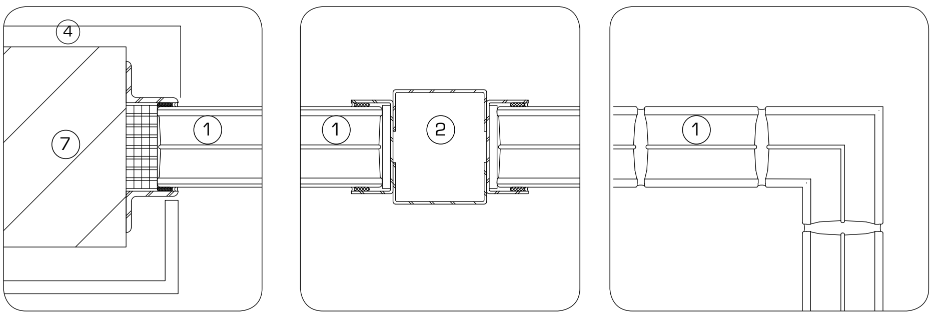
(Above) 3D view showing glass blocks supported by steel box-sections



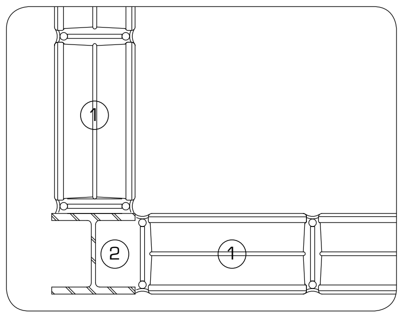
Details
1. Glass block
2. I-section or box section
3. Metal edge frame
4. External cladding
5. Steel flat or T-section
6. Thermal insulation
7. Enclosing wall or adjacent wall
8. Window casement
9. Cast glass channel
10. Floor slab



vertical section 1:20. Double skin of interlocking glass horizontal channels



Vertical section 1:20. Double skin of interlocking glass horizontal channels



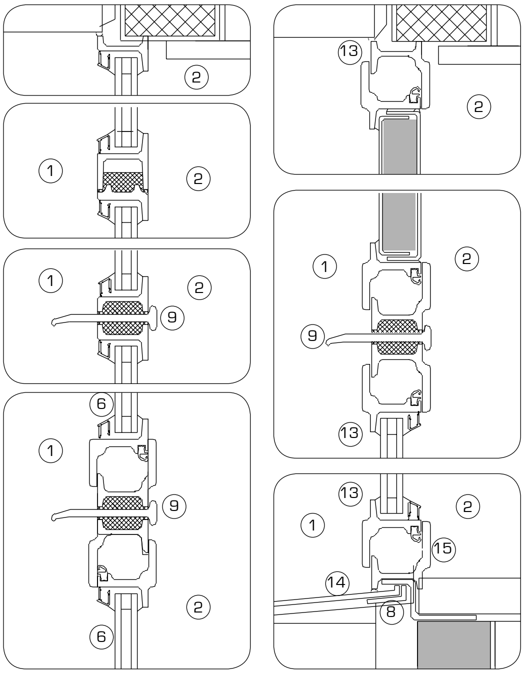
Vertical section 1:20. Double skin of interlocking glass horizontal channels

System details

Both glass blocks and cast channels can also be set into steel frames made from I-sections, box sections, T-sections or a combination of these. In smaller openings, a T-section is set into joints to stiffen the panels at mid-height between floor and ceiling/soffit. Larger panels can be formed by adding a rectangular box section to the back edge of the T-section to form a complete structural frame. Some manufacturers offer these materials as proprietary systems which include edge framing channels, though the appearance of these can be concealed by adjacent finishes.

Glass blocks usually have bed reinforcement between joints, typically a metal ladder-type reinforcing strip which is set within the joints and is not visible. Silicone is also used to bond blocks, with a sealing silicone used on the external face to provide a weathertight seal. Cement-based mortars are also used, with the choice of material being governed largely by visual considerations. Corners are formed usually with either the structure that supports the panel or special corner panels which form a part of most proprietary systems, mainly 90º and 45º corners. Junctions of blocks with adjacent walls are formed with a flexible seal, either silicone-based or with metal angle restraints. The angles are usually concealed by wall finishes, both internally and externally. Flexible seals are used where a door or window opening is introduced into a glass block wall. The door is usually fixed at its base only in order to allow the block wall to be structurally independent, but sometimes the door is tied into the horizontal joints of the glass block wall, depending on the amount of expected structural movement.

Cast glass channels are fixed into aluminium extrusions at their ends, and are sealed with silicone-based seals between long joints. Vertically-set channels can be bottom supported, but in horizontally-set arrangements, each channel is individually supported rather than each channel being supported on the channel below. As with glass blocks, the edge frame can be concealed by wall finishes, but cast channels are increasingly being used as a primary material on facades where they are used, as they are not required to be set into framed panels, and can be used in storey height form in long lengths.



Vertical sections 1:5. Rolled steel frames glazed internally and externally

Details
1. Outside
2. Inside
3. Rolled steel glazing section
4. Transom
5. Mullion
6. Single glazed or double glazed unit to suit application
7. Fixing bead
8. Fixing lug
9. Projecting transom
10. Rubber-based seal
11. Fixed light
12. Inward opening light
13. Outward opening light
14. Window cill
15. Condensation tray
16. Internal finish
17. External wall
18. Thermal insulation

3D view showing rolled steel window embedded within masonry wall construction

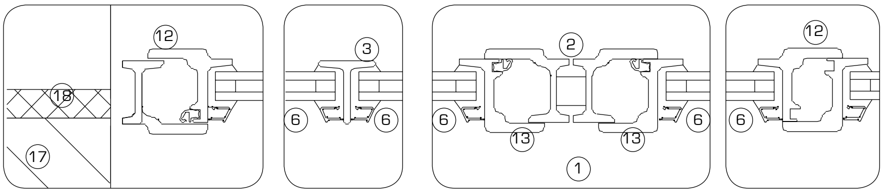
3D detail views showing rolled steel window embedded within masonry wall construction at head and cill conditions

System design

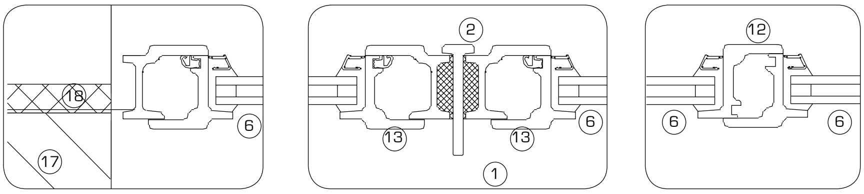
Steel framed windows made from rolled sections have been preferred for their thin sight lines when compared to those in aluminium for small-scale window openings. However, the thermal performance of the frames is considerably less than thermally broken aluminium sections, due to the difficulty of introducing a thermal break into small sections. Larger scale steel windows and glazed walls made from pressed steel sections, used mainly for their fire resisting qualities, can incorporate a thermal break but their sightlines are similar to those of an equivalent aluminium window or glazed wall. Steel framed windows are either fitted into wall openings or are joined together to form a glazed wall with deeper sections as framing members, which is slightly different to full aluminium-based stick glazing.

Steel framed windows with thin frames without thermal breaks in thin double glazed units are made with rolled steel sections to form windows of a maximum size of around 3000mm x 1800mm down to a minimum size of 250mm x 400mm. Fixed lights and opening windows can be joined together with T-sections to provide a supporting frame. Larger-scale steel curtain walling has a grid of pressed steel mullions (verticals) and transoms (horizontals) to which double glazed units are fixed with steel pressure plates. Seals are provided with synthetic rubber gaskets similar to those used in aluminium curtain walling systems. Single glazed units have small channels or angle shaped glazing beads to hold the glass in place, while double glazed units usually have extruded clips that hold the glass in place.

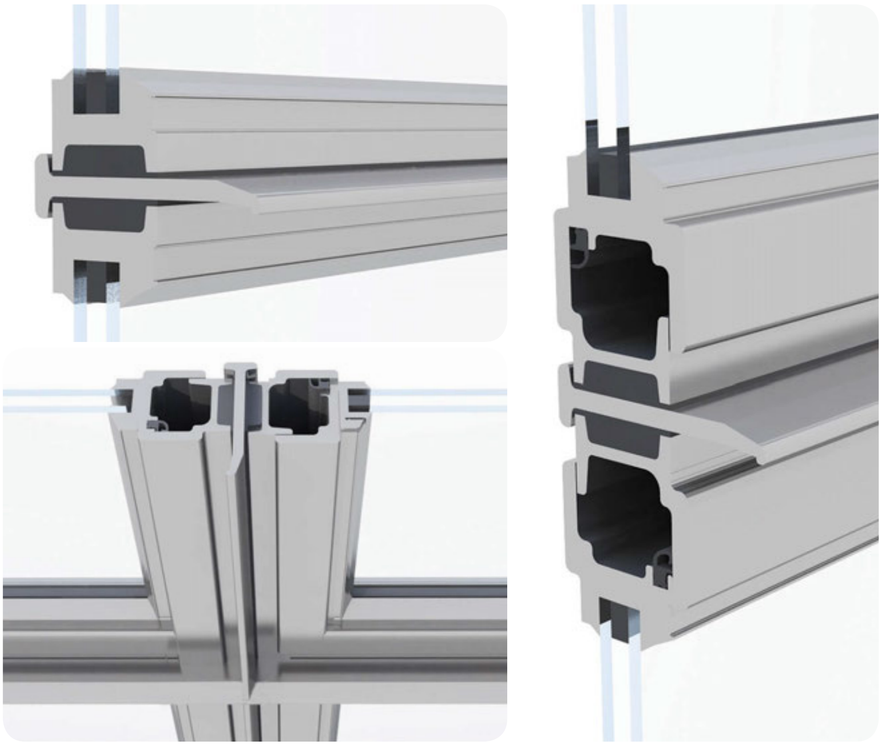
Larger scale, thermally broken, windows and doors are used primarily for their ability to provide fire resistance. They are made as pressed steel sections in sizes similar to an equivalent in aluminium but with slightly different profiles governed by the process of pressing, which cannot provide the complexity in section of extruded aluminium profiles. Unlike aluminium windows, where new extrusions can be made economic for each project, pressed and rolled sections for steel windows cannot produce new sections as easily. Fully glazed walls are made by fixing individual windows into a frame of pressed box sections with integral thermal breaks. There is a wide variety of standard sections available for the pressed steel profiles that support the glass, though it is more difficult to develop a profile for an individual project due to the constraints of pressing steel sheet, which is expensive to modify for individual projects.



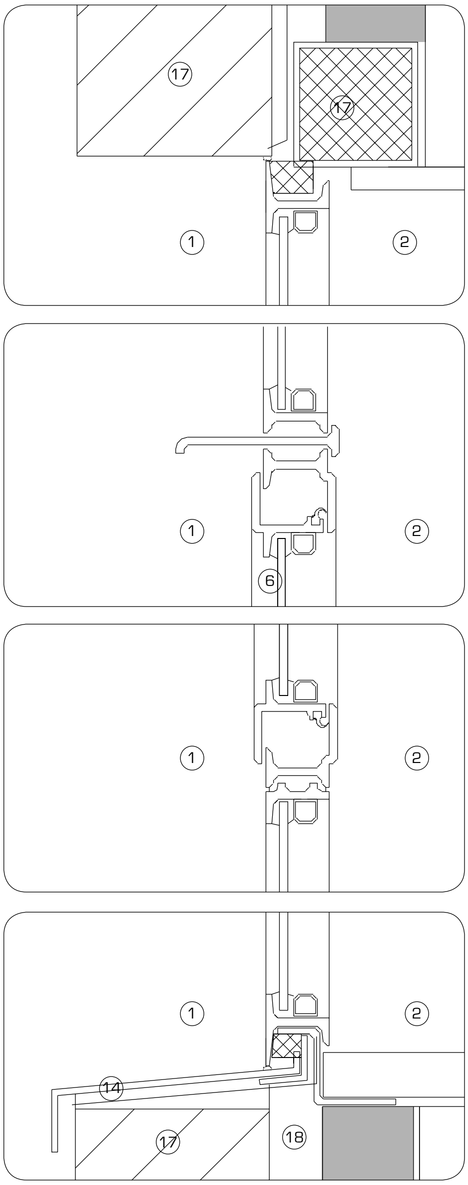
Horizontal section 1:5. Rolled steel frames glazed internally



Horizontal section 1:5. Rolled steel frames glazed externally



3D detail view showing rolled steel frames with double glazing in glazing configurations



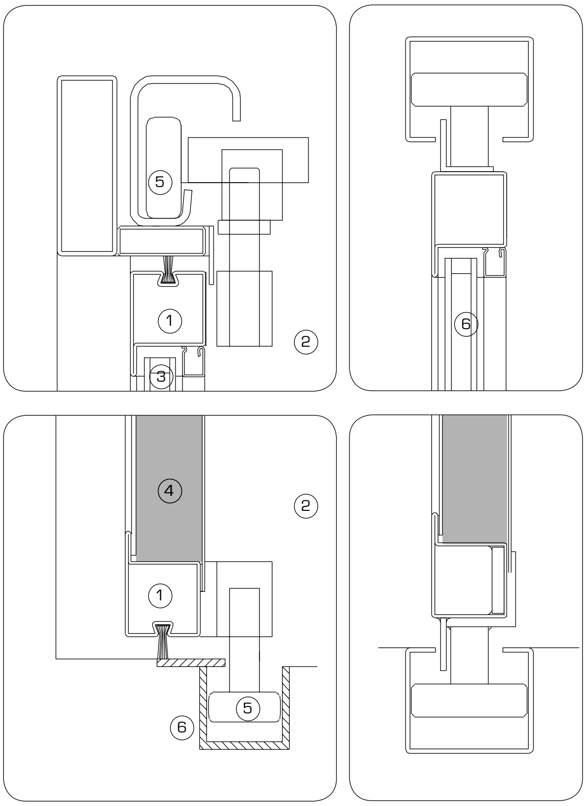
Vertical section 1:15. Rolled steel frame with single glazing

System details

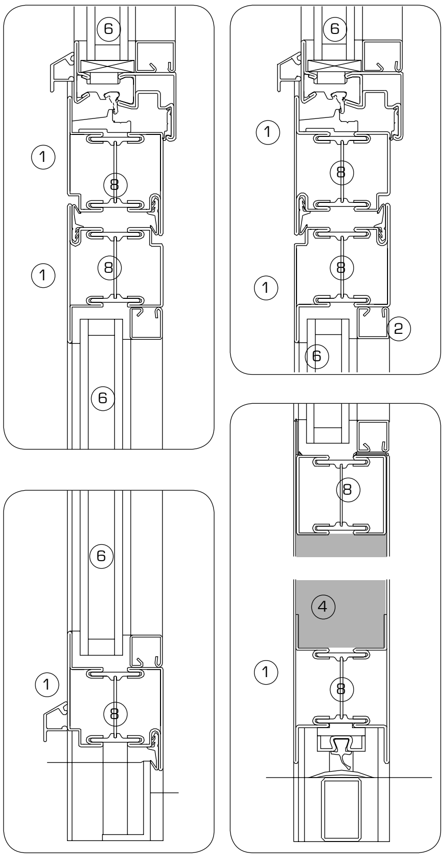
Outward opening lights for both windows in small-scale rolled sections and larger-scale pressed sections have profiles that lap over the front of the surrounding fixed frame, with a drip above the window to avoid rainwater finding its way in through the top of the frame. Any water that finds its way into the frame is drained down the sides and out at the bottom. Most windows have synthetic rubber seals to both assist drainage and reduce air infiltration through the opening light. With inward opening lights the top of the window is protected by the top transom of the fixed frame. The window is more vulnerable at its bottom edge where it is protected by a projecting cill. With steel windows made from rolled sections, any water penetrating the outer seal runs around a groove in the frame of the opening light and down the sides into the bottom transom below, where it is drained through weep holes to the outside. This is similar to the principle of traditional timber windows, but windows made from thermally broken pressed sections can follow the principles of aluminium framed curtain walling, with a ventilated and pressure equalised chamber behind the outer seal which drains moisture away and back to the outside at the bottom. Opening windows and doors are set into steel framed glazing with an additional frame which is visible from the outside, a principle which is followed in aluminium windows and glazed walls. Door and window lights are formed from pressed steel sections which are folded together to form a family of profiles to suit different sizes and glass types. Steel framed windows and doors are also made as separate items for glazing into openings in masonry walls. In this instance they are fixed through the frame into the adjacent structural wall. An EPDM foil or silicone sealant is then used to seal the gap between the steel window/door and the adjacent concrete or masonry wall.

Larger-scale glazing has framing with a continuous indented groove that forms a channel into which toggle-type fixings are inserted to receive the fixings that secure the pressure plates. The synthetic rubber seals, on either side of the glass provide a sealed chamber behind the pressure plate which is used to drain away any water that penetrates the outer line of defence. This void is ventilated, with transoms draining water at the base of each glazed unit using a synthetic rubber strip that slopes down to drain water to the outside.

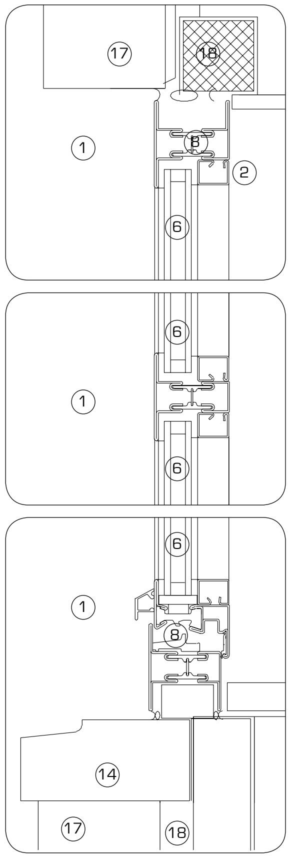
For both small-scale rolled sections and larger-scale pressed sections, doors are constructed in the same way as windows, but with horizontal rails to provide greater stiffness where rolled



Vertical sections 1:5. Sliding/folding door with rubber seals

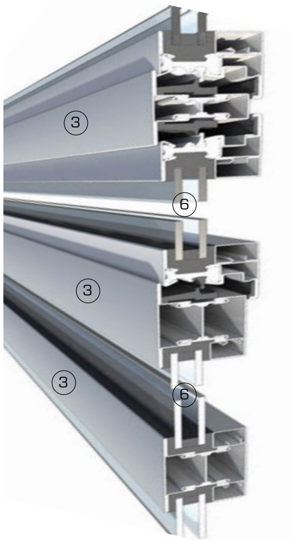


Vertical sections 1:5. Pressed steel doors with thermal breaks, both outward opening and inward opening



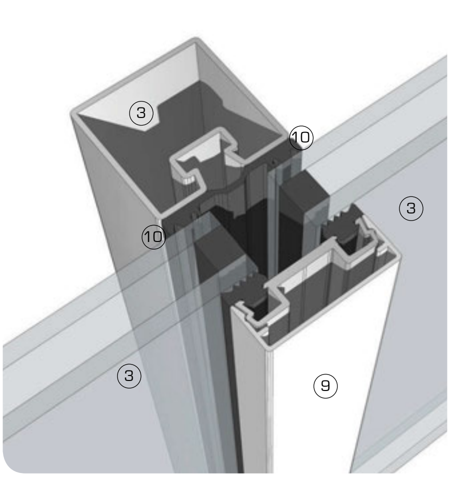
Vertical section 1:5. Pressed steel window, thermally broken

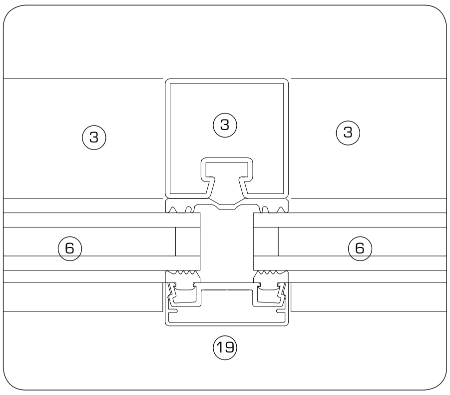
Details
1. Outside
2. Inside
3. Rolled steel glazing section
4. Transom
5. Mullion
6. Single glazed or double glazed unit to suit application
7. Fixing bead
8. Fixing lug
9. Projecting transom
10. Rubber-based seal
11. Fixed light
12. Inward opening light
13. Outward opening light
14. Window cill
15. Condensation tray
16. Internal finish
17. Concrete external wall
18. Thermal insulation



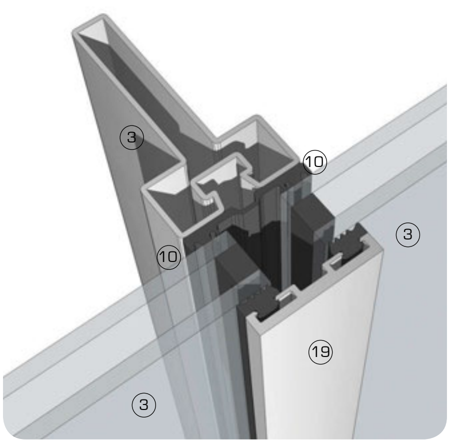
sections are used, and with thicker horizontal sections in doors where pressed steel sections are used. Corners are framed with either glazed or glass-to-glass corners in the manner of aluminium curtain walling, but where the glazing is fire resistant, panel sizes are limited. Those in small-scale rolled sections are formed with either T-sections that meet to form a recessed corner, or with a square-shaped hollow section to form a solid corner. Corners using larger-scale pressed sections are formed in a similar way to stick glazing, with mullion profiles set together joined by a thermally insulated panel on the surface of the glass. Some manufacturers provide standard corner sections as part of a proprietary system. Parapets are formed by fixing a folded metal coping into the top transom and folding it over the parapet behind. Metal flashings with an EPDM foil behind it are also used to seal steel glazing against areas of adjacent walls, typically of masonry or concrete construction.

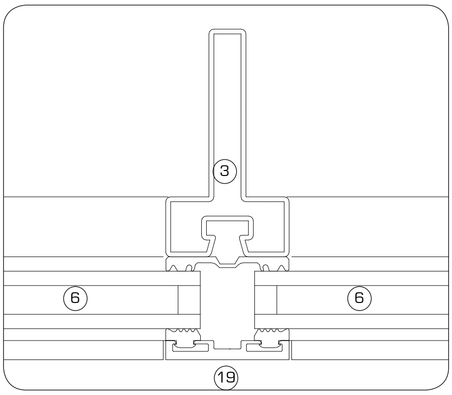
3D views (internal and external) showing pressed steel window, thermally broken and set within masonry wall construction



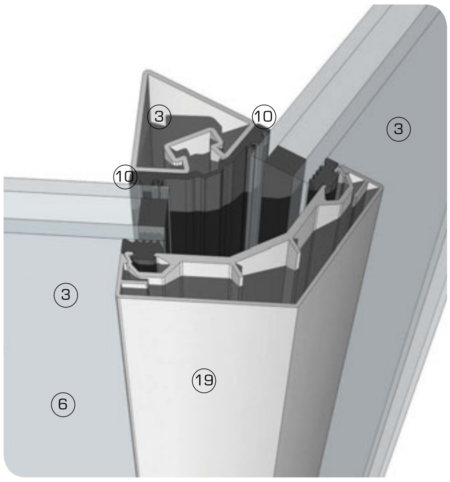


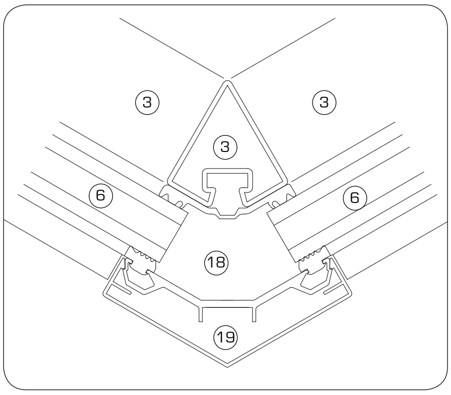
3D view and horizontal section 1:2. Alternative capping profile for steel glazing system



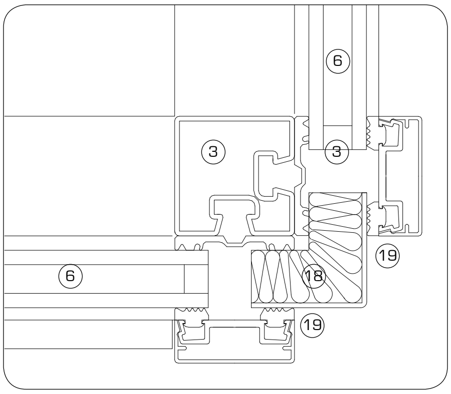


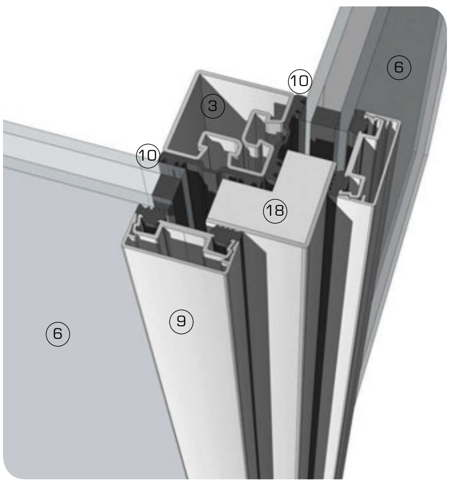
3D view and horizontal section 1:2. Alternative capping profile for steel glazing system



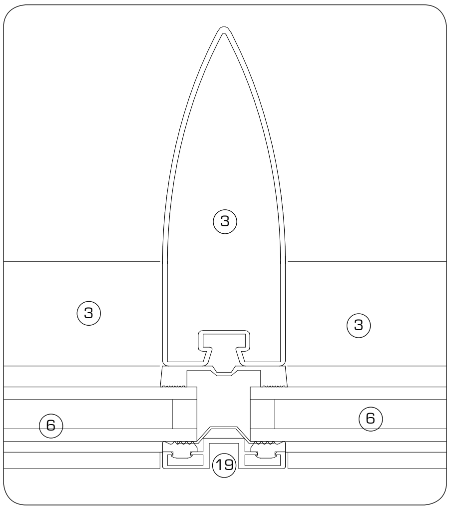


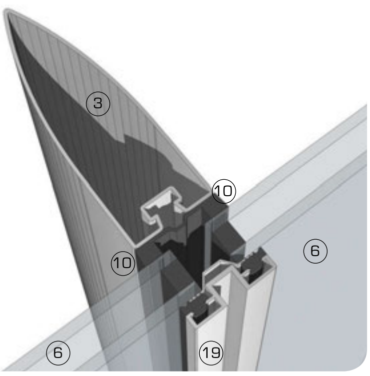
3D view and horizontal section 1:2. Alternative capping profile for angled steel glazing system



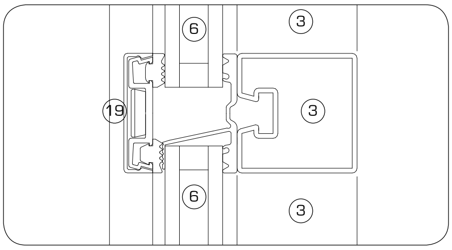


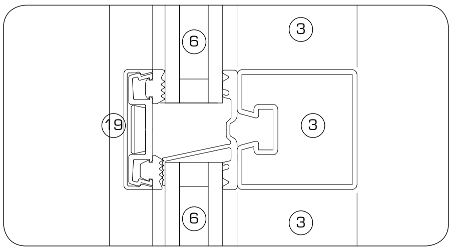
3D view and horizontal section 1:2. Alternative capping profile for steel glazing system corner condition





3D view and horizontal section 1:2. Alternative capping profile for steel glazing system corner condition

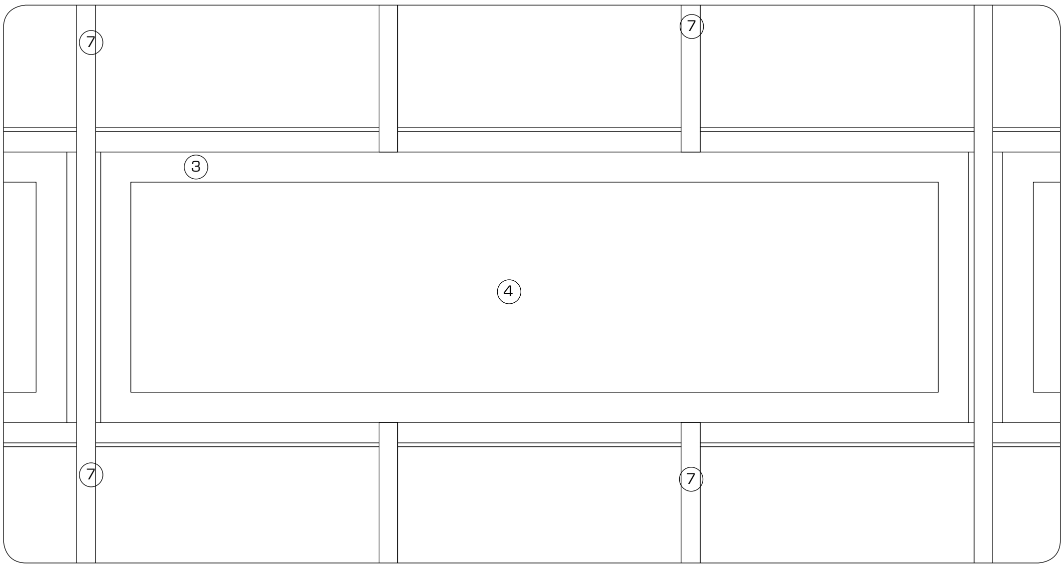




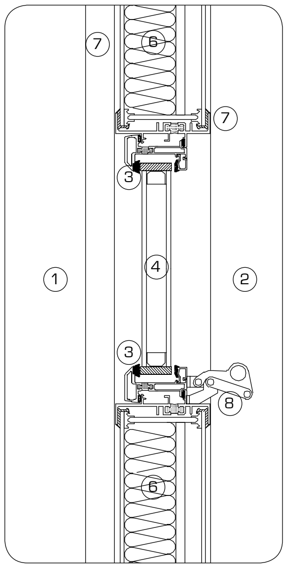
Horizontal section 1:2. Capping profiles for steel double-glazed system

Details

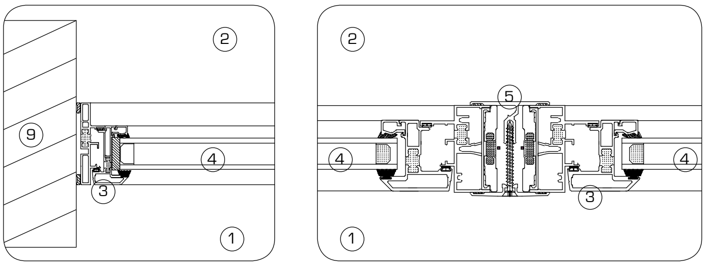
1. Outside
2. Inside
3. Pressed steel glazing section
4. Transom
5. Mullion
6. Single glazed or double glazed unit to suit application
7. Fixing bead
8. Fixing lug
9. Projecting transom
10. Rubber-based seal
11. Fixed light
12. Inward opening light
13. Outward opening light
14. Window cill
15. Condensation tray
16. Internal finish
17. Concrete external wall
18. Thermal insulation
19. Cap piece



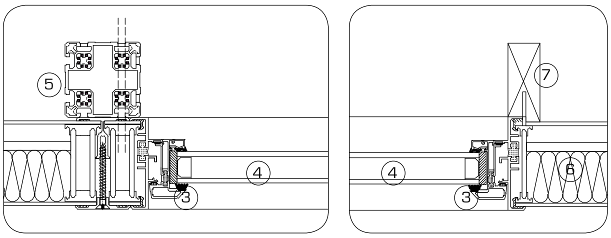
Elevation 1:10. Opening window set within large scale aluminium window section



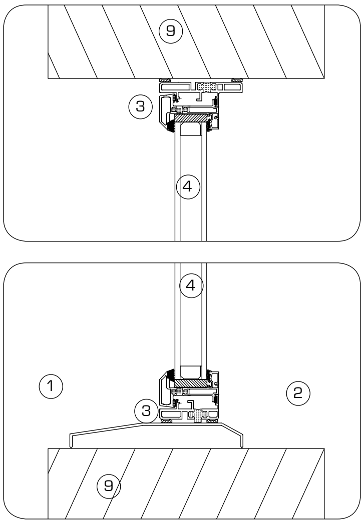
Vertical section 1:10. Outward opening aluminium window



Horizontal section 1:10. Outward opening window set typical wall construction



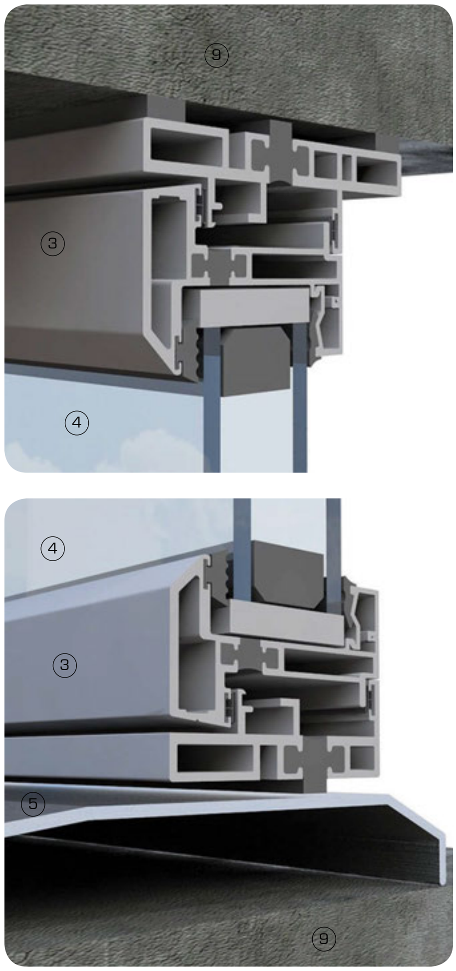
Horizontal section 1:10. Outward opening windows set within large scale window assembly



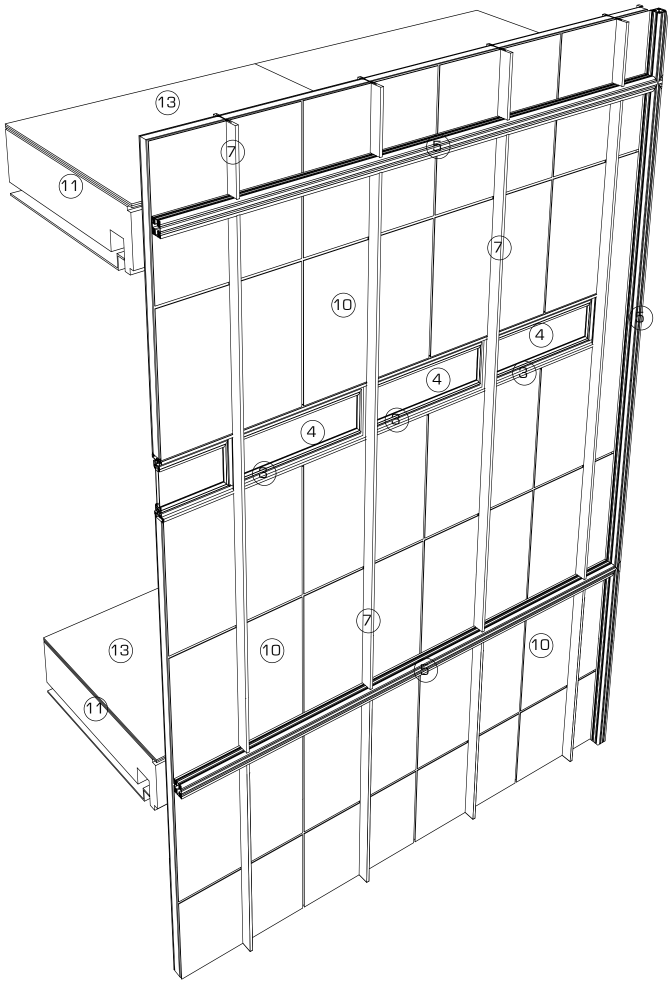
Vertical section 1:10. Outward opening aluminium window set within typical wall construction

Details
1. Outside
2. Inside
3. Window frame
4. Single glazed or double glazed unit to suit application
5. Extruded aluminium section
6. Thermal insulation
7. Aluminium battens for decoration
8. Opening mechanism
9. Surrounding wall
10. Insulated composite panel
11. Floor construction
12. Roof construction
13. Internal finish

3D view showing overview of aluminium glazing system set in masonry wall



3D detail views showing details aluminium glazing system set in masonry wall at head and cill



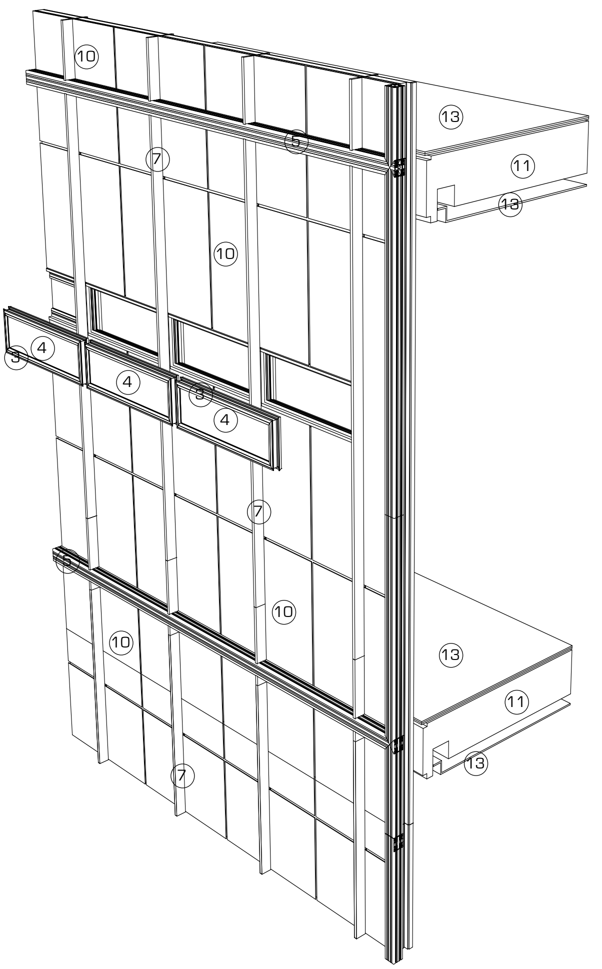
3D view showing build-up of aluminium glazing system

3D cutaway view showing build-up of aluminium glazing system

System design
Windows made from aluminium are formed either as individual frames set into structural openings or are set in groups to form a complete glazed wall where individual lights are linked to give the appearance of an overall modular glazed facade. A glazed wall, formed as a large scale window assembly is used typically where the glazed wall is not of sufficient size to require it to be supported or hung from floor to floor, which is the principle of stick glazing and unitised glazing in curtain walling. In contrast to curtain walling, which is a structurally independent external wall, 'window walls' have windows fixed onto a structural frame or backing wall, which is set into a larger structural opening in a facade. Window walls provide the appearance of a curtain wall combined with the acoustic and fire resisting properties of its backing wall, making it suitable for apartments, for example. Window walls are typically supported at their base, but can also be top hung or side hung depending on their geometry.

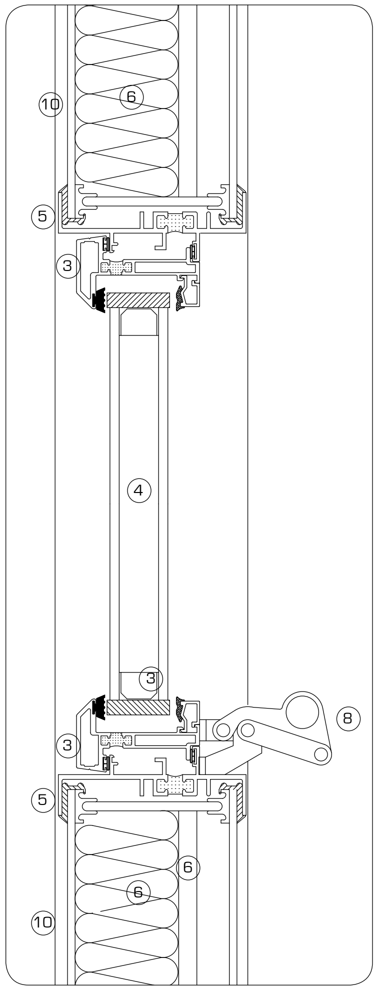
An advantage of aluminium windows over those in other materials is their use of extruded profiles which can take up complex shapes in section to which thermal breaks and seals can be fixed with ease, and within which water can be drained with a high level of precision. This allows aluminium window frames to be relatively well thermally insulated, and have low rates of air infiltration when compared to other materials. The main disadvantage, from the visual point of view, is the wide sightlines required for structural reasons in accommodating seals for internal drainage and thermal breaks. Where sightlines are reduced, the overall depth of window is increased to compensate for the loss of stability of the frame. In common with aluminium curtain walling, extruded aluminium window frames are pressure equalised and internally drained in order to provide two lines of defence against rainwater penetration. An outer seal, typically a synthetic rubber gasket, excludes most of the rainwater, but any water that passes through is drained away at the bottom of the profile to the outside. The internal barrier serves as an air seal rather than as a full weathertight seal. An additional function of the gasket seal is to provide a continuity with the thermal break so that the air temperature of the inner chamber is much closer to the internal temperature than the external temperature.

Where window frames tend to be narrow and deep in section, in order to accommodate the seals and thermal breaks, doors are usually wider in order to provide greater stiffness for the glazed units which they support. Doors were not usually thermally broken until recently, since rigidity and durability of the frame is usually the most important consideration, but thermal breaks are becoming much more common in door sections. Doors with lower air infiltration rates and a thermal break are made from window sections rather than door sections. The increased performance usually results in smaller maximum door sizes, at around 2400mm for a thermally broken, internally drained and ventilated door. Doors with thermal breaks can reach a maximum of around 3000mm to 3500mm without wide sightlines. Doors with thermal breaks can exceed 2400mm high by silicone bonding the glass to the frame so that glass assists in stiffening the frame. The maximum width of doors is



3D exploded view showing opening window set into large scale aluminium frame assembly

3D detail views showing opening window set into large scale aluminium wall system



Vertical section 1:5. Opening window detail

a function of their height, in order to restrict the overall weight, but a 850mm wide door leaf forming a 1700mm wide pair of doors is not uncommon. Minimum width of opening lights is about 250mm where a double glazed unit is used. Minimum heights of glazed ventilators, such as those set above doors for night time ventilation, are around 250mm to suit the needs of the opening mechanism. Side hung, top hung, bottom hung and tilt/turn windows use similar aluminium profiles.

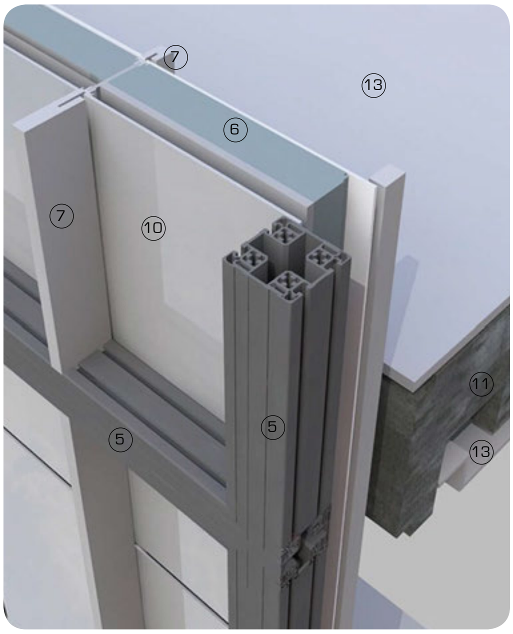
System details

A recent development has been the introduction of parallel opening lights, where windows open in a direction parallel to that of the frame. This has an advantage of increasing the amount of air that is admitted without exposing a complete section of wall to the effects of both wind and solar radiation. If solar control glass is used in the opening light, then that shading function is largely maintained when the window is in the open position. These windows also help smoke evacuation where used as smoke vents, but an essential characteristic is visual, in having opening lights in glazed walls which do not interrupt the visual continuity of the overall facade design. Parallel opening windows use a scissor-shaped hinge which slides within the frame to provide a stable support for the open window in any position. These opening lights are used with windows that use stick glazing sections used in curtain walls, particularly where the double glazed units are silicone bonded to reduce the visual impact of their supporting frames.

Windows and doors are sealed at their interface with the surrounding walls usually with a synthetic rubber strip which forms an integral part of the window frames, or alternatively with a seal between window frame and opening, typically with a silicone-based product. Some synthetic rubber seals have a metal facing for additional protection, called a ‘foil’, which is bonded to the adjacent wall and is usually concealed by the adjacent construction. The EPDM-foil seal is used where the window is fitted first, since the surrounding wall must be clear in order to fix it, and a perimeter seal is usually used where the window is fitted after the adjacent external wall has been completed.

Where aluminium window walls are used, opaque glazed infill panels are set between window panels as a facing to the insulated backing wall arranged immediately behind. Metal infill panels are also used, sometimes in rainscreen configuration, but more typically sealed in a supporting framework. Where opaque panels are used, opaque panels are fitted to a simple support as required by rainscreens and composite panels rather than a full window wall framing system. In this window wall configuration, windows are set forward of the opening where the complete facade is required to be in a single plane, rather than within the opening itself. The gap between window and opening is closed with metal flashings, which can be concealed with internal finishes.

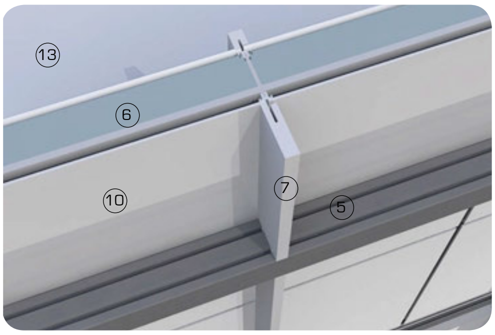
3D view showing aluminium-framed timber window wall system



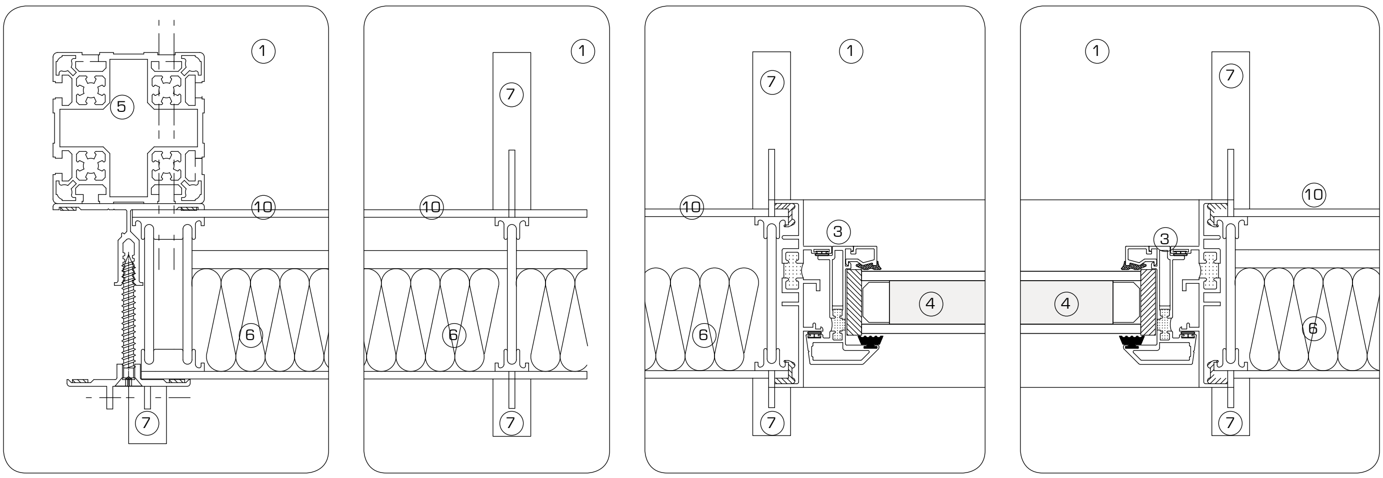
3D detail view showing aluminium-framed timber window wall system

Details
1. Outside
2. Inside
3. Window frame
4. Single glazed or double glazed unit to suit application
5. Extruded aluminium section
6. Thermal insulation
7. Aluminium battens for decoration
8. Opening mechanism
9. Surrounding wall
10. Insulated composite panel
11. Floor construction
12. Roof construction
13. Internal wall finish

(Below) 3D view showing build up of aluminium-framed timber window wall system

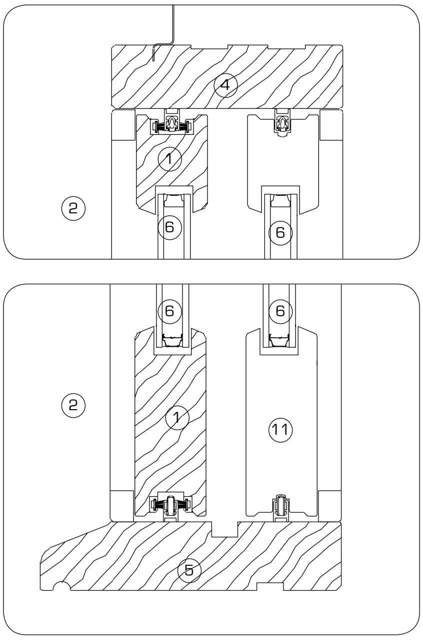


3D rear view showing aluminium-framed timber window wall system

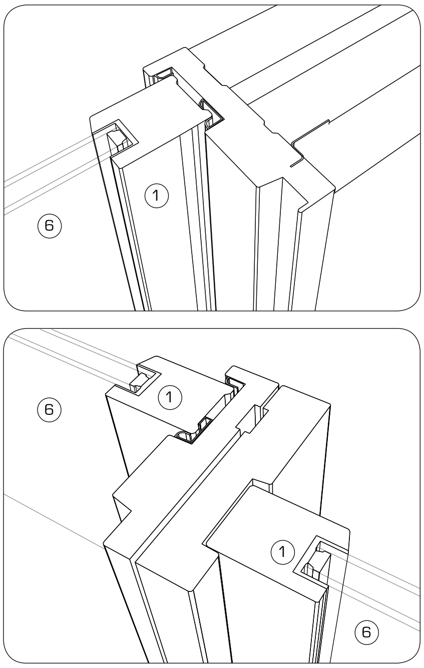


Horizontal sections 1:5. Aluminium window wall system showing typical panel and window details

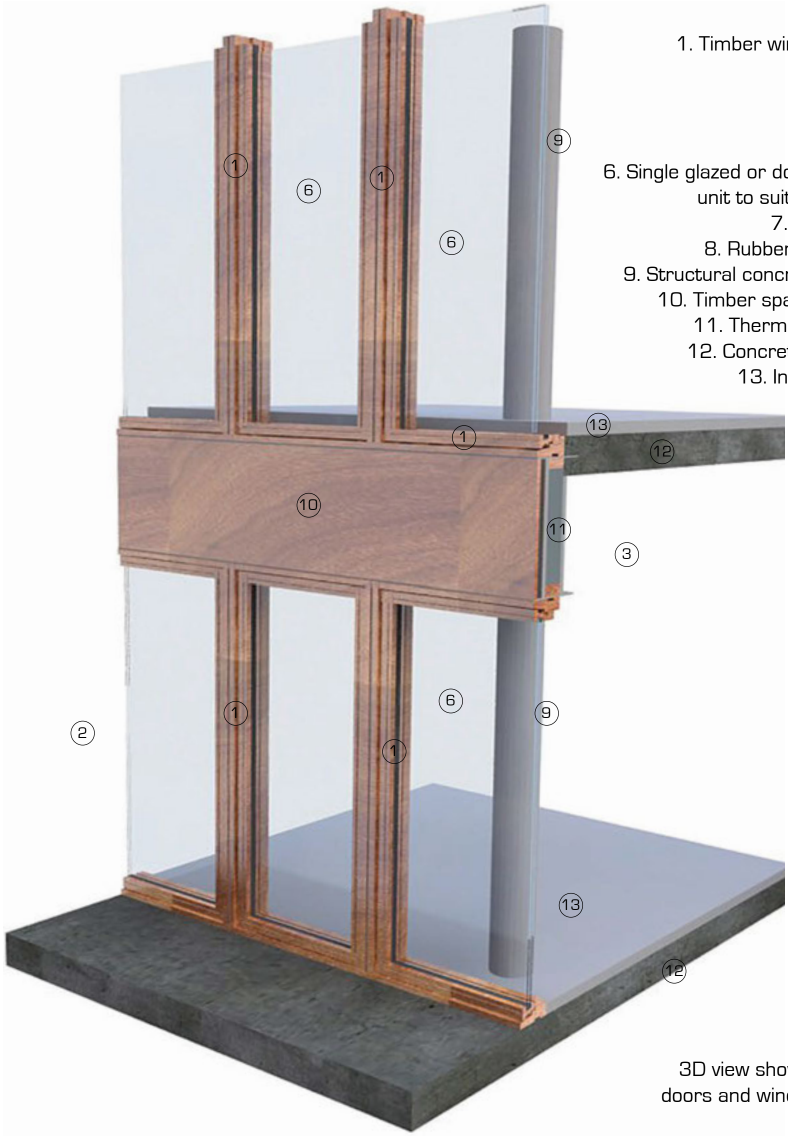
Glass systems 8: timber windows



Vertical section 1:5 Sliding doors

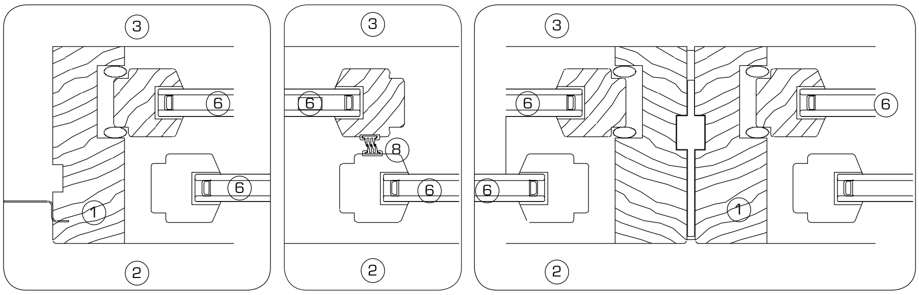


3-D detail views of sliding doors

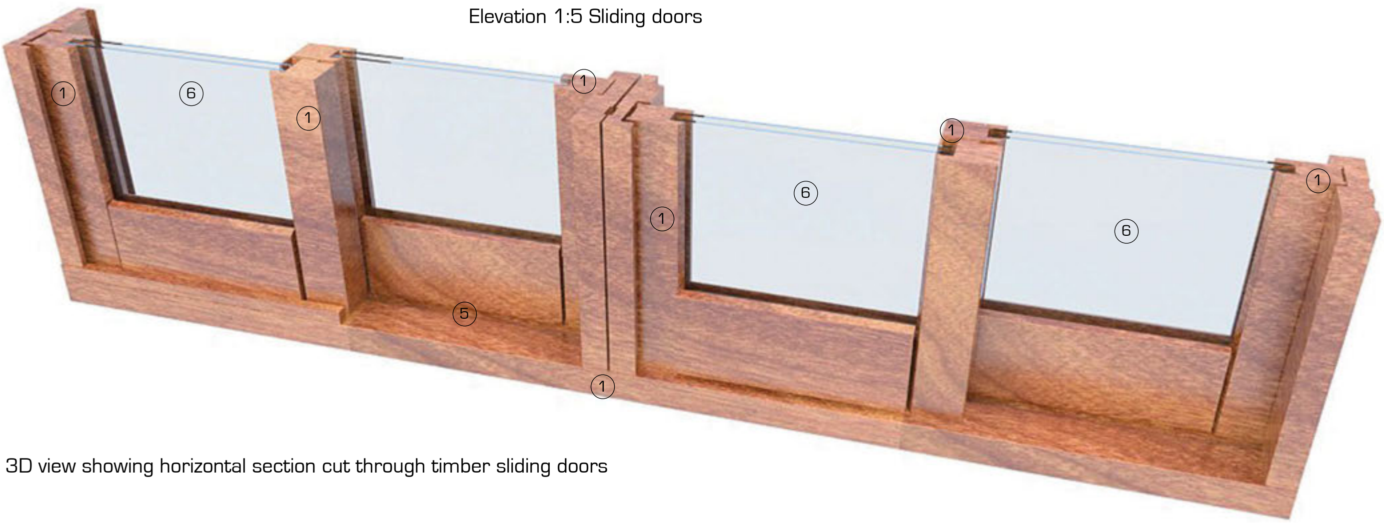


Details
1. Timber window frame
2. Outside
3. Inside
4. Head
5. Cill
6. Single glazed or double glazed unit to suit application
7. Fixing bead
8. Rubber-based seal
9. Structural concrete column
10. Timber spandrel panel
11. Thermal insulation
12. Concrete floor slab
13. Internal finish

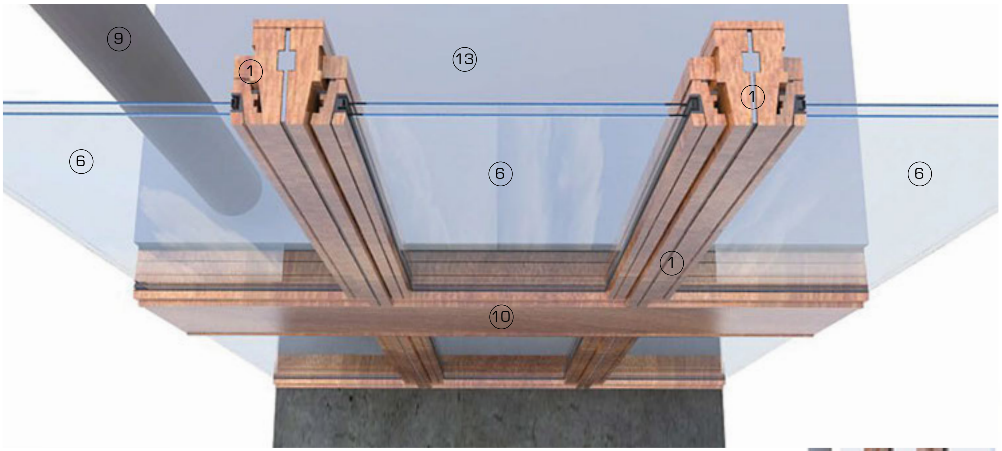
3D view showing timber doors and windows in wall system



Elevation 1:5 Sliding doors

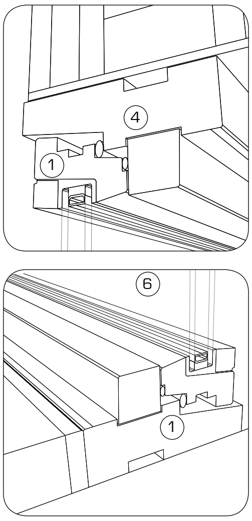


3D view showing horizontal section cut through timber sliding doors

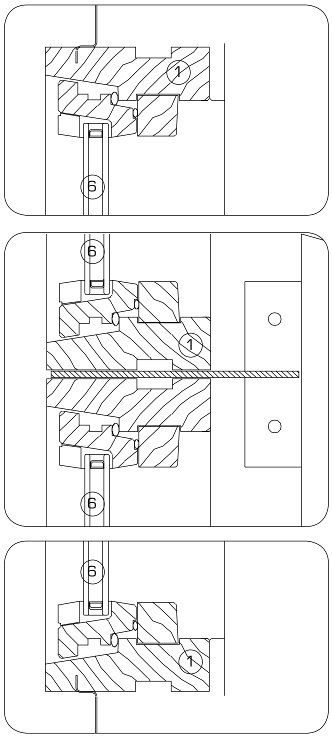


3D view showing timber doors and windows in wall system

3D detail view showing spandrel panel in timber door and window wall system



3D views showing head and cill conditions in timber door



Vertical section 1:5 Outward opening casement windows

Details
1. Timber window frame
2. Outside
3. Inside
4. Head
5. Cill
6. Single glazed or double glazed unit to suit application
7. Fixing bead
8. Rubber-based seal

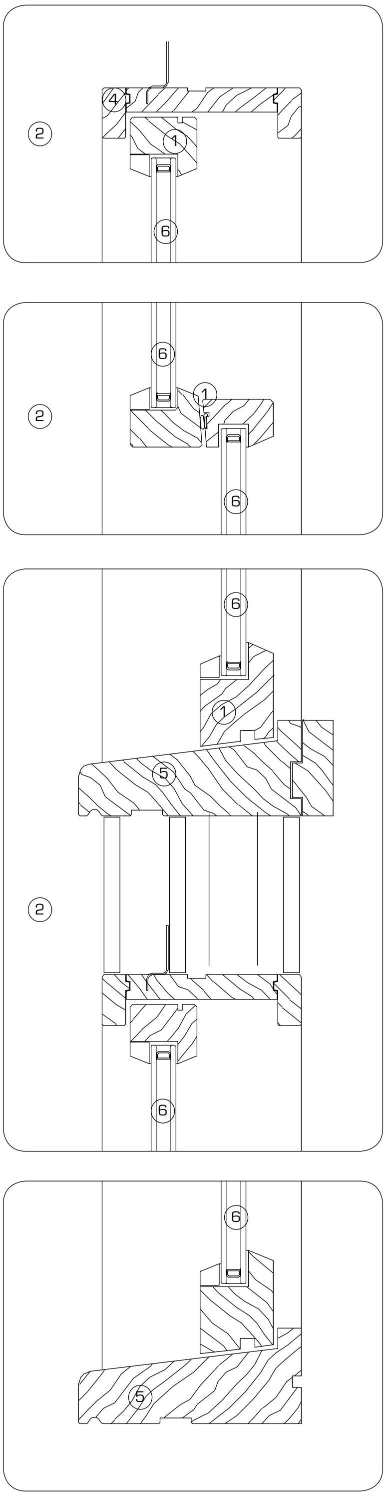
System design

In common with aluminium windows, timber windows are used either individually within wall openings or are grouped to form a complete 'window wall', formed by linking windows into a continuous arrangement. They are supported by an integral timber frame, typically reinforced internally by steel flats or sometimes supported by separate secondary steel supports in the form of columns or complete frames. Where individual windows are linked together with thin steel reinforcing plates, the panel size is limited to storey height, and the window wall arrangement is fixed back to the supporting structure of floor slabs or supporting wall. Where the visual presence of timber framing members is not the preferred expression of the facade from the outside, a secondary steel frame can be set internally, typically made from tubes, T-sections or box sections to reduce their visual impact. Alternatively, the steel components can be set within timber members forming the supporting frame to the window wall, depending on the required sizes of the steel members. These steel components are set within the timber construction to avoid being exposed to the effects of the weather. In addition, the high moisture movement associated with timber makes the penetration of the steel supporting structure through the external face of the timber glazed wall more difficult to waterproof. Where windows are linked and reinforced with a mild steel flat, a drainage groove set into the joint ensures that any water that penetrates the outer joint is drained away to the outside at the bottom of the window or window wall. Drainage channels are used on all four sides of the window in the manner of aluminium curtain walling. The steel stiffening rib or bracket does not extend forward of the drainage groove to allow water to be drained away unimpeded. Mullions and transoms (verticals and horizontals) may be of different depth to suit their individual structural requirements and may be in a different wood. Hardwoods and softwoods can be mixed in a single window wall construction, but the relative moisture movements associated with each type are taken in account to ensure that this movement does not adversely affect the appearance or stability of the window wall.

Timber framed window walls typically span up to two floors, typically restricted by the self weight of the panels, which are usually supported at their base. This is due to the need to tie the frame into large single units to avoid the effects of thermal movement of the sections. If timber sections are not tied together, they tend to wrap and twist when exposed to outside elements. Even if the surfaces are painted or sealed with varnish, any movement due to moisture will crack the outer finish and allow further movement to occur. Timber sections are jointed with either tongue-and-groove or rebated joints. Where tongue-and-groove joints are used, the linking material can be a durable hardwood or aluminium. Sections can also be bolted together if the sections are of sufficient size, such as around 75 x 50mm.

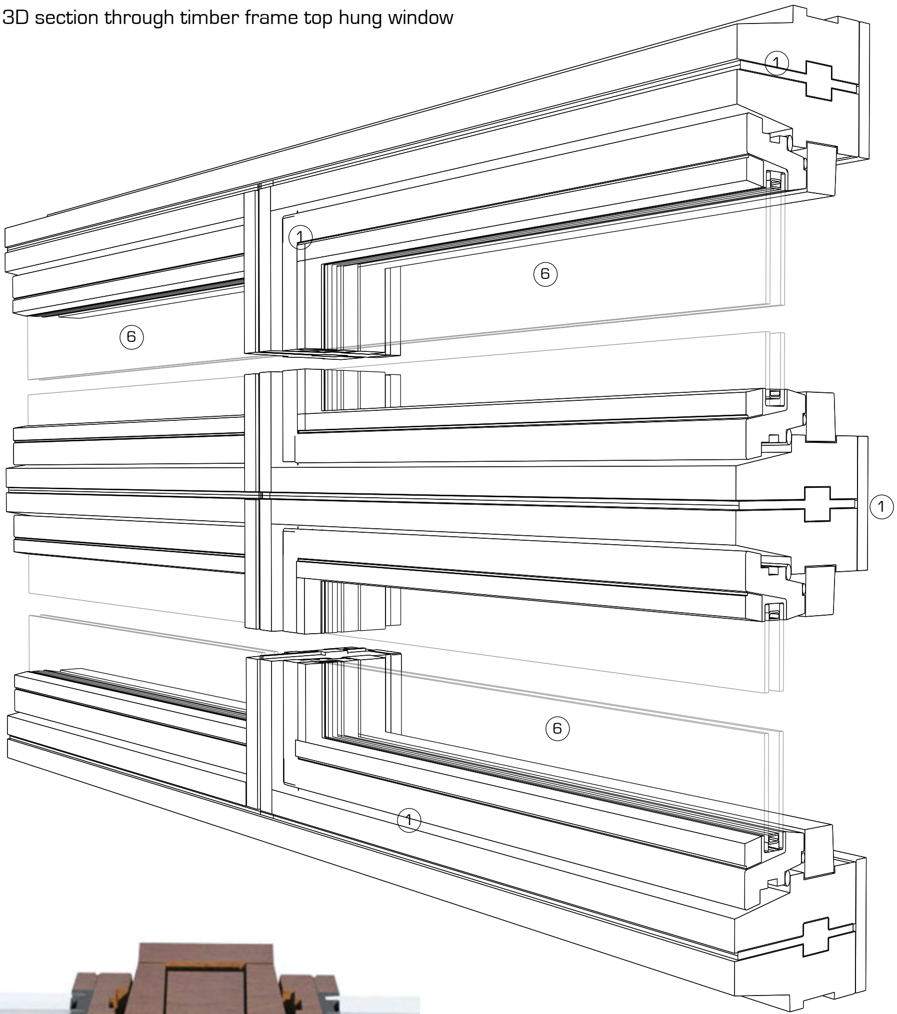
Walls 02

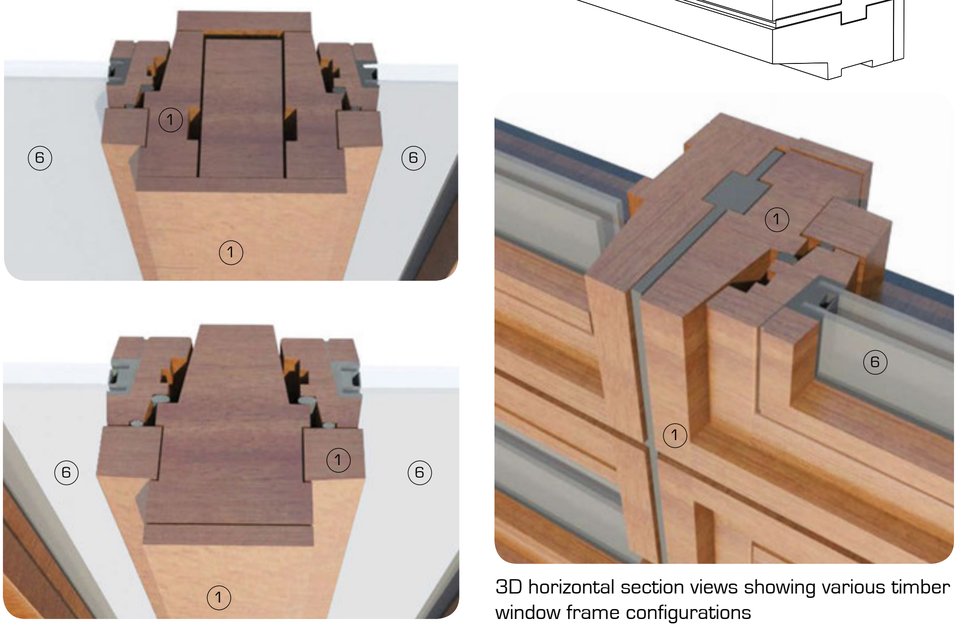
Glass systems 8: timber windows



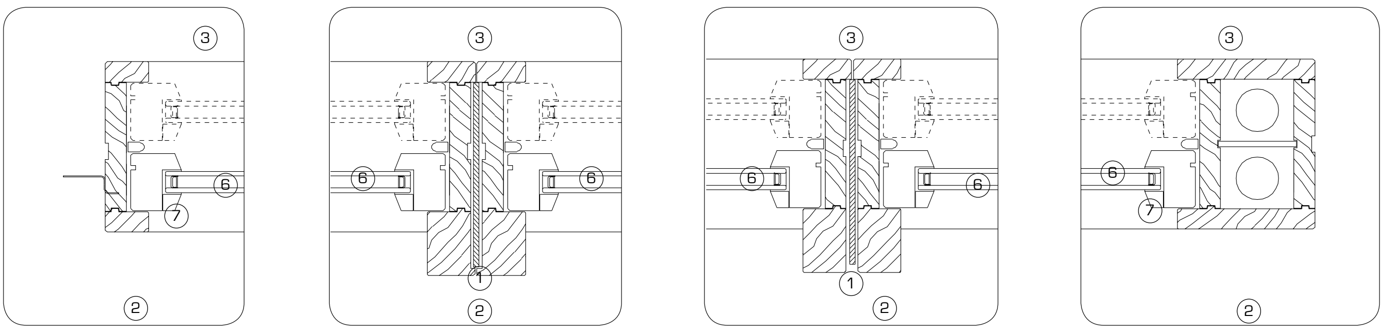
Vertical section 1:5. Vertical sliding sash window

3D section through timber frame top hung window

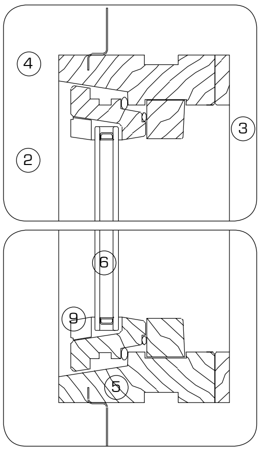




3D horizontal section views showing various timber window frame configurations

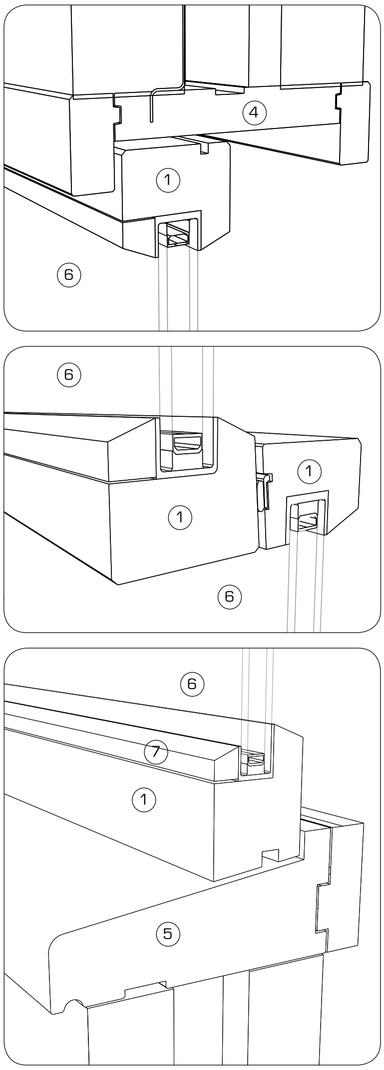


Horizontal section 1:5. Sliding sash windows



Vertical section 1:5. Top hung windows

3D view showing timber window within masonry wall construction



(Far Right) 3D detail views showing timber window within masonry wall construction at head, window and cill junctions

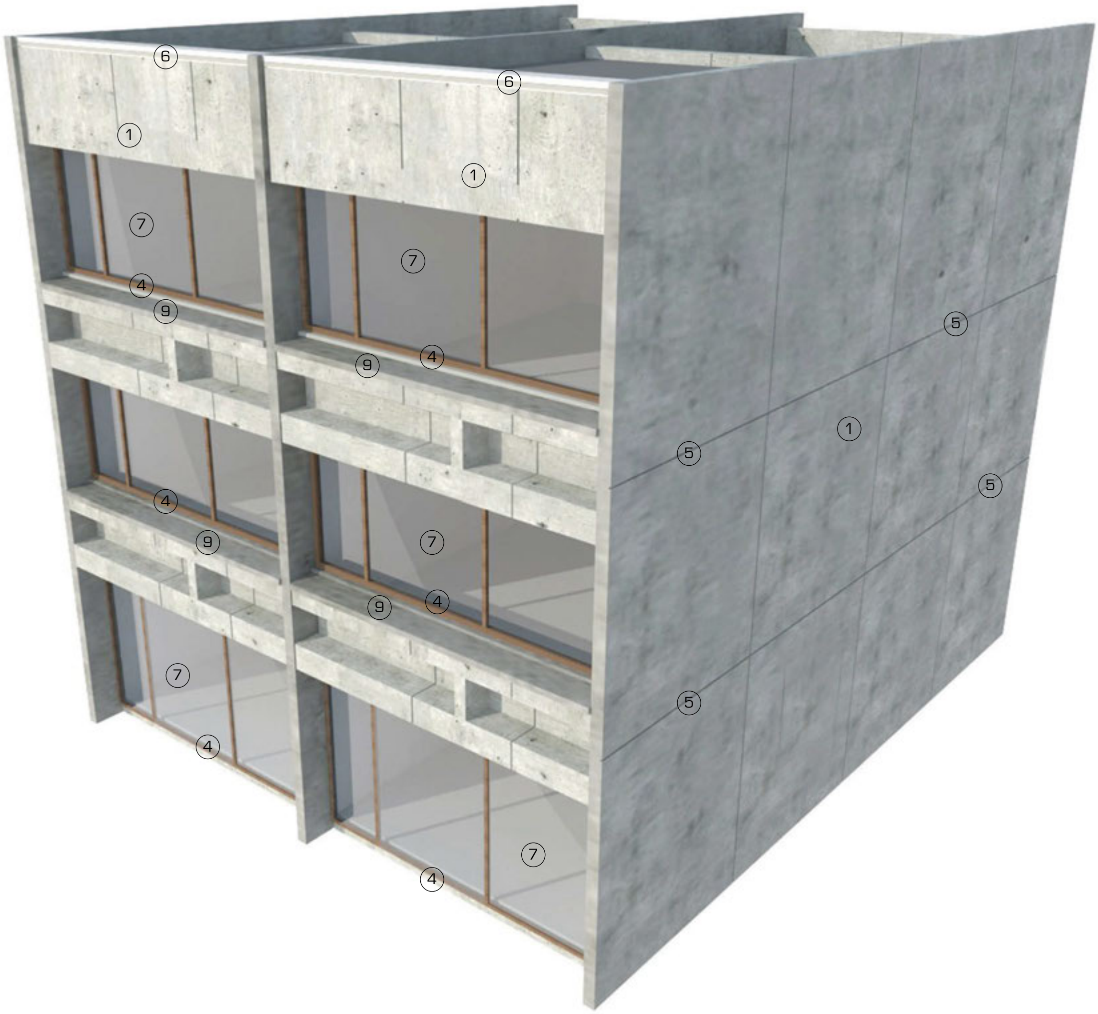
Details
1. Window frame
2. Outside
3. Inside
4. Head
5. Cill
6. Single glazed or double glazed unit to suit application
7. Fixing bead
8. Rubber-based seal
9. Surrounding wall
10. Thermal insulation

System details

Inward opening windows are inherently vulnerable to water penetration at the bottom of the frame, while outward opening frames are weaker at the head of the frame. For this reason, drainage channels are provided within the frames, together with weather seals and weather bars. Like aluminium windows, timber windows use a single section for all four sides of an opening light, and a single section for three sides of the frame, with the cill being different to drain water away from the window. Timber windows can achieve relatively low levels of air infiltration and have vastly improved in their weather performance in recent years, primarily as a result of the use of synthetic rubber seals and aluminium weather bars. Weather tightness has been enhanced by the use of pressure equalised rebates in the window section so that any water passing through its outer seal is drained away without being drawn through by capillary action as a result of an air pressure difference between inside and outside the framing. The inner synthetic rubber seal also serves as an acoustic barrier, providing improved sound insulation. Seals between the window and the opening have been enhanced in recent years with the increased use of folded aluminium and UPVC profiles which are set into a groove around the window during manufacture and are sealed against the surrounding wall. There has been an increased control of moisture movement of the timber used with better controlled kiln-drying. Treatments to timbers are also changing to avoid toxic runoff while providing some protection against colour fading from UV radiation from sunlight. Some more economic timber windows have traditionally suffered from poor jointing at the corners of the frame. These have been improved across all window types in recent years with the use of double mortise and tenon joints and wood glues with better resistance to heat and moisture. Where timber windows are set into an opening rather than being part of a window wall, the most common materials used are masonry block, brick or timber boarding. With all these materials, timber windows are fixed either into the reveals of the opening or are fixed into the face of the opening. The position of the window in the opening has more influence over the junction with the surrounding wall than the choice of material for the wall. In proprietary ranges of windows from manufacturers, a common frame design is used for different hinge arrangements in opening lights, which gives a harmonious appearance to window walls with lights that are required to open in different directions.

Timber glazed walls can be sealed against adjacent wall construction with metal flashings which can be formed either as an integral part of the window frame, or alternatively be fixed to it with synthetic rubber based seals mechanically fixed to the frame. Corners can be formed with either a timber post forming the corner or as a fully glazed junction. Where transoms meet at a corner without the benefit of a mullion (vertical) the junction is usually joined with a toothed junction to ensure that no visible movement occurs. The full interlocking connection between components in these exposed conditions is vital to the success of timber glazed walls.

3D view of concrete cast-in-place panels in structure



Details
1. Concrete external wall
2. Concrete internal wall
3. Metal lining to gutter
4. Window frame
5. Slot formed as part of casting concrete.
6. Metal parapet flashing
7. Single glazed or double glazed unit to suit application
8. Metal cill, though precast concrete could be used
9. Internal floor slab
10. Single concrete wall
11. Thermal insulation
12. Internal finish

System design

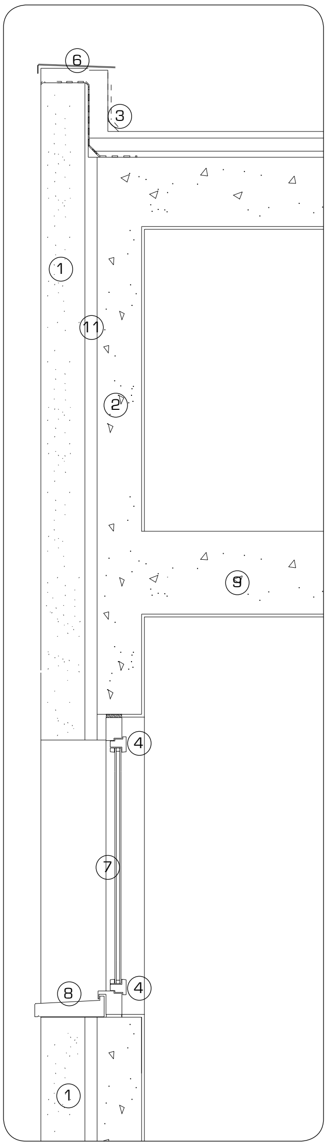
The method of forming concrete by pouring it into a shape created by formwork makes its construction quite different to working with other materials. While metal, glass, timber and masonry are made in relatively small panel and unit sizes, concrete is restricted only by the available formwork and the amount that can be poured at one time. The use of in-situ loadbearing concrete walls as a facade system exposes the cast concrete as a surface finish. This is in contrast to the use of in-situ loadbearing walls as backing walls to a different facade system, where the function of the wall is only as primary structure, while the external skin is non-loadbearing cladding. The use of in-situ reinforced concrete as a self-finish to external walls was popular in avant-garde architecture throughout most of the 20th century, but walls were constructed without thermal insulation within the wall depth. Instead, insulation was eventually added on the inside face of the wall, which both prevents the thermal mass of the concrete wall from being used to regulate the air temperature within the building as well as prevent the concrete surface from being seen inside the building. An important development in recent years has been an increase in the provision of thermal insulation set typically within the depth of the construction, allowing the external face to have a visible concrete finish.

Setting thermal insulation within the wall allows the thermal mass of the concrete to contribute to night-time cooling as part of an environmental design strategy. Continuity of thermal insulation at the interface of concrete and glazed openings is increasingly important in order to avoid thermal bridging. In this method of construction, diaphragm walls are used with two walls linked structurally being set either side of a rigid thermal insulation core. This allows part of the concrete structure to remain closer to the internal temperature of the building, and benefiting from the thermal mass of the primary structure as well as permitting the internal face of the building to have a visible concrete finish. In diaphragm wall construction, the two linked concrete walls are joined structurally by concrete ribs which form limited thermal bridges, or alternatively are linked by stainless steel ties. The use of metal ties reduces the thermal bridging with its associated risk of condensation and pattern staining forming on the inside of the wall in temperate climates.

An alternative method of constructing an in-situ cast concrete wall is to set the thermal insulation on the inside face of the wall, but this results in the loss of the wall's thermal mass. This method has the benefit of economy, especially where there is no requirement for night-time cooling.

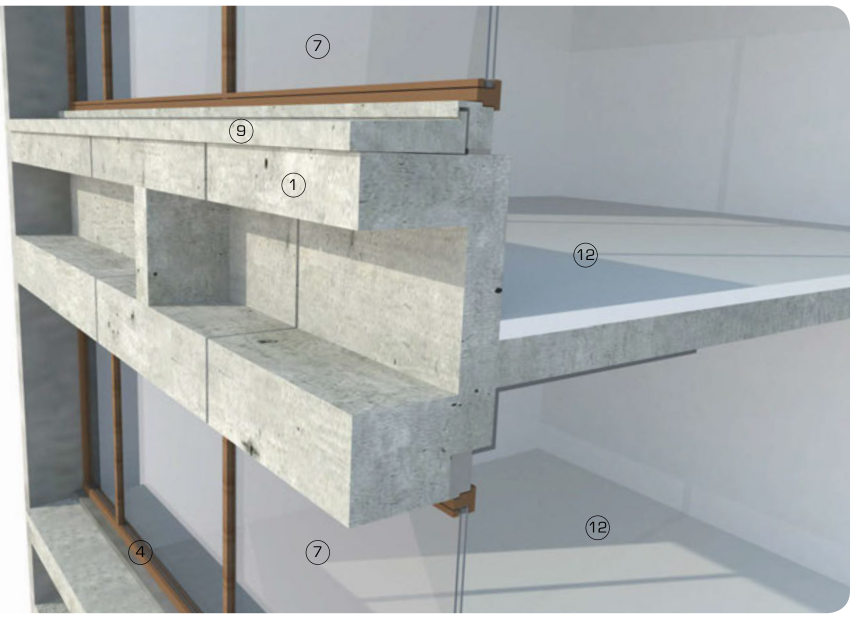
System details

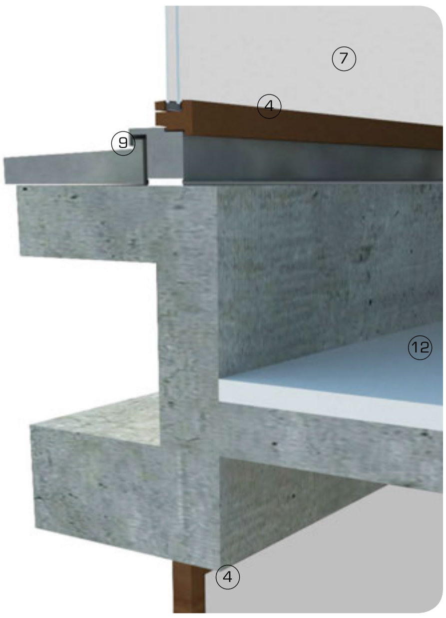
Dust particles that settle on horizontal or slightly sloping surfaces such as window cills are washed off during rain and can be deposited on the wall below. Consequently, openings, parapets and cills in exposed concrete walls have projecting cills and flashings to ensure that rainwater is thrown as clear as possible from the external wall surface. In urban conditions,



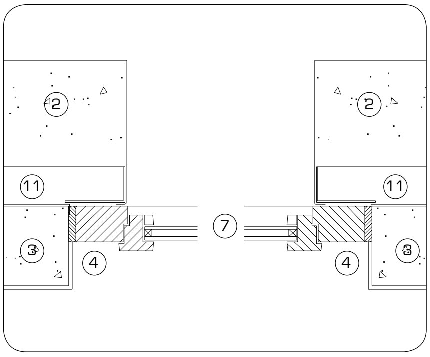
Section 1:25. In-situ cast concrete wall cast in two skins with rigid closed cell insulation between skins

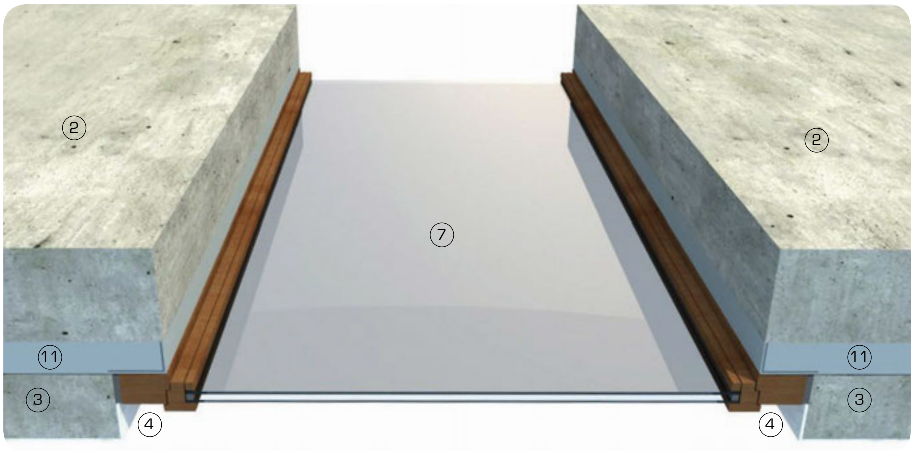
3D view showing roof parapet and window details within cast in-situ concrete wall system



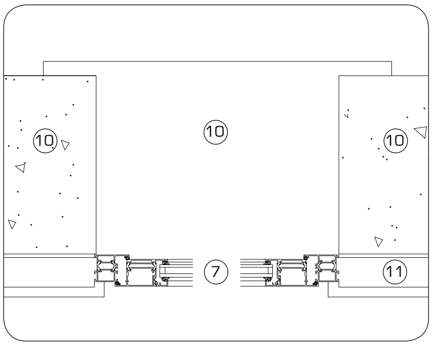


3D sectional view showing window opening in in-situ cast concrete wall and floor slab interface





Horizontal section 1:10 and 3D view. In-situ cast concrete wall with internal insulation at window opening



Horizontal section 1:10 and 3D view. In-situ cast concrete wall with external insulation at window opening

dust-catching surface textures are usually avoided and smooth finishes are often preferred. However, where protective treatments are applied to the external surface of the concrete to reduce porosity, this can give a reflectivity to the material that reduces its characteristic stone-like appearance.

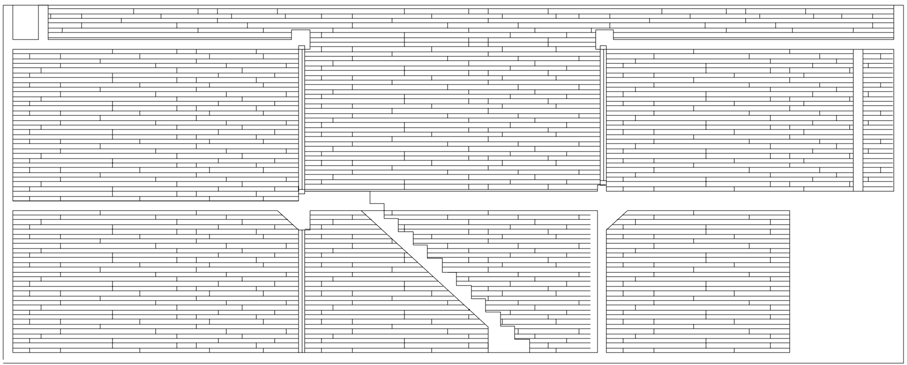
Drips in the form of continuous grooves are cast into the tops of window reveals to reduce both staining to the soffit and to reduce the amount of water reaching the windows. Cills are usually formed with a metal sheet apron that helps throw water clear of the wall below, while metal copings are usually inclined in order to drain water onto the roof or gutter behind rather than down the face of the concrete wall.

The colour of concrete for in-situ loadbearing concrete walls is influenced mainly by the choice of cement, with fair faced visible concrete walls using either grey or white cement bases to produce the surface colours associated with each. The physical properties of these two cement types are very similar, with grey being associated with architectural concrete finishes which usually provide a consistent appearance, when pouring methods and conditions remain consistent during construction of the facade. The tone of grey will vary with the cement/water ratio, the porosity of the shuttering, vibration conditions, formwork stripping time and weather conditions. White cement is much more tolerant of variations in methods and site conditions in providing a consistent white colour.

The most common finishes for concrete walls cast in-situ are either an as-cast finish or a washed finish. Other finishes are discussed in the section on precast panels: acid etching, sand blasting, tooling and polishing, though these additional finishes can be used on in-situ cast concrete. With as-cast finishes, the colour variations result not usually from the cement colour, but rather from the marbling effect of fine particles of sand, becoming unevenly distributed during vibration when the concrete is poured in place. Smooth concrete is typically self-coloured in large areas of facade to avoid colour variations associated with pigment additives. Smooth and visually consistent natural finishes are achieved largely by both the accuracy of mixed proportions including water.

Textured finishes can be achieved with specially formed shuttering boards or with an additional lining sheet containing the texture pattern. Polystyrene (one time use) or synthetic rubber sheet (multiple use) are commonly used. Recessed joints are usually introduced between the formwork boards to avoid uneven and blurred lines at the junction between boards. Washed finishes are formed by applying a deactivator to the external face of the concrete, either to the face of the formwork before casting or to the concrete surface when the formwork has been removed. The deactivator is used to slow down or stop hydration of the cement, and is applied by brush or spray. The concrete is then sprayed with water or aqueous acid solution to remove the surface, revealing the material below.

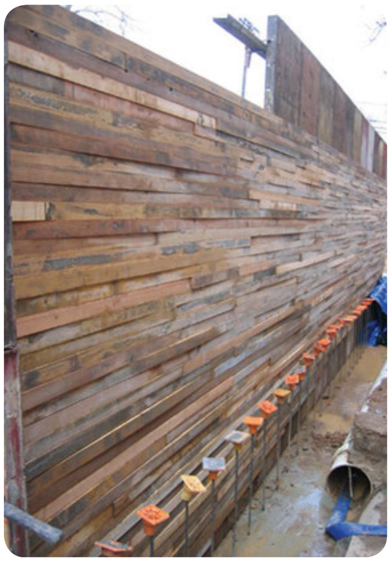
Photos illustrating texture that can be achieved through in-situ casting



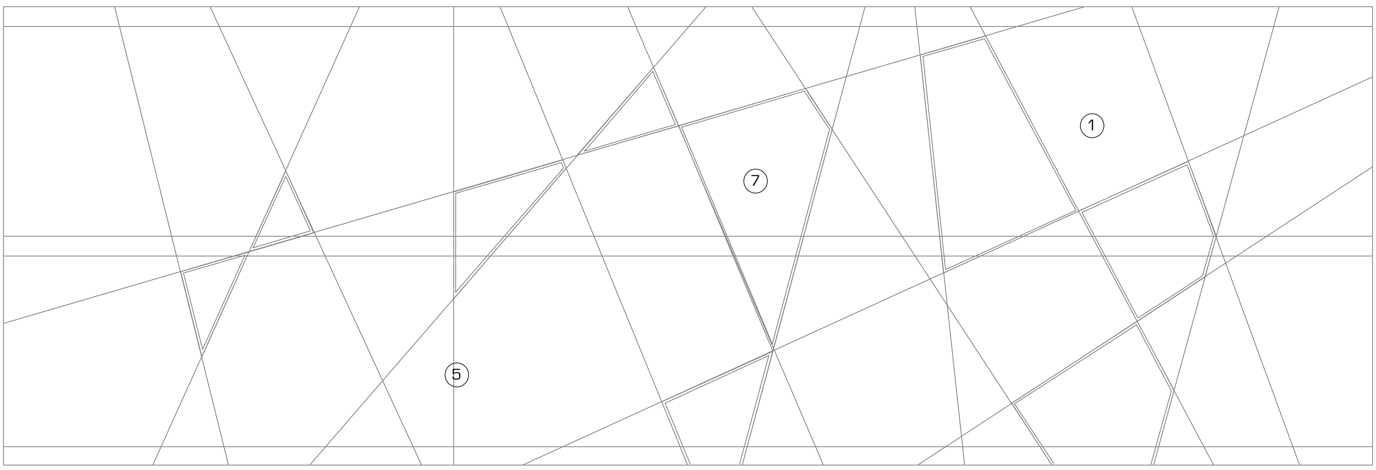
Internal wall elevation 1:50 In-situ cast concrete wall with textured effect as above right

Details
1. Concrete external wall
2. Concrete internal wall
3. Metal lining to gutter
4. Window frame
5. Slot formed as part of casting concrete.
6. Metal parapet flashing
7. Single glazed or double glazed unit to suit application
8. Metal cill, though precast concrete could be used
9. Internal floor slab
10. Single concrete wall
11. Thermal insulation

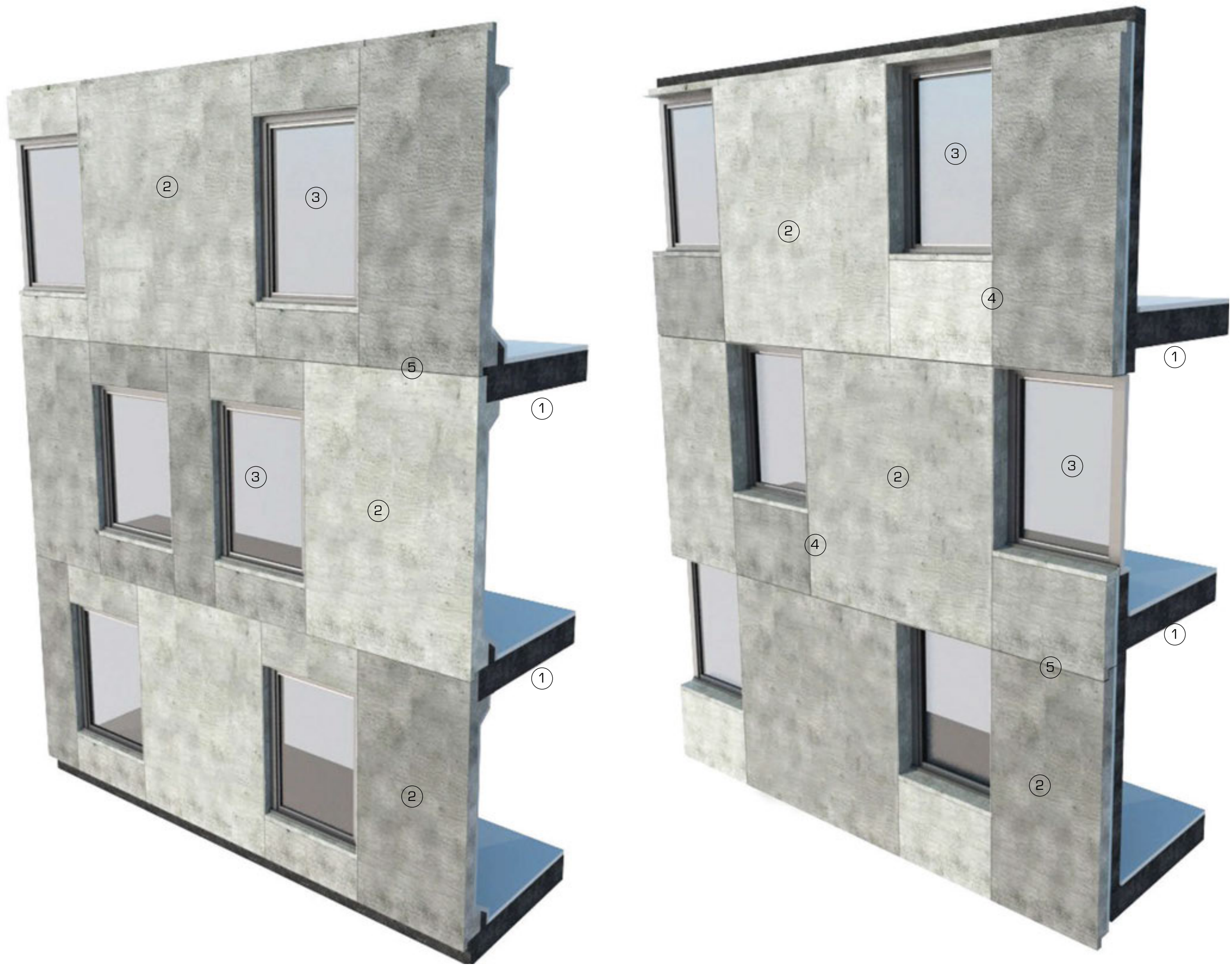
Timber/aluminium formwork on upper floors of building construction



Timber formwork used to achieve texture



Elevation 1:50 In-situ cast concrete wall showing how formwork can be arranged and cut to form different shaped panels and window openings



3D view showing typical storey-height panel wall assembly with windows, in various panel configurations

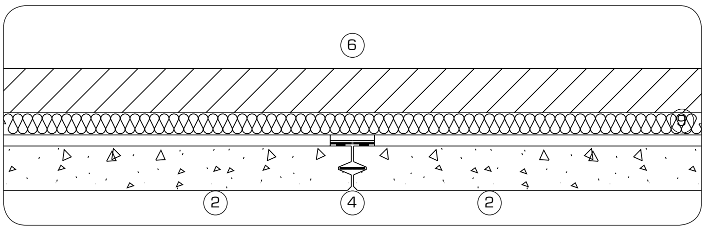
System design

The method of casting in-situ walls described in the previous section is one of forming loadbearing construction. With precast panels, walls can be formed as either loadbearing walls or as cladding panels to a structural frame. Loadbearing types have storey height panels 'stitched' together to become integral with the floor slabs. Junctions are usually pin jointed, with structural stability provided by other components such as service cores elsewhere in the building. Precast panels may have a decorative finish on one side, with thermal insulation set within the panel, or may be used as a backing wall to another facade system such as a rainscreen set forward of the panel, where thermal insulation is set on the outer face of the precast panel. In addition to setting panels full height from floor to floor, loadbearing panels can also be set horizontally to form structural beams between precast columns, typically around 1200mm high to provide spandrel panels. This allows full length glazing to be used, set between the top of the panel and the bottom of the panel above, rather than glazing individual openings associated with full-height precast panels. Non-loadbearing precast cladding panels typically span from floor to floor, with panels supported either directly on the floor slabs or set forward of them, fixed back to the floor structure with brackets made typically from stainless steel or reinforced concrete. The method of fixing panels is very dependent on both spatial requirements within the building and whether concrete nibs can remain a visible part of the panel design or are required to be concealed within the internal finishes. Storey-height panels can have either thicker edges, to form an integral 'frame' to the panels, or be completely flat, but the later will usually be thicker, and consequently heavier. The 'framed' version has a visual language of framing which can be visible from either the outside or the inside.

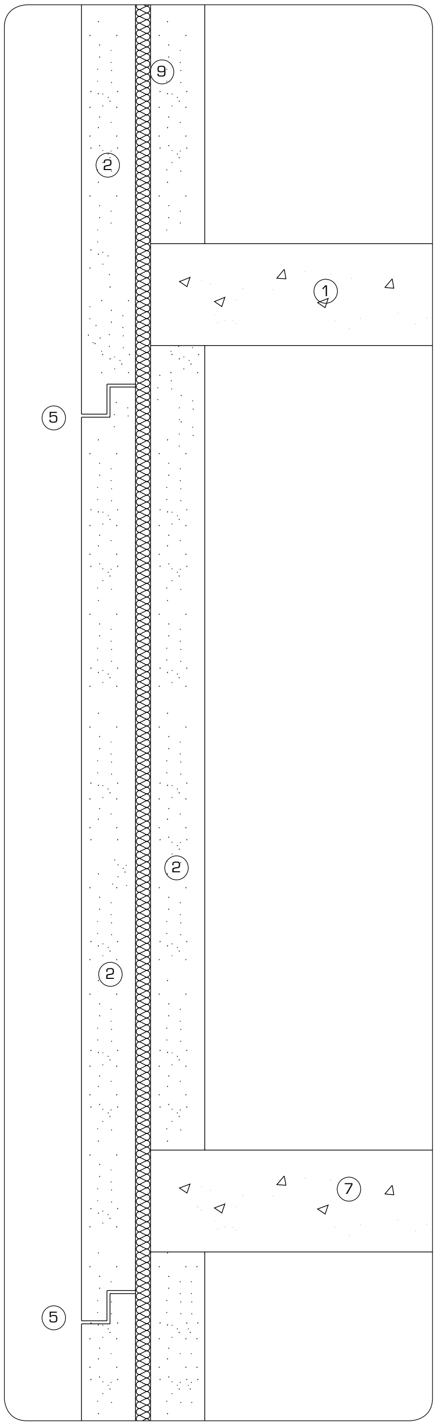
Due to their self weight, panels are usually supported at their base at the floor slab and are restrained at the top of the panel with mechanical fixings. Panels are usually a maximum of around 3600mm wide to suit road transportation, with a maximum weight of around 10 tonnes to suit regular site cranes. As with in-situ cast concrete walls, the thermal insulation can be set either on the inside face of the panels or within a diaphragm wall construction. Panels are manufactured in flat moulds, with the finished face at the bottom of the mould when the concrete finish is required to be visible, or with the finished face on the top of the mould where another material is applied such as ceramic tiles, or where metal fixings for a masonry finish are cast into the face of the panel. Where a concrete finish is formed in the bottom of the panel, textured finishes are formed within the mould, usually by a synthetic rubber mat or polystyrene. The

Details
1. Concrete floor deck
2. Precast concrete panel
3. Window
4. Vertical joint (typically a baffle) between panels
5. Horizontal joint (typically a lap) between panels
6. Drywall/dry lining
7. Steel dowel
8. Concrete coping
9. Thermal Insulation
10. Roof construction

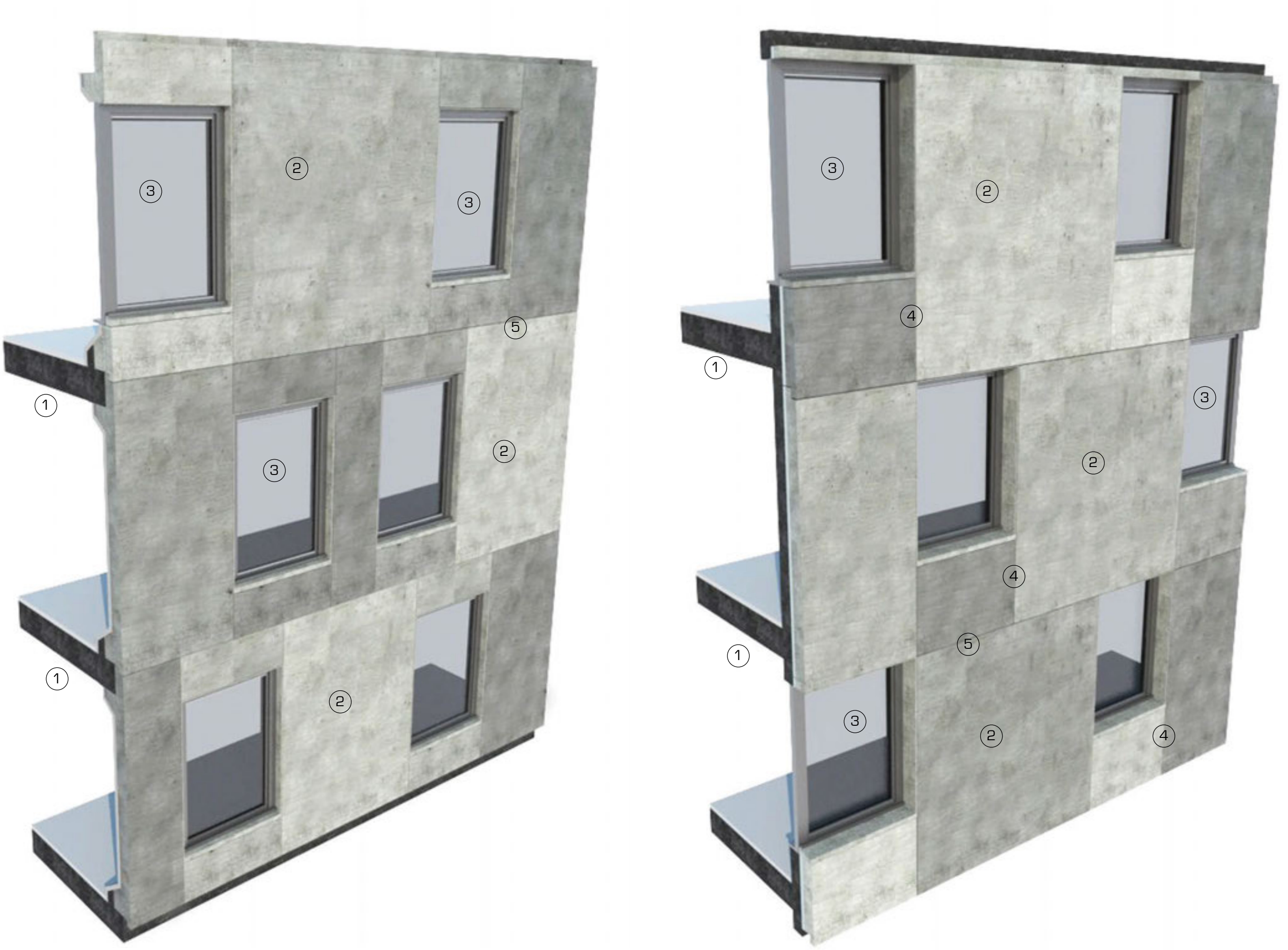
3D detail view showing storey-height concrete panels at window and floor interface



Horizontal section 1:25. Typical wall construction



Vertical section 1:25. Typical wall construction



3D view showing typical storey-height panel wall assembly with windows, in various panel configurations

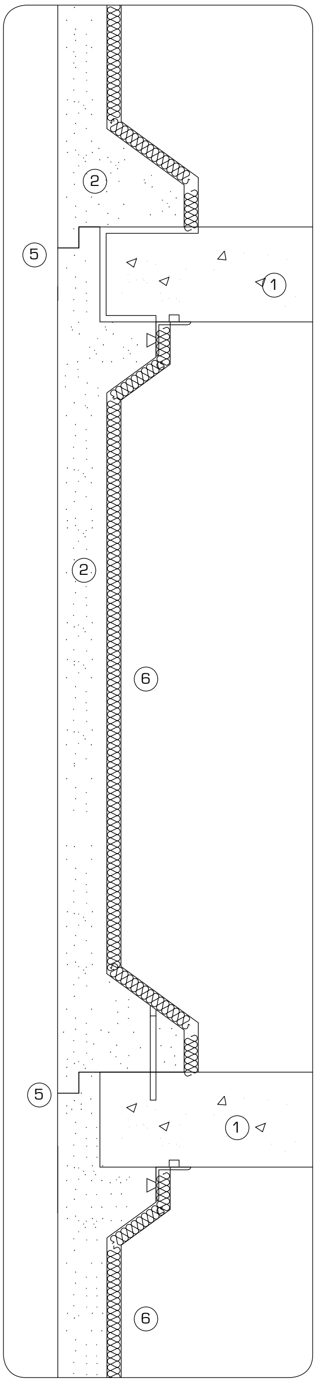
shape of the panel is adjusted to suit the ease of removing the mould when the concrete has been poured in place, but most panels can achieve sharp lines that do not have an obviously 'moulded' appearance.

System details

Joints between panels are similar for both loadbearing and cladding panel types, with a common use of either 'open' or 'closed' joints. Open joints have an outer open joint that is narrow but admits small amounts of rainwater, which is drained down an inner chamber and released back to the outside at the base of the panel through a stepped horizontal joint. This internally drained and pressure equalised system is similar in concept to that used in unitised curtain walling. In closed joints the outer face is sealed with a wet applied silicone or polysulphide sealant in a similar way to the sealing of joints between bolt fixed glazed panels. Joint widths both vertically and horizontally for both open and closed joints vary from 10-25mm increasing with panel width up to a maximum of around 6000mm. The inner chamber between panels in vertical open joints is closed with a synthetic rubber strip which provides a primary seal. The interior face of both vertical and horizontal joints is closed with an air seal formed with either an extruded synthetic rubber gasket or a wet-applied sealant. Loadbearing panels are sealed with a cement-based grout. Closed joints are mostly used in loadbearing panel construction where panels are joined together with mechanical fixings. Panel fixings are positioned near the corners, with slotted fixings used in order to allow for both thermal movement between the panel and supporting structure and for adjustment during construction. The cleats are typically fixed to a small channel fixing cast into the concrete. Panels are lifted into place on site by crane, using hooks that are screwed into threaded tubes set into the concrete typically on top or on the back face of the panel. The hooks are unscrewed when the panel is in place, and the holes plugged.

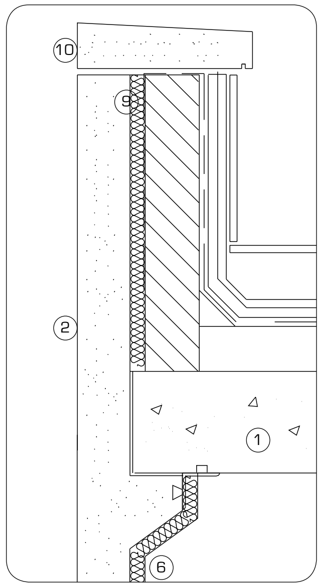
The most common finishes in precast panels are acid etching, polishing, sand blasting and tooling. The last two techniques are discussed in the next section on small precast panels but can be applied equally here. Polished finishes are formed by an abrasive grinding wheel lubricated with water that removes up to 2mm of the material with a single pass of the grinder to a honed or fully polished finish. This exposes the colour of the aggregate but the surface does not shine naturally. Varnishes can be applied to achieve this stone-like appearance. Acid etched finishes are well suited to precast panels since the amount of acid applied can be more carefully controlled in the factory than can be achieved on site. The outer face of the panel is treated with hydrochloric acid to reveal the concrete texture beneath, which is then rinsed off, having the effect of revealing the concrete texture immediately beneath. Acid etching attacks limestone aggregates, and sometimes more quickly than it does the cement, while silica-based aggregate remains. The surface texture achieved varies with the fine aggregate used, being more granulated in the case of silica and less coloured in the case of limestone.

Details
1. Concrete floor deck
2. Precast concrete panel
3. Window
4. Vertical joint (typically a baffle) between panels
5. Horizontal joint (typically a lap) between panels
6. Drywall/dry lining
7. Steel dowel
8. Concrete coping
9. Thermal Insulation
10. Roof construction

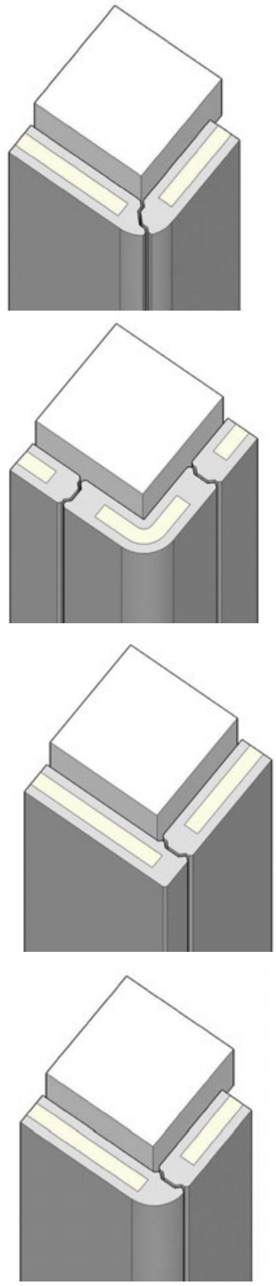


Vertical section 1:25. Typical details

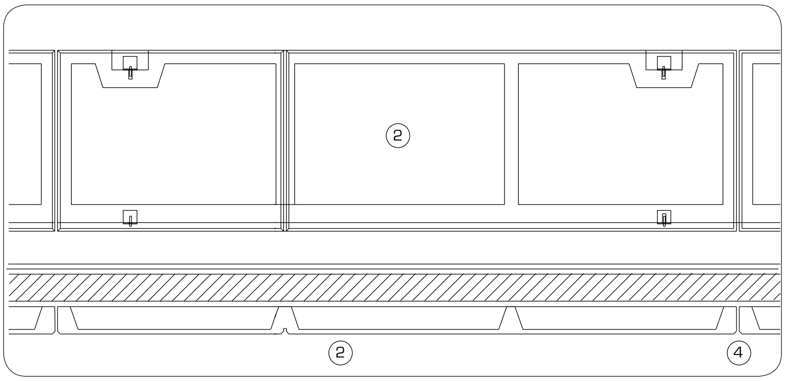
3D detail view showing typical wall assembly



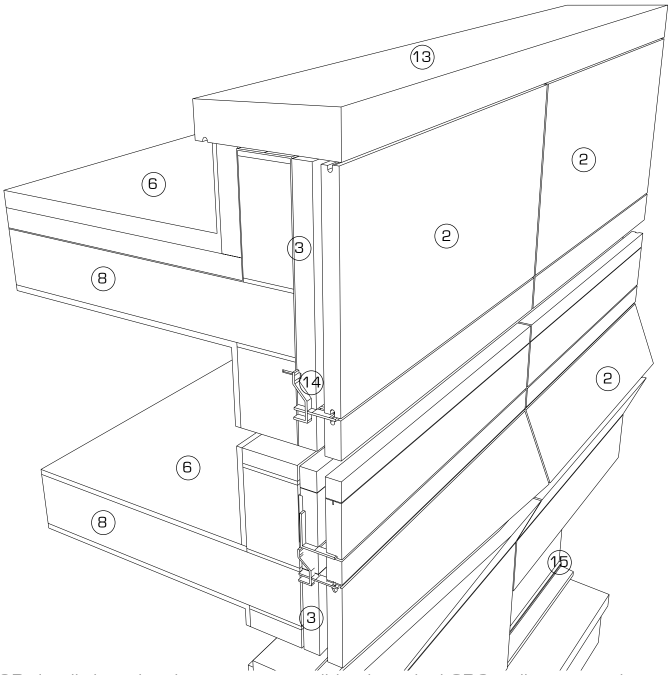
Vertical section 1:25. Parapet detail



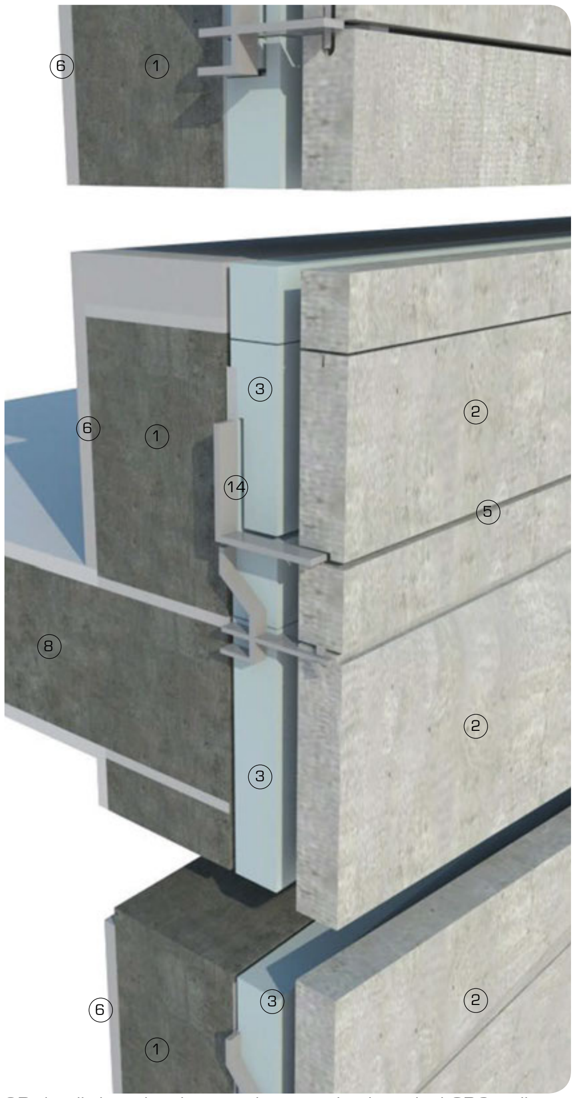
3D detail views showing various corner details



Horizontal section 1:25. Glass reinforced concrete (GRC) panels with open joints



3D detail view showing parapet condition in typical GRC wall construction



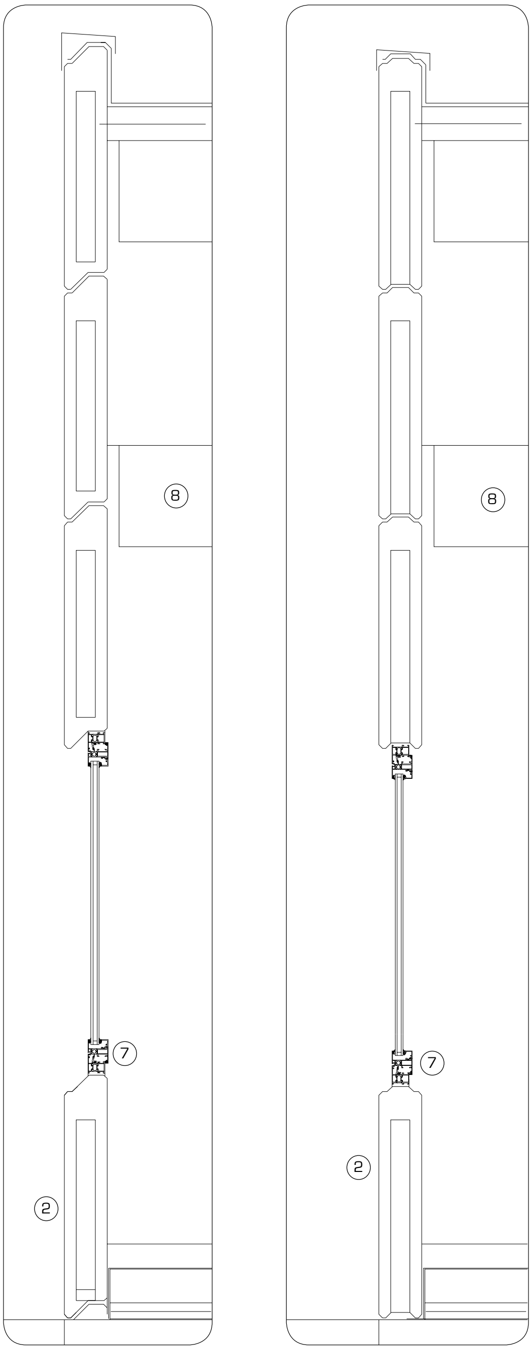
3D detail view showing panel connection in typical GRC wall construction

System design

Small precast concrete panels have a greater sense of visual variety possible with a reduced unit size than large panels. While storey height panels suit larger scale projects, smaller self-supporting and interlocking panels can be stacked together in the manner of composite metal panels. Panels have an inner core of thermal insulation with a finished concrete face on each visible side of the panel. Alternatively, individually supported rainscreen panels use the visual language of stone or metal cassette facades to a backing wall in a different material. Small precast rainscreen panels are fixed to a backing wall either directly with individual fixing brackets or onto an aluminium or stainless steel carrier frame, with open joints that follow the rainscreen principle.

Panels can also be made as self supporting walls supported at their base. These panels are shaped so as to ensure they interlock to provide a stable form of construction. Panels can be stacked to a single storey height of around 10 metres, with lateral restraint provided by the structural frame, and at every floor level in buildings with more than one storey. Panels at ground floor level are set on a beam edge to a concrete floor slab or structural beam. Panels are stacked with continuous vertical joints and are restrained by columns. The need to restrain panels on their vertical joints results in interlocking panels being long in order to optimise the distance between structural columns, avoiding intermediary posts that would be required to provide lateral restraint. In terms of weight, the long panels compensate by being low in height in order to ensure their weight can be lifted by a site crane, typically with a lifting capacity of 4 to 6 tonnes. Since the stacked, interlocking panels have concrete on all sides, both horizontal joints and vertical joints usually have a limited thermal bridge which can lead to pattern staining as a result of different rates of thermal transmittance in the material, in addition to the increased risk of condensation occurring on the internal face. The thermal bridge can be avoided by the use of metal connections between two skins of concrete in place of a fully encased concrete panel, but this makes it more difficult to stack panels and to maintain the economy of the system. Self-supporting stacked panels fabricated in thicknesses of 75 - 100mm can also form the outer skin of a complete cavity wall construction of 200 - 300mm thickness. The inner wall can vary widely in its construction from concrete block to light gauge metal stud wall with an outer waterproof facing. The cavity between concrete panels and backing wall is 50 - 75mm, ventilated at the top and bottom of the wall.

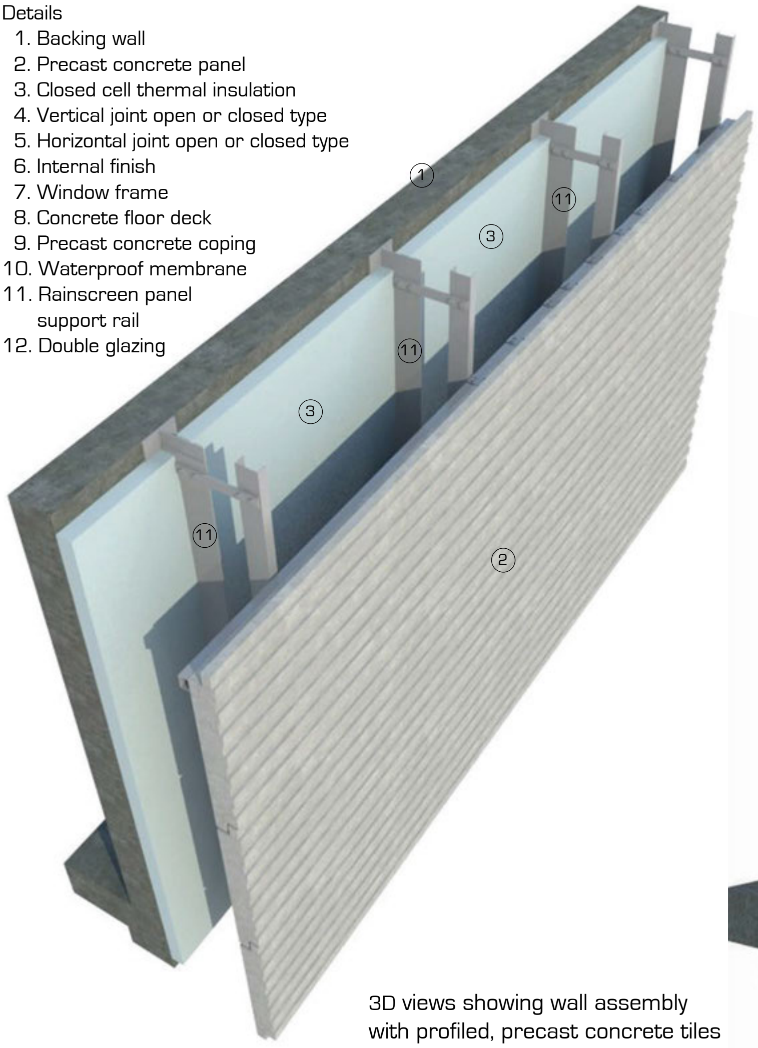
Small precast rainscreen panels can be formed with narrower joints than those possible in full height panels, together with the possibility of a non-rectilinear arrangement of joints. Fixing brackets are similar to those used for stone cladding, but are usually bigger to support the heavier panels. While stone panel



vertical sections 1:25. Typical precast concrete wall construction (Left) Panels with drained joint.
(Right) Panels with sealed joint

Details
1. Backing wall
2. Precast concrete panel
3. Closed cell thermal insulation
4. Vertical joint open or closed type
5. Horizontal joint open or closed type
6. Internal finish
7. Window frame
8. Concrete floor deck
9. Precast concrete coping
10. Steel angle
11. Rubber-based baffle
12. Waterproof membrane
13. Parapet
14. Metal bracket
15. Double glazing
16. Window cill

Details
1. Backing wall
2. Precast concrete panel
3. Closed cell thermal insulation
4. Vertical joint open or closed type
5. Horizontal joint open or closed type
6. Internal finish
7. Window frame
8. Concrete floor deck
9. Precast concrete coping
10. Waterproof membrane
11. Rainscreen panel support rail
12. Double glazing



3D views showing wall assembly with profiled, precast concrete tiles

sizes are typically around 1500mm x 750mm or 1500mm x 1000mm, depending on stone type, precast rainscreen panels can typically reach 1500mm x 3000mm. Panels are supported on stainless steel brackets which are fixed either to primary structure or to a carrier frame that is in turn fixed to primary structure. Slotted holes in the bracket provide adjustment vertically, horizontally and laterally. In common with stone cladding, individually supported concrete panels are supported on short lengths of stainless steel angle at each floor level in order to avoid the possibility of progressive collapse of cladding panels in the event of a single panel failing or slipping from its position. Fixings are designed so that they can support the full load of the panels immediately above it in the event of fixings to panels above failing either partially or completely.

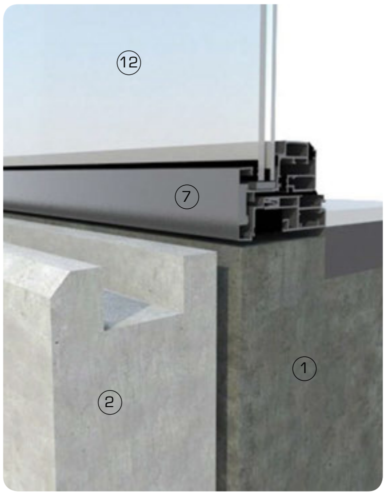
System details

Interfaces for individually supported panels are similar to those for stone cladding. An advantage of small precast panels is that interfaces of stacked panels with openings, parapets and cills are relatively straightforward. Windows are fitted into openings relatively easily, since the stepped profile at the base of the panel provides an integral cill profile to the opening. The concrete facing to all sides of the panel provides weathertight edges on the jambs and at the head of the opening. Windows are set in a position which suits the position of the thermal insulation in the precast panel, typically in the middle, but windows are positioned to provide continuity with the thermal insulation.

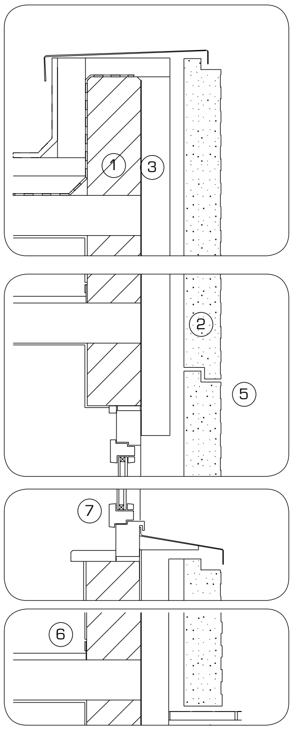
The closing of parapets is provided by a metal flashing that covers the top of the panel and the vertical face of the parapet wall that may be set behind the panels to close off the roof. The coping is sloped towards the roof to ensure that rainwater is drained onto it and not directed down the facade. A precast coping can also be used instead of metal, but an additional membrane is set under both metal or concrete copings to ensure a fully watertight seal. The base of walls is detailed in a similar way to other forms of loadbearing masonry. A continuous damp proof membrane (DPM) extends up from the outside of the structure beneath and forms a damp proof course (DPC) which is positioned so that it extends at least 150mm above external ground level, depending on climate conditions. The DPC is positioned so that the lowest row of panels at ground level appears to sit on the ground with its bottom edge either level, or slightly above the adjacent ground level or pavement. This avoids the need for a 150 - 200mm waterproofed plinth at the base of the wall.

Sandblasting and tooling are common on small cladding panels. Panels are sandblasted with iron filings rather than sand particles, with the blasting slightly eroding the face of the concrete, either back to the surface or more deeply to the coarse aggregate beneath, resulting in a matt finish. Tooled concrete is a method of texturing concrete with chisels or picks to make grooves or continuous textures. The textures usually stop short of corners of walls to give a crisp edge.

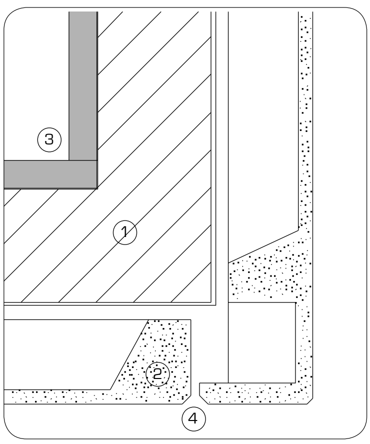
3D detail view showing typical wall assembly for GRC panels with open joints and window



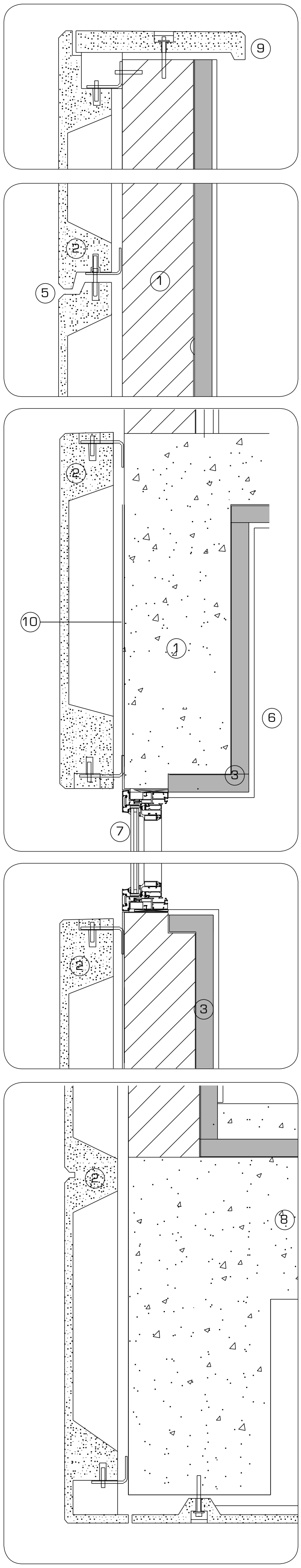
3D detail view showing window opening in typical GRC panel wall system



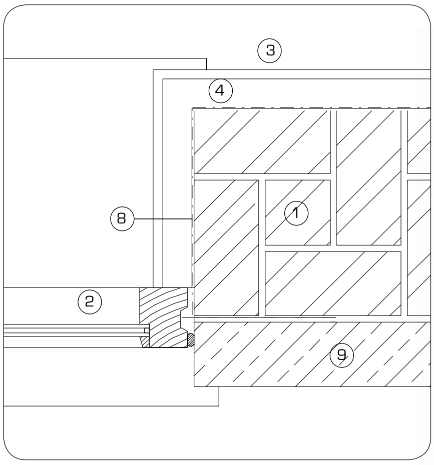
Vertical section 1:10. Junction at window jamb and at parapet



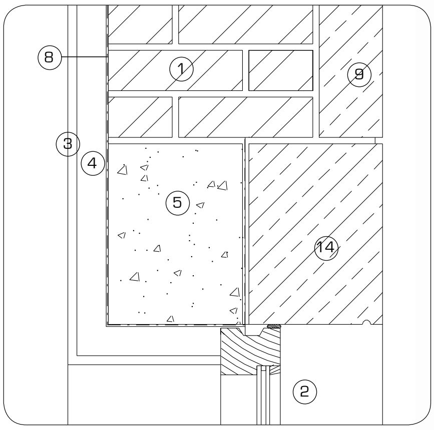
Horizontal section 1:10. Corner GRC panel with open joint



Vertical section 1:10. Panel soffit and window junctions of GRC panels with open joints



Horizontal section 1:10. Window jambs in brick loadbearing wall with stone facing blocks



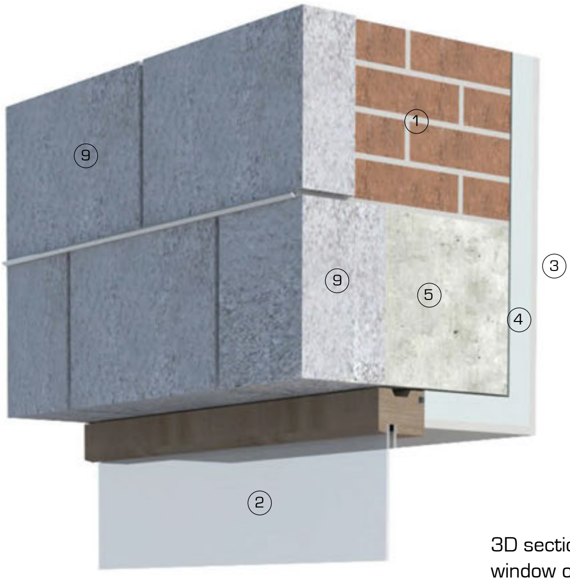
Vertical section 1:10. Window jambs in brick loadbearing wall with stone facing blocks

3D sectional view through loadbearing wall with stone facing blocks

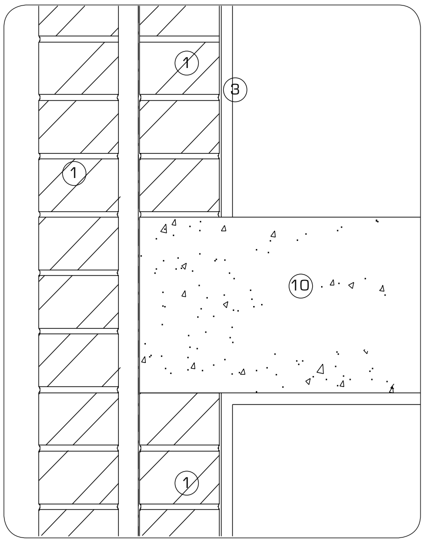
System design

Loadbearing masonry walls are used mainly in small scale construction, but in recent years there has been a revival in their use for larger scale buildings as an alternative to the language of cavity wall construction. Walls are most commonly made from brick or concrete block. In continental Europe, terracotta blocks are more common, but are usually rendered on their external face, both to enhance their appearance and for its traditional role as a weathertight outer layer. Concrete blocks are similarly protected by render. Only brickwork is fully exposed, relying on the depth of wall to avoid the ingress of rainwater.

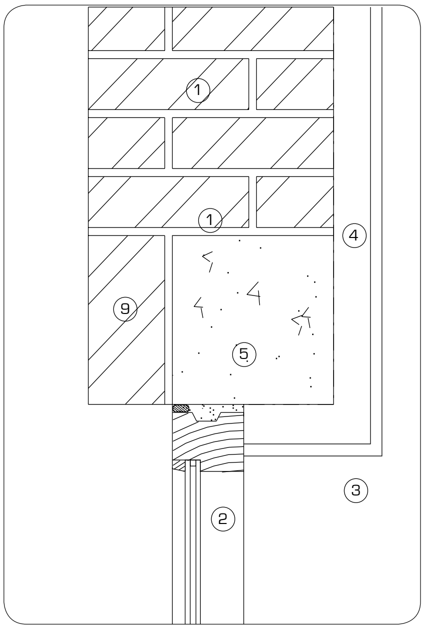
In brick construction, it is assumed that a 315mm thick wall (1½ bricks) is the minimum depth sufficient to resist rainwater penetration in temperate climates. This is dependent upon brick density and manufacturing dimensions. With brick, thermal insulation is set on the inside face to allow the material to be visible on the outside, but with concrete block, the insulation can be set on the outside with an external layer of render to provide the weatherproof skin. An alternative solution is to set thermal insulation within the wall, creating a loadbearing diaphragm wall where the brick or block can be seen on both sides of the wall, and also allows the internal face of the wall to be used for night time cooling within the building. Two skins of brick, typically 215mm to 315mm thick, are set apart, joined by fin walls set perpendicular to the main walls. Concrete block walls are made from skins 200mm to 300mm thick. The position of the insulation within the walls, or on the internal face of the wall, allows a straightforward continuity with the thermal insulation provided by windows within openings. An essential benefit of using loadbearing masonry walls is their ability to avoid movement joints through the use of lime mortar. This traditional material has lower strength than mortars used in contemporary cavity wall construction but has greater flexibility, allowing it to move more freely without cracking. This reduces, or can even avoid the need for, movement joints which are introduced to avoid cracking in masonry walls. Movement joints in walls where cement-based mortars are used are set typically at 6.0–8.0 metres depending on the required strength and size of wall. In lime mortars the strength of mortars is varied by altering the proportion of cement and lime which are used to bind the mortar together. Increasing the proportion of cement will increase its strength, while increasing that of lime increases its flexibility, with mortar mixes having different proportions of strength and flexibility. In addition, the comparatively low water permeability of lime gives it greater resistance to rain penetration than mortar mixes with a high proportion of cement. Lime has the effect of making mortars increasingly

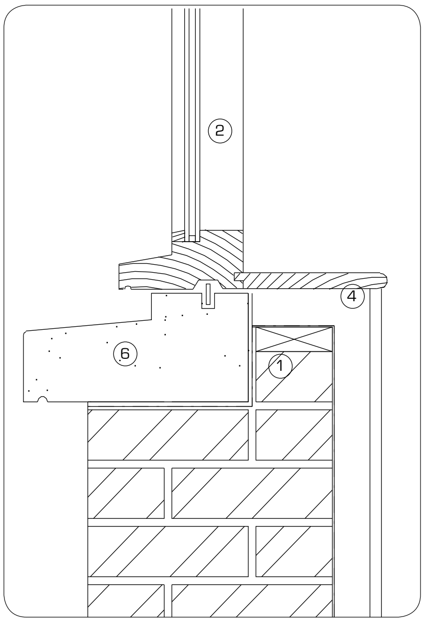


3D section view showing window opening and connection to ground in typical brick loadbearing wall assembly



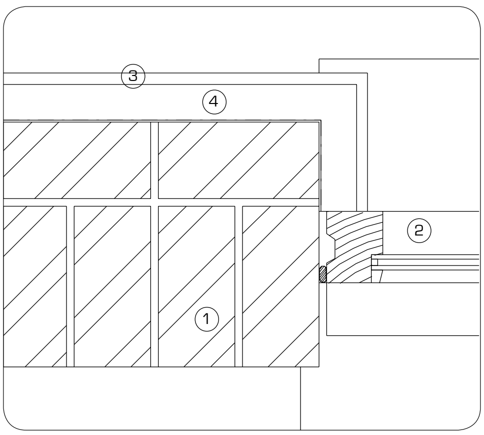
Vertical section 1:10. Floor connection in brick loadbearing wall





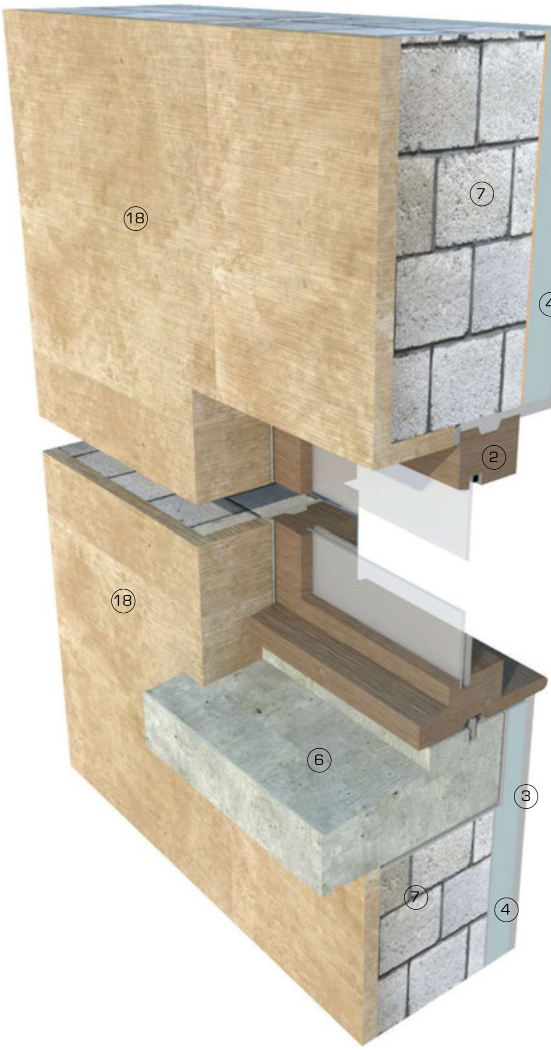
Details

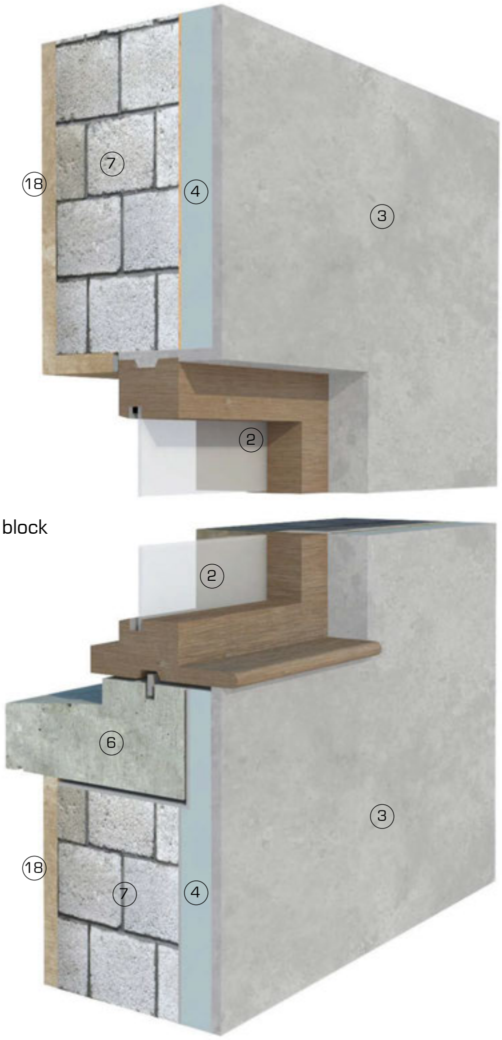
1. Loadbearing brick wall
2. Timber framed window
3. Internal plaster finish or dry lining/drywall
4. Thermal insulation
5. Precast concrete lintel
6. Precast concrete cill
7. Concrete loadbearing blocks
8. Damp proof course (DPC)
9. Stone facing blocks
10. Floor slab
11. Floor construction
12. Hollow bricks
13. Roof construction
14. Stone lintel/arch
15. Stone cill
16. Parapet
17. Loadbearing concrete block wall
18. External finish
19. Ground



Horizontal section 1:10. Window jamb connection in loadbearing brick wall

Vertical section 1:10. Window opening in loadbearing brick wall





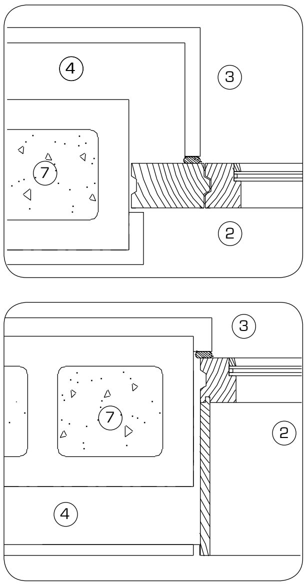
3D views showing window opening in typical concrete block wall, with insulation applied interior of wall system

light in colour with its increased proportion in the mix. However, mortar colour can be modified by adding pigments to the mix. Where stone is used on the outer face of the loadbearing wall, typically facing a brick wall behind, the mortar has crushed stone added in place of sand in order to give mortar its texture and some of the texture of the stone itself.

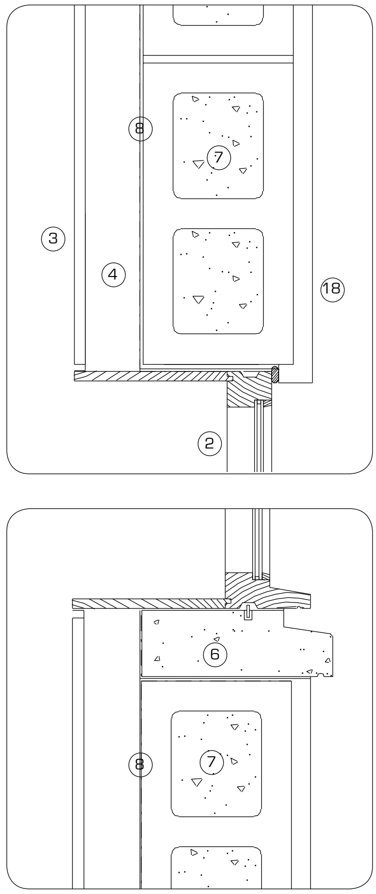
System details

An essential aspect of loadbearing masonry walls is the need for the structural requirements of walls to take precedence in the ways openings are formed, particularly where the wall supports both itself and other elements such as floors and roof. For example, the use of flat arches to window openings that form the equivalent of lintels to support the wall above result in the structural requirements being the dominating criterion in bringing components together. There are visual benefits, such as openings in loadbearing masonry walls having the ability to reveal the thickness of the wall to give it a massive appearance. Cills to openings are formed from either the same material if stone is used for the wall or, more commonly, precast concrete. Sometimes the timber or metal cill that forms part of the window is used to form the cill where visual criteria permit its use. Cills are sloped with a projecting edge that throws the rainwater clear of the wall beneath. A throating is also used to avoid water running back to the external face of the wall from the underside of the projecting cill. Where stone is used to form cills, the material must be sufficiently impervious or alternatively have sufficient slope to ensure that water runs off quickly. Where softer stones are used such as sandstones and limestones, the material must be sufficiently dense and durable to avoid staining occurring due to water absorption. Cills are usually made as single pieces to avoid joints being formed which are less impervious than the cill material. A DPC is set under the cill to ensure that rainwater penetrating the outer cill drains away any water that soaks through the cill, particularly at the joints. The heads of openings in loadbearing masonry walls are supported by lintels or arches which are structural, taking on an appearance informed by that primary requirement. In brick construction, a flat or curved arch is typically used to support the brickwork above. In concrete block construction, a reinforced concrete lintel is used, which spans the complete width of the wall, while in stone a thin arch is used on the outer face of the wall, often with a more rudimentary brick arch behind it, concealed by the window frame. In parapets, the coping piece has a damp proof course (DPC) set beneath it to avoid rainwater being absorbed into the wall beneath. The DPC is continuous with the waterproof layer used for the roof immediately behind the parapet. In common with copings in other facade systems, the top is sloped inwards to drain water towards the roof rather than down the facade where it would cause staining. The coping usually projects beyond the face of the wall on the roof side in order to throw water clear of the wall.

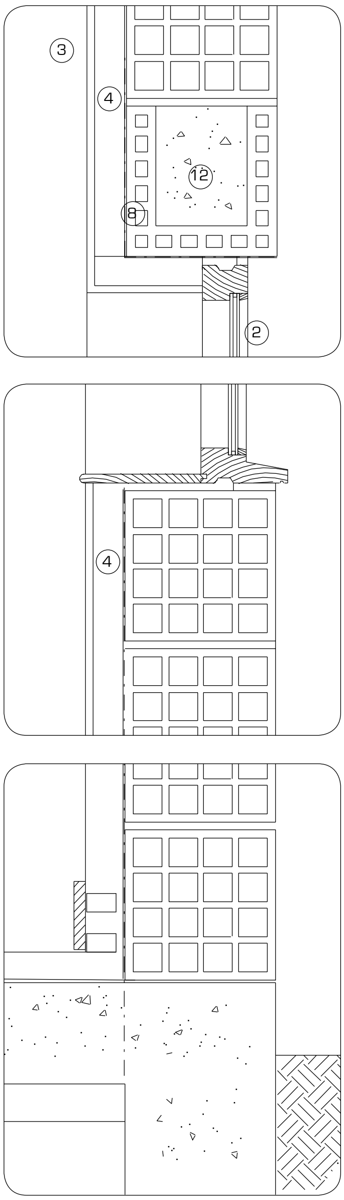
3D detail view showing window opening in typical concrete block wall, with insulation applied interior of wall system



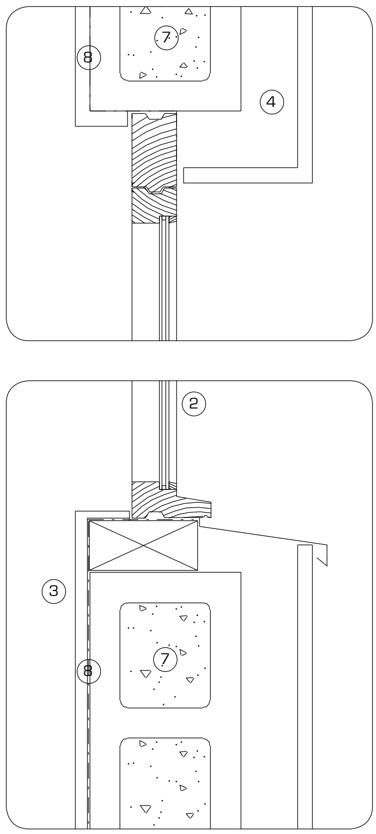
Horizontal sections 1:10. Window opening in concrete block wall illustrating application of insulation to interior or exterior of wall system



Vertical sections 1:10. Window opening in concrete block wall illustrating application of insulation to exterior of wall system



Vertical section 1:10. Window opening in hollow brick wall

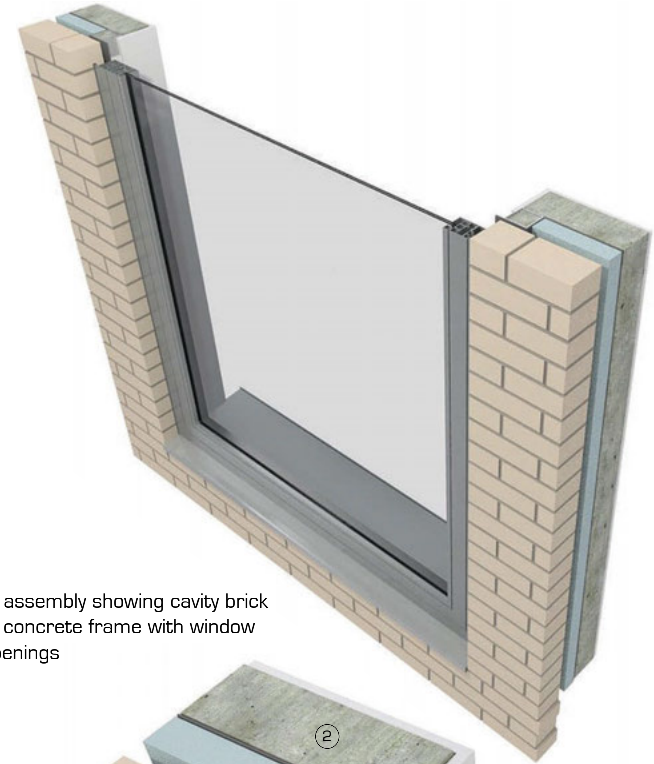


Vertical sections 1:10. Window opening in concrete block wall illustrating application of insulation to interior of wall system

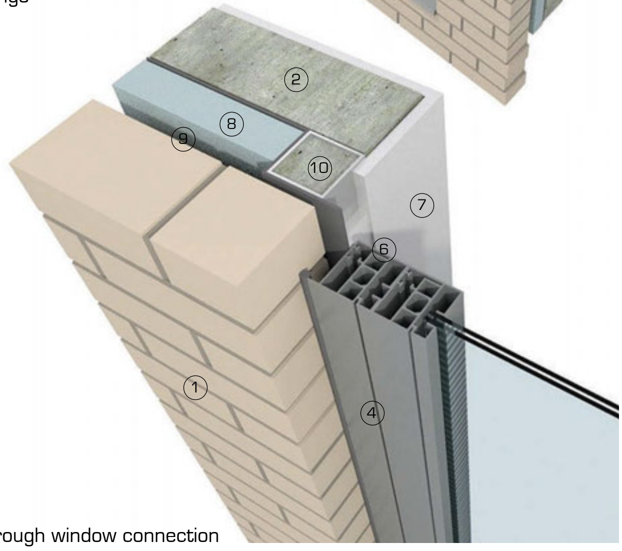
Details

1. Loadbearing brick wall
2. Timber framed window
3. Internal plaster finish or dry lining/drywall
4. Thermal insulation
5. Precast concrete lintel
6. Precast concrete cill
7. Concrete loadbearing blocks
8. Damp proof course (DPC)
9. Stone facing blocks
10. Floor slab
11. Floor construction
12. Hollow bricks
13. Roof construction
14. Stone lintel/arch
15. Stone cill
16. Parapet
17. Loadbearing concrete block wall
18. External finish

Walls 02
Masonry cavity walls: 1. brick



3D views of assembly showing cavity brick wall fixed to concrete frame with window and door openings



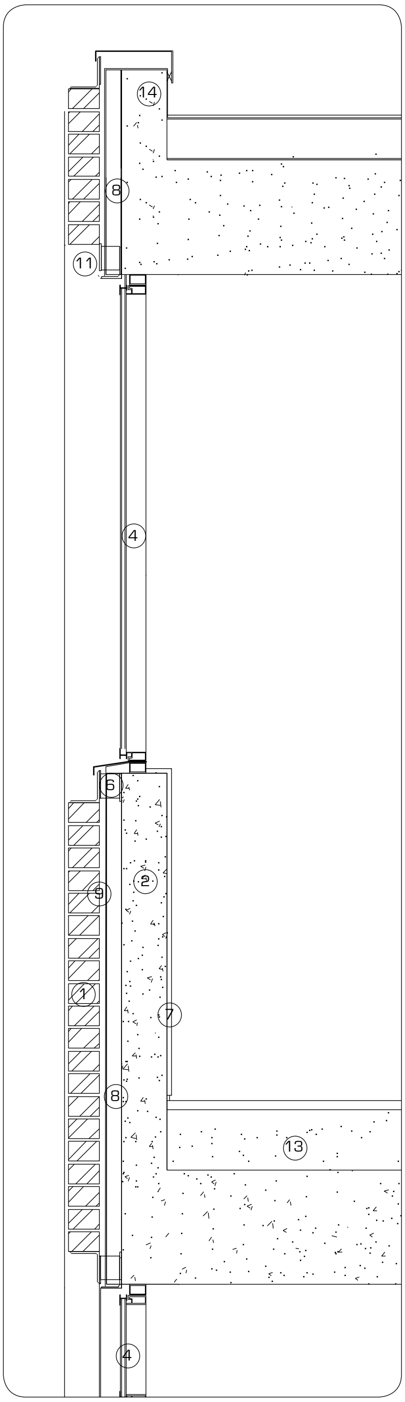
3D detail view through window connection

Details
1. Outer brick wall (or 'leaf')
2. Inner blockwork wall (or 'leaf')
3. Timber framed window
4. Steel/aluminium window
5. Timber cill
6. Cavity closer
7. Internal plaster finish or dry lining/ drywall
8. Thermal insulation
9. Air cavity (sometimes omitted where insulation fills cavity)
10. Inner precast concrete lintel
11. Pressed steel lintel
12. Outer precast concrete lintel or brick flat arch
13. Floor construction
14. Roof parapet
15. Stainless steel tie
16. Damp proof course (DPC)
17. Ground
18. Primary structure

System design
Where loadbearing brick walls use the overall wall thickness to stop the passage of rainwater from outside to inside, cavity walls use two skins of masonry separated by a ventilated air gap, where only the outer skin is saturated with water. The inner skin is usually formed in concrete block or timber studwork, with thermal insulation usually set on the external face of the inner skin. Earlier examples of cavity walls were built by tying inner and outer skins together with floor slabs to form diaphragm walls, so that both inner and outer skins performed a structural function. Their use was reduced with concern over the thermal bridge created by linking the two skins of brick, with its attendant issues of heat transfer across the wall and condensation risk. Current practice uses the outer skin as cladding to a drained and ventilated void behind, with an inner skin that is waterproofed with a high level of thermal insulation. The cavity is vented top and bottom to ensure the free passage of air through the cavity. This allows the cavity to remain dry as well as assisting in drying out the outer skin of brick, which can become fully saturated in a rainstorm. The cavity is bridged only by openings for windows and doors, but typically this is done with proprietary cavity closers, which are insulated strips that create a thermal break between inner and outer skins.

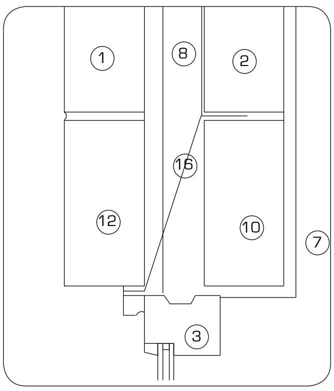
The outer brick skin is usually only one brick thick, typically of 100mm width, with both skins being supported at ground level, at intermediary floor levels and at the roof, depending on the height of the building. The inner skin is built off each floor slab and is restrained at the head by the floor slab or roof structure above. Taller buildings have the inner skin built directly onto floor slabs in the same way, but the outer skin is supported at each floor level on a series of continuous stainless steel angles, fixed back to the floor slab. A damp proof course (DPC) is set on top of the steel angle to drain the cavity. Weep holes (vertical slots) are formed in the vertical joints immediately above the steel angle in order to allow water in the cavity to drain to the outside. In addition to being restrained at floor slabs, the outer skin is also tied at intermediary points back to the inner skin with stainless steel ties. These are set typically at 450mm horizontal centres and 900mm vertical centres. Vertical movement joints are provided at around 7500mm centres, or are avoided altogether in the construction by keeping lengths of wall within this limit.

System details
Unlike loadbearing masonry walls, the inner and outer skins of cavity walls can be supported separately, with the outer

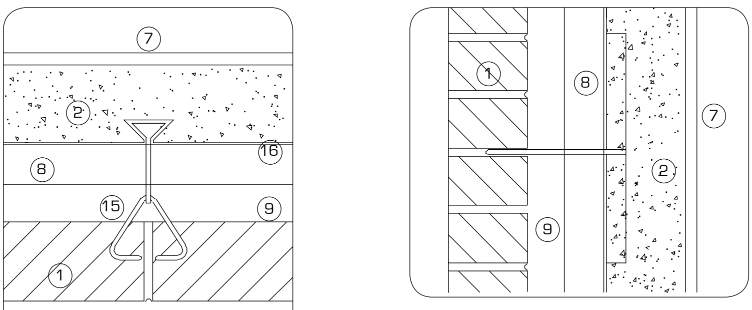


Vertical section 1:25. Wall assembly

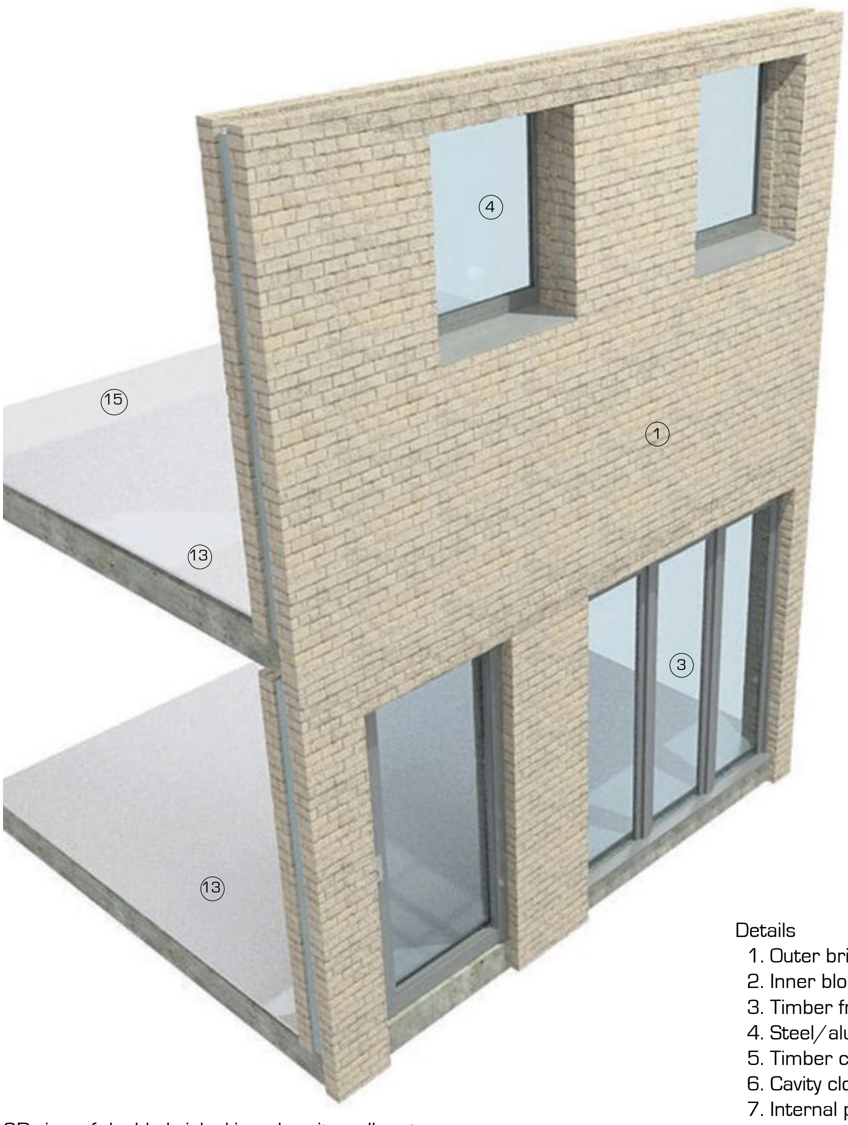
3D view of assembly showing cavity brick wall fixed to concrete frame



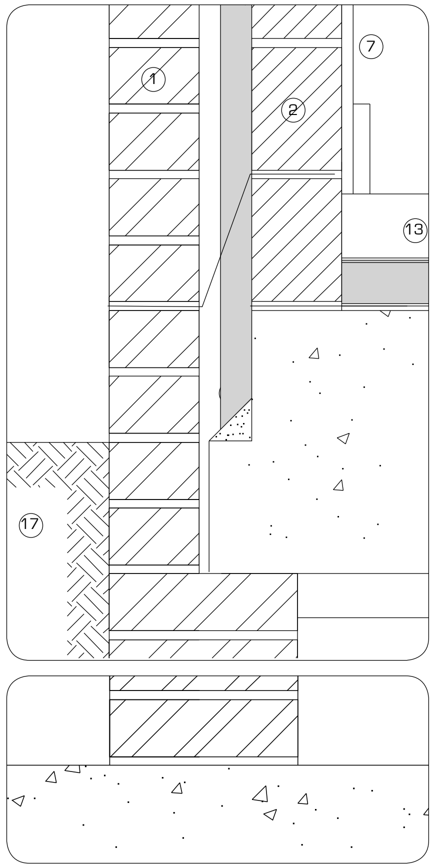
Vertical section 1:10.
Window assembly



Horizontal and vertical section 1:10. Typical connection or restraint to primary structure



3D view of double brick skinned cavity wall system



Vertical section 1:10. Junction at ground floor level

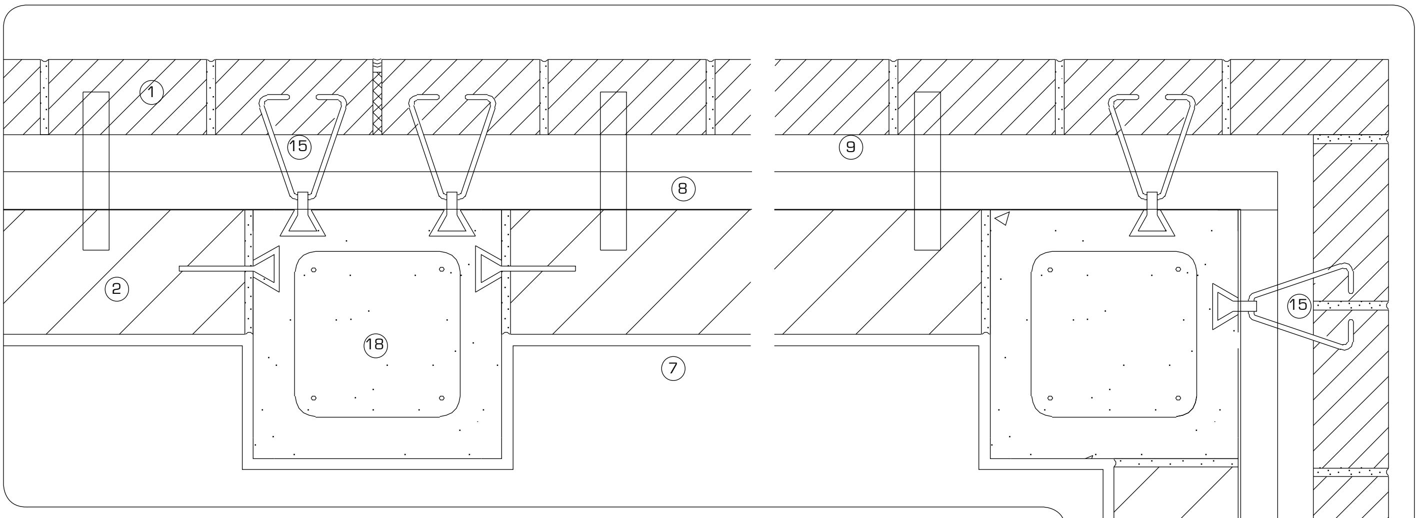
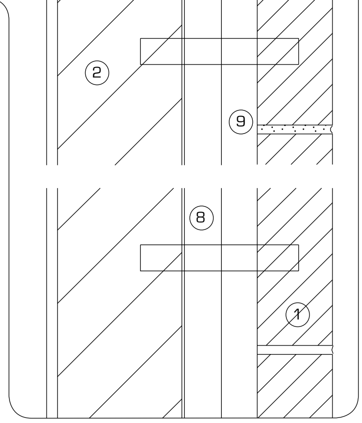
Details

1. Outer brick wall (or 'leaf')
2. Inner blockwork wall (or 'leaf')
3. Timber framed window
4. Steel/aluminium window
5. Timber cill
6. Cavity closer
7. Internal plaster finish or dry lining/drywall
8. Thermal insulation
9. Air cavity (sometimes omitted where insulation fills cavity)
10. Inner precast concrete lintel
11. Pressed steel lintel
12. Outer precast concrete lintel or brick flat arch
13. Floor construction

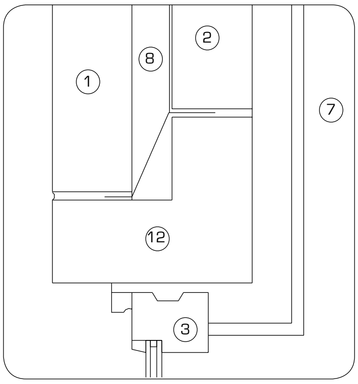
skin required to support only itself. However, when an opening is formed, the cavity is closed by a lintel to support the inner and outer skins at the top of the opening, and is closed by a cill at the bottom of the opening. The jambs (sides) are closed by either returning one of the two skins so that they meet, or by setting an insulated cavity closer, usually made as an aluminium extrusion filled with thermal insulation. Because the downward passage of water inside the cavity is interrupted by the lintel at the head of the opening, a cavity tray formed from bituminous felt is set above the lintel to drain water out of the cavity. Water is drained at the bottom of the tray through weep holes in the vertical joints immediately above the DPC. The ends of the DPC are tucked down into a vertical DPC set into the jambs of the opening which is in turn linked to a DPC set under the cill to form a complete watertight seal to the opening, which in turn is drained to the outside. A similar cavity tray principle is used to drain water at roof level and at ground level. In addition, a DPC is used at ground level to avoid water being drawn up into the wall construction to the inside face of the wall within the building. DPCs are also used beneath parapets and copings as well as at the junction of wall and pitched roof.

The position of the DPC at ground floor level is dependent upon the difference in height between ground floor level in the building and the adjacent external level. The DPC in the outer skin is set at around 150mm above external ground level. The DPC for the internal skin is set at the same level if the step up from outside to inside is around 150mm. If the difference between outside and inside levels is around 300mm then the DPC is stepped up from outer skin to inner skin in the same place but a separate DPC is added to the inner skin at the same level as the bottom of the cavity tray.

At roof level there are many variations for eaves junctions, with the top of the wall maintaining a consistent principle of closing the cavity at the top with a brick or block that allows the load from the roof structure to be supported on the inner skin. Alternatively, the roof structure may be supported on a column set into the inner skin of the wall or on blockwork piers, also forming part of the inner skin. The closing of the cavity wall at the top allows for continuity of thermal insulation from cavity wall to roof structure while allowing the roof construction to be ventilated if required, and the top of the cavity in the wall to be ventilated. A DPC is set on the underside of the brick or block that closes the cavity to ensure continuity of waterproofing between wall and roof. Parapets are closed at the top by a coping, either in masonry or metal. A DPC is set beneath the coping to stop the passage of water downwards from the top of the cavity.

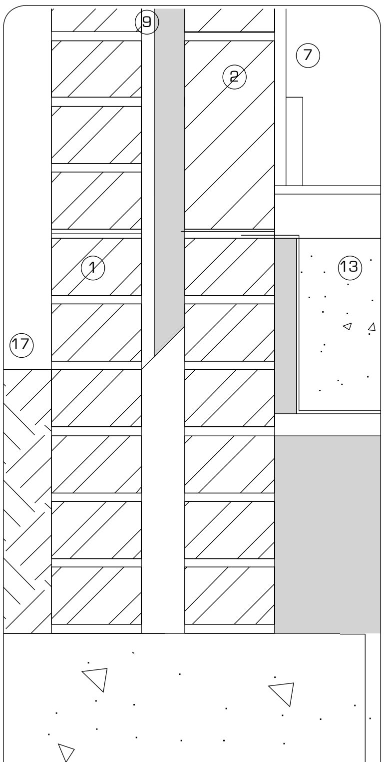



Horizontal section 1:10. Corner conditions



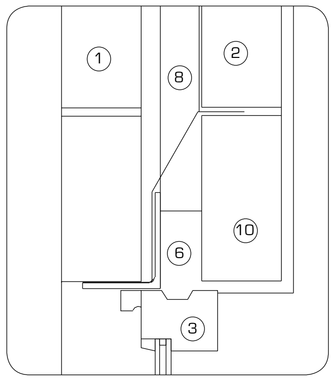
Vertical section 1:10. Window assembly

14. Roof parapet
15. Stainless steel tie
16. Damp proof course (DPC)
17. Ground
18. Primary structure

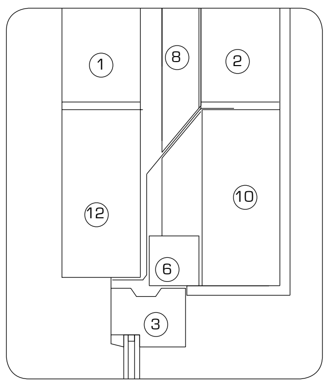


Vertical section 1:10. Junction at ground floor level

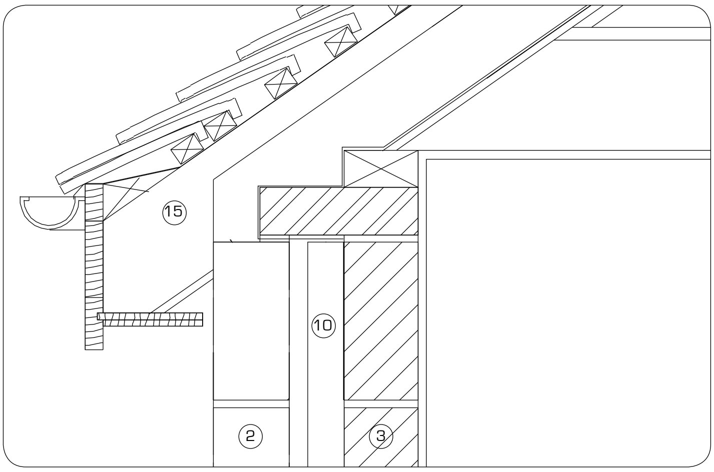
3D view showing typical timber window connections in brick cavity wall



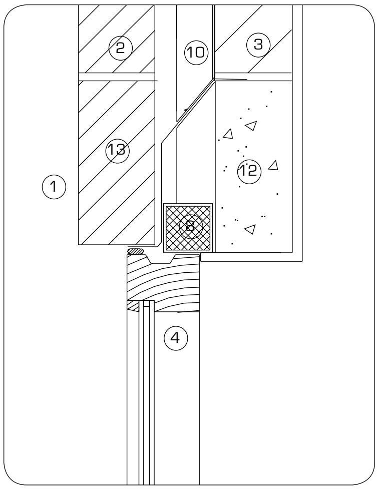
Vertical section 1:10. Window assembly

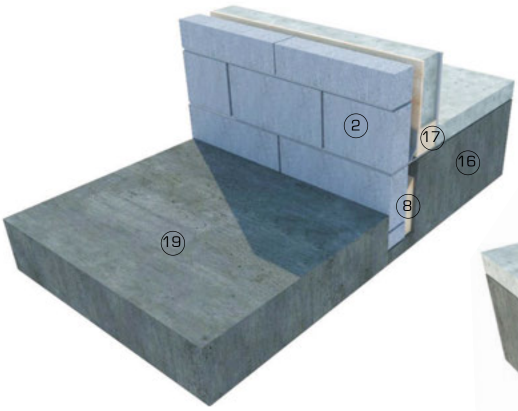


Vertical section 1:10. Window assembly

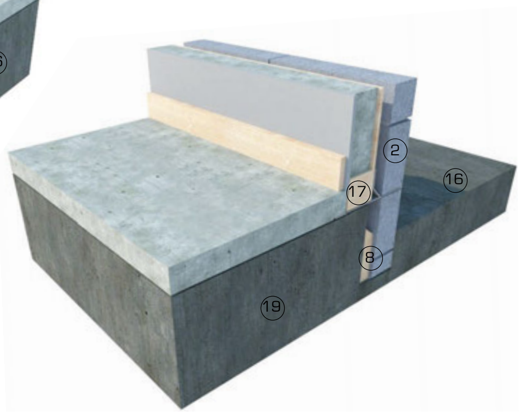


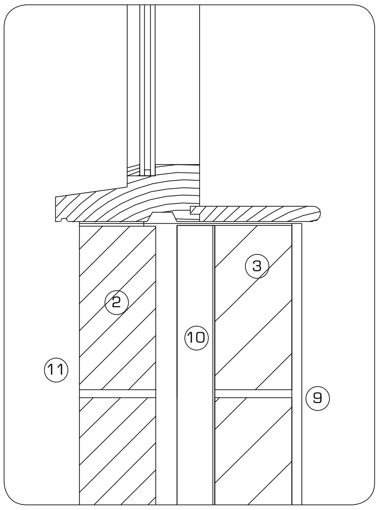
Vertical section 1:10. Roof connection to stone faced cavity wall system





3D fragment views showing junction at ground floor level of cavity wall





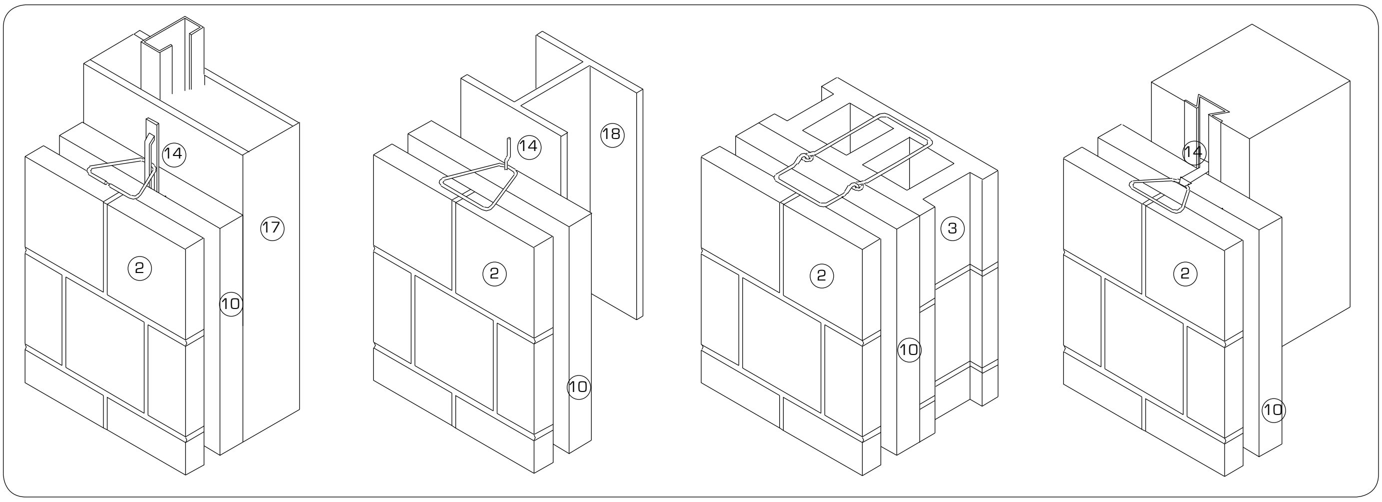
Vertical section 1:10. Typical window at cill and head in stone cavity wall

System design

The principles of cavity wall design are set out in the previous text on brick cavity walls. The same principles can be applied for use when stone and concrete blockwork are used to form an outer skin.

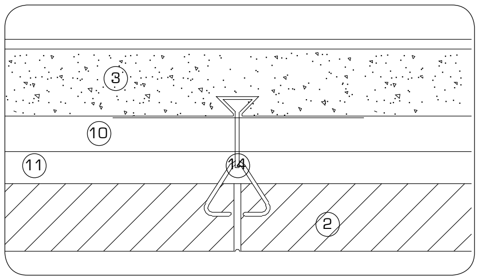
Stone can be used either as an outer skin approximately 100mm thick, or as panels around 40mm thick bonded to an outer brickwork skin. When used as a 100mm thick skin in order to be self-supporting, the stone becomes expensive, so sandstones and limestones are most commonly used. This method suits granites and denser limestones. An essential difference between the detailing of brick cavity walls and stone/block cavity walls is that there are fewer joints in the material due to their large size. Consequently there are fewer opportunities to design a damp proof course (DPC) with floor slabs, for example, particularly where shelf angles are used. The smaller unit size of brick makes it a very flexible material when detailing; stone/block requires careful co-ordination of stone/block size and floor to floor heights to allow for windows to be suitably placed. For this reason, alternating bands of thick and thin stone are used in coursing. This allows horizontal joint lines to be provided at shelf angles, cavity trays and DPCs at ground level, without disturbing the stone pattern with additional horizontal joints. Unlike open jointed stone cladding, where the mortar is omitted, the mortar and joint profile have a big visual impact.

Loadbearing cavity walls used to support two storey structures on their inner skins are very common in housing construction in Europe and North America. Vertical movement joints are provided at around 7500mm centres, or else are avoided altogether in the construction by keeping lengths of wall within these dimensions. When cavity walls are used with large scale building frames in either steel or concrete, the inner leaf is no longer loadbearing and instead the complete wall construction forms a cladding to the frame. When reinforced concrete frames are used, the junction between inner skin, typically concrete block or terracotta block, is straightforward with a gap between the two to allow for structural movement in the frame. Stainless steel sliding anchors are used either in the sides of the inner skin panel where it meets the column, or at the head where it meets the floor slab. The outer skin runs continuously in front of it. The situation is more complicated with a steel frame, where the column needs to be protected from corrosion from water vapour in the cavity. Typically the column is painted to form a protective coating and thermal insulation is set across the face of the steelwork to provide a continuity of thermal insulation. Sometimes the outer skin is restrained with cavity ties fixed to the face of the reinforced concrete or steel column. This is particularly useful when forming a movement joint in lengths of brickwork, or movement joints that form part of the building structure, which typically occur at columns in the building frame. The vertical movement joint is filled with two parts polysulphide sealant that also matches the colour of the mortar as closely as possible and provides a seal that can accommodate the structural movement within the cavity wall.

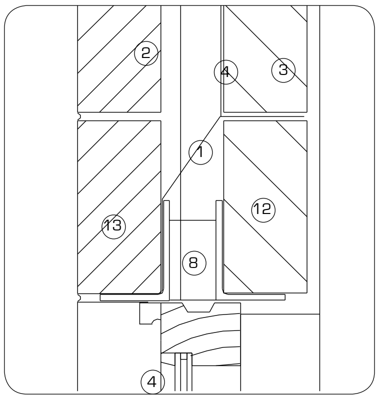


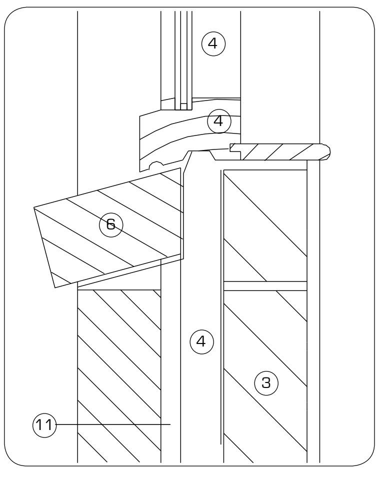
3D fragment views showing various wall assemblies

3D view showing timber window frame in stone cavity wall



Horizontal section 1:10. Typical wall system showing wall tie



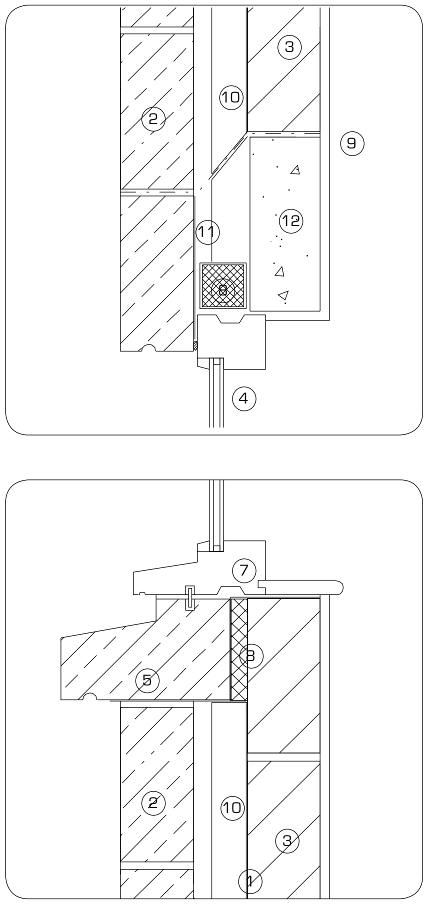


Vertical section 1:10. Typical window at cill and head

Details

1. Damp proof course (DPC)
2. Outer block wall (or 'leaf')
3. Inner block wall (or 'leaf')
4. Timber framed window
5. Precast concrete cill
6. Stone cill
7. Timber inner cill
8. Cavity closer
9. Internal plaster finish or dry lining/drywall
10. Thermal insulation in cavity
11. Air cavity (sometimes omitted where insulation fills cavity)
12. Inner precast concrete lintel
13. Outer precast concrete/stone lintel
14. Stainless steel tie
15. Roof construction
16. Floor construction
17. Timber framed inner skin
18. Steel framed inner skin
19. Ground

3D views showing typical window at cill and head in block cavity wall system



Vertical section 1:10. Typical window at cill and head in block cavity wall system

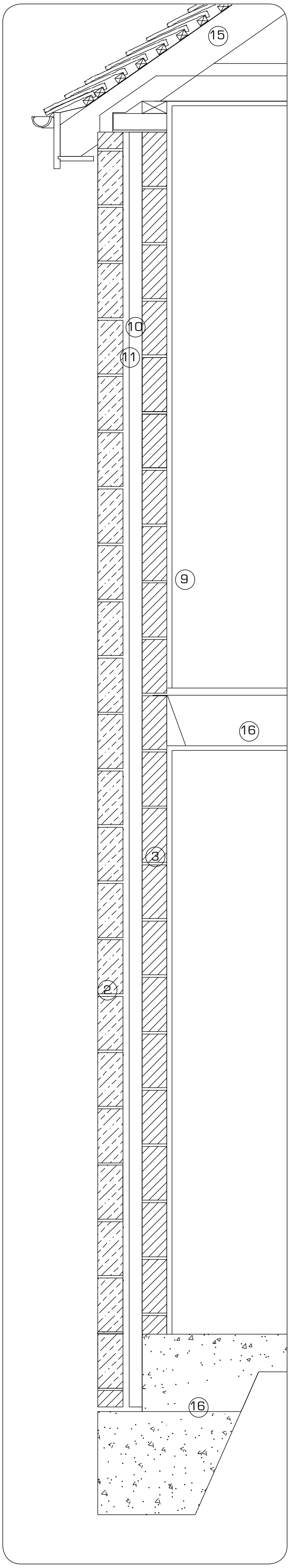
System details

This section discusses variations and details additional to those set out in the previous section on brick cavity walls and focuses on different materials for the inner skin.

When a timber framed inner skin is used, the window is usually an integral part of that inner skin so that a complete enclosure is formed in timber with masonry used as an outer skin providing some lateral stability. The outer masonry skin can be returned to form a reveal up to around 125mm depending on the thickness of insulation in the cavity. Alternatively, the timber window can be set forward close to the line of the outer face with a timber cill projecting forward of the wall. This gives the outer wall an appearance of a brick texture, giving a planar appearance to the material.

With reinforced concrete inner skins, stainless steel fixings and restraints are usually post-fixed to the concrete. In recent years, outer masonry skins have been made as prefabricated panels on some projects when fixed back to a reinforced concrete wall. Panels of stone, terracotta or even brick are bonded together with mortar and then held in a steel edge frame, which is fixed to the inner skin. The concrete inner skin is waterproofed with bituminous paint and thermal insulation is set on the outside face of the inner skin. The steel angle on the bottom edge forms a closer to the window below, while the steel on the top edge forms a cill to the window above. The vertical steel angles are usually concealed within the cavity to give a continuous masonry appearance. The masonry is sometimes restrained within the panel by vertical stainless steel rods which are tensioned against the frame to form lightly prestressed panels. Vertical joints between panels are sealed, typically with a polysulphide sealant.

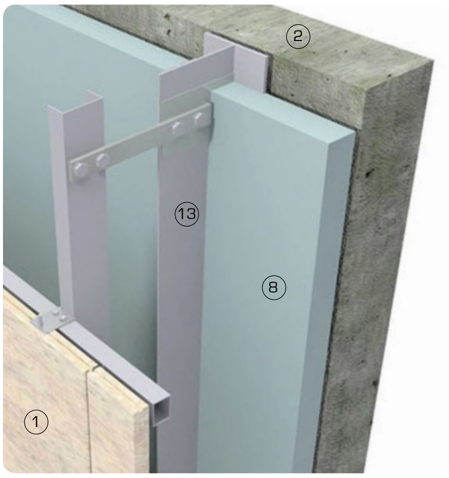
For parapets the inner skin is thickened up when used as a balustrade. A handrail on top of the coping is fixed by drilling through the top and bolting it to the inner skin beneath. The coping is cut to receive the balustrade or handrail, unless the uprights supporting the handrail pass between the joints. The adjacent area of flat roof or gutter usually has a waterproofing layer returning up the wall, regardless of the roof finish. The waterproofing layer is set into horizontal joints in outer masonry skin. A metal flashing is set into the same horizontal joint and is set over the top of the waterproofing to protect it from damage. Metal copings are used increasingly on parapets in order to match the appearance of windows and doors, particularly where metal cills are used. The same principles apply as for concrete copings, with a DPC set on top of the masonry wall. Drips are formed on either side of the vertical face to ensure that water is thrown clear of the wall. For all parapets, the waterproofing layer is continued up the wall to become continuous with the DPC in low parapets. For high parapet walls, a stepped DPC is used to drain water back to the inner skin to ensure that water inside this part of the cavity wall is drawn away.

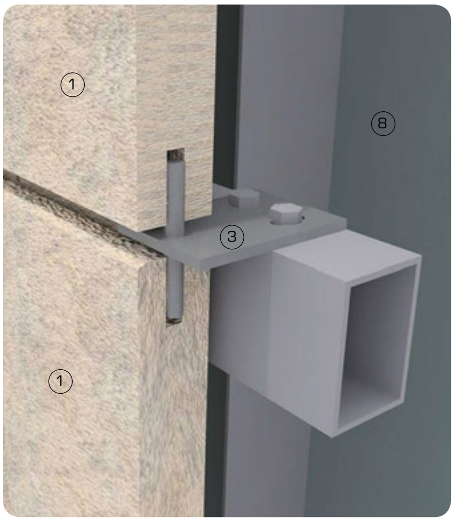


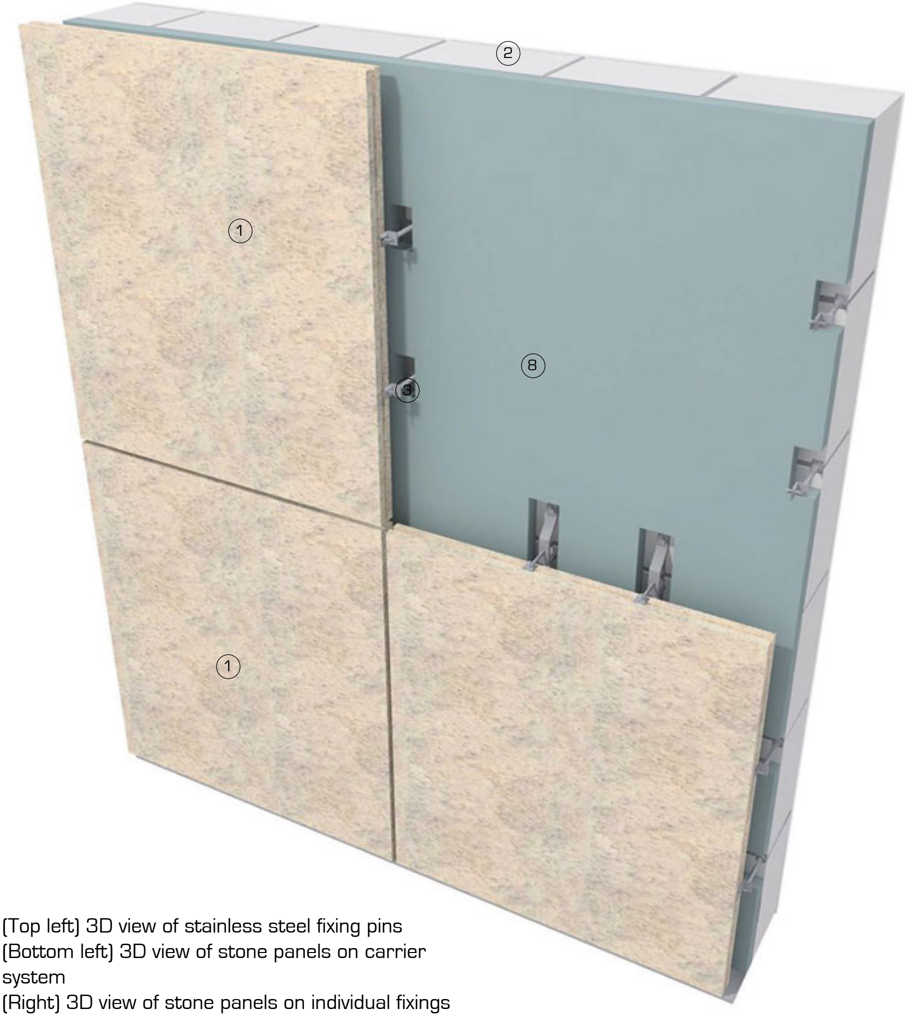
Vertical section 1:25 showing typical details

3D view showing section through block cavity wall system

Details
1. Damp proof course (DPC)
2. Outer block wall (or 'leaf')
3. Inner block wall (or 'leaf')
4. Timber framed window
5. Precast concrete cill
6. Stone cill
7. Timber inner cill
8. Cavity closer
9. Internal plaster finish or dry lining/drywall
10. Thermal insulation in cavity
11. Air cavity (sometimes omitted where insulation fills cavity)
12. Inner precast concrete lintel
13. Outer precast concrete/ stone lintel
14. Stainless steel tie
15. Roof construction
16. Floor construction
17. Timber framed inner skin
18. Steel framed inner skin
19. Ground







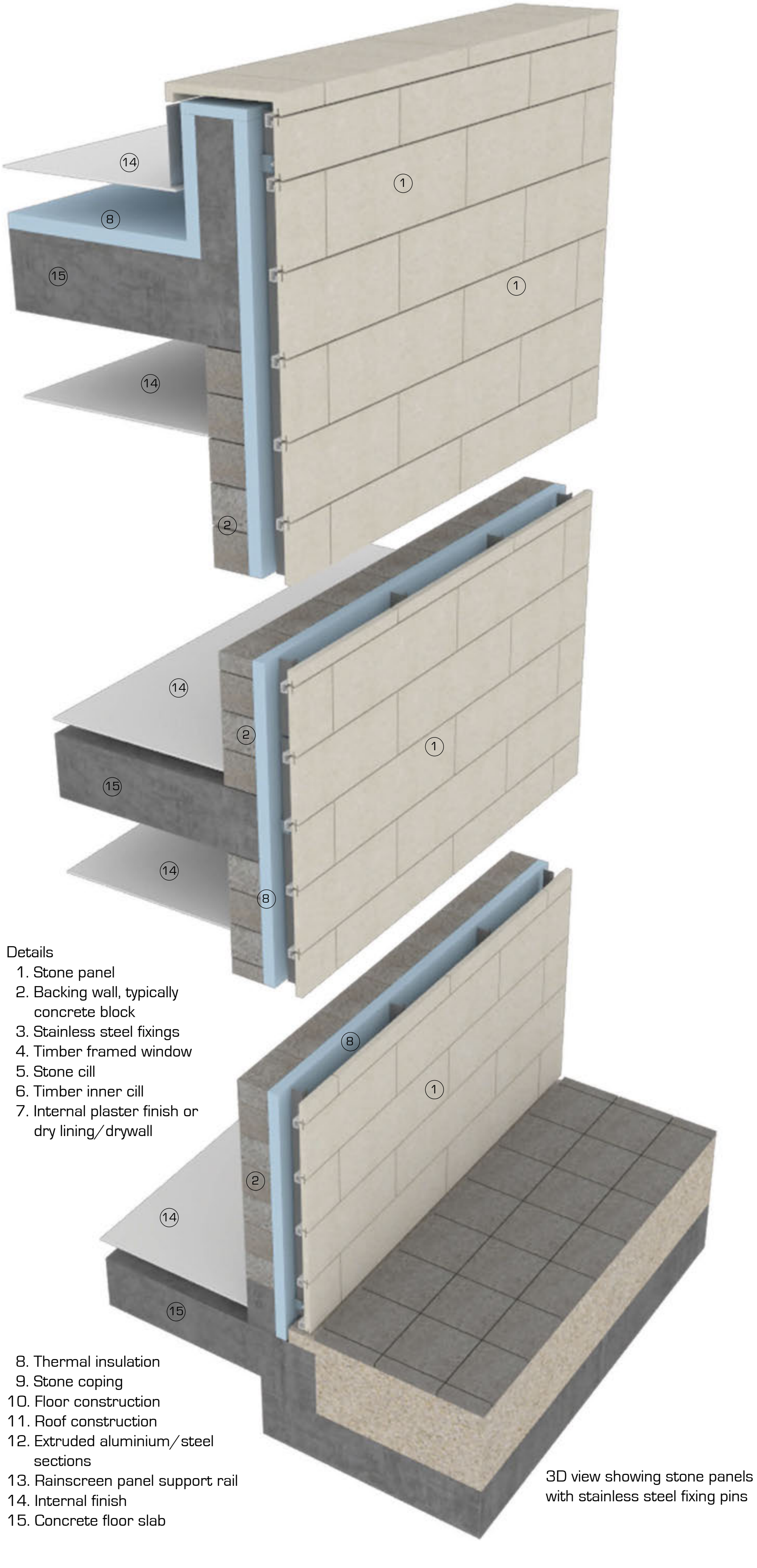
(Top left) 3D view of stainless steel fixing pins
(Bottom left) 3D view of stone panels on carrier system
(Right) 3D view of stone panels on individual fixings

System design

Stone cladding panels are typically fixed back either directly to a backing wall or to a metal carrier frame with a separate backing wall behind. The use of stone for cladding requires an emphasis in the design stage on choosing not only the specific material, but also setting the range of colours and textures of the material. This requires an investigation into establishing the physical properties of the actual stone to be used if this is not already known, to a structural-based design to establish or confirm maximum panel dimensions and suitable fixing methods for the proposed sizes of panel. The physical properties of the stone may be available from the quarry at an early stage, but sometimes testing is done during the early procurement stage to ensure that the material meets the requirements of the building code. The thickness of stone required for a facade is usually established by structural calculation. Flexural strength, also called the modulus of rupture, is usually the most significant structural consideration in establishing panel size. Codes of practice often set out minimum thickness for various panel sizes, but this is only a general guide and calculation is usually undertaken for specific facade applications. Since the material may not already be cut from the quarry at the time of its selection, stone facades can involve longer procurement times than other facade systems, particularly on larger projects. The stones used are typically granites, sandstones, limestones and slates, and are once again being considered as a material that might be locally sourced; a material laying in abundance beneath the region in which the building is to be constructed.

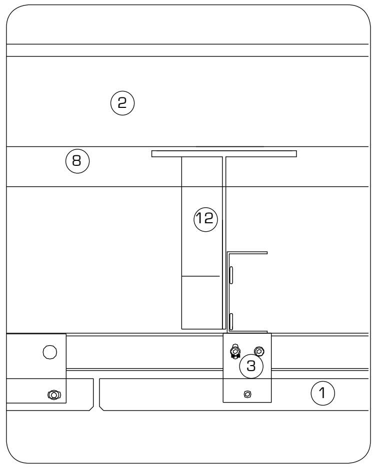
Stainless steel is used for stone fixings because of its resistance to corrosion combined with high strength and rigidity. Fixings have a three-way adjustment vertically, horizontally and laterally in order to align the stone panels accurately. The type of fixing used varies with the thickness and stone type used. Fixings are usually set at the top and bottom of the panel, with the bottom fixings being loadbearing and the fixings at the top of the panel being restraints. Side fixings are sometimes used depending on the weight and strength of the panel.

Stone cladding can be used as a ‘wrap’ to a structural frame as well as its more traditional use for cladding walls with punched openings. The mixture of large stone panels with long narrow panels associated with reinforced concrete structural frames gives a visual drama not usually associated with stone cladding until recently. The arrangement of stone panels can imitate traditional patterns of jointing such as stretcher bond, but can also benefit from the mechanical fixing of each stone panel by forming an arrangement that is independent of the backing wall behind, mixing both stone sizes and different shapes in a single wall composition. The development of water jet cutting techniques in addition to development of established stone cutting tools has led to a greater variety in the size and shape that remains within the limits of economic construction. The introduction of triangular panels in rainscreen configuration has encouraged the use of stone cladding on folded facade surfaces to complement the geometries used in glazed walls. Finishes for stone have also developed in recent years, with rubbed, honed, polished and flamed finishes for different stone types.

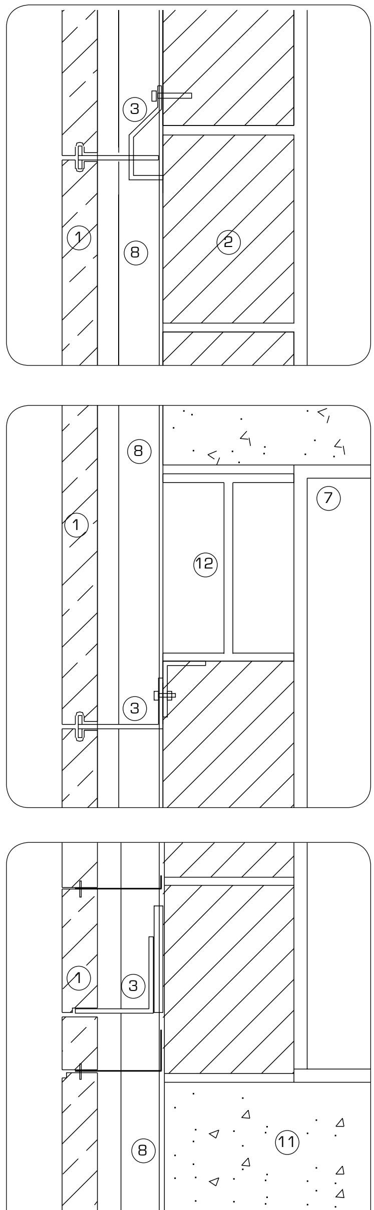


Details
1. Stone panel
2. Backing wall, typically concrete block
3. Stainless steel fixings
4. Timber framed window
5. Stone cill
6. Timber inner cill
7. Internal plaster finish or dry lining/drywall
8. Thermal insulation
9. Stone coping
10. Floor construction
11. Roof construction
12. Extruded aluminium/steel sections
13. Rainscreen panel support rail
14. Internal finish
15. Concrete floor slab

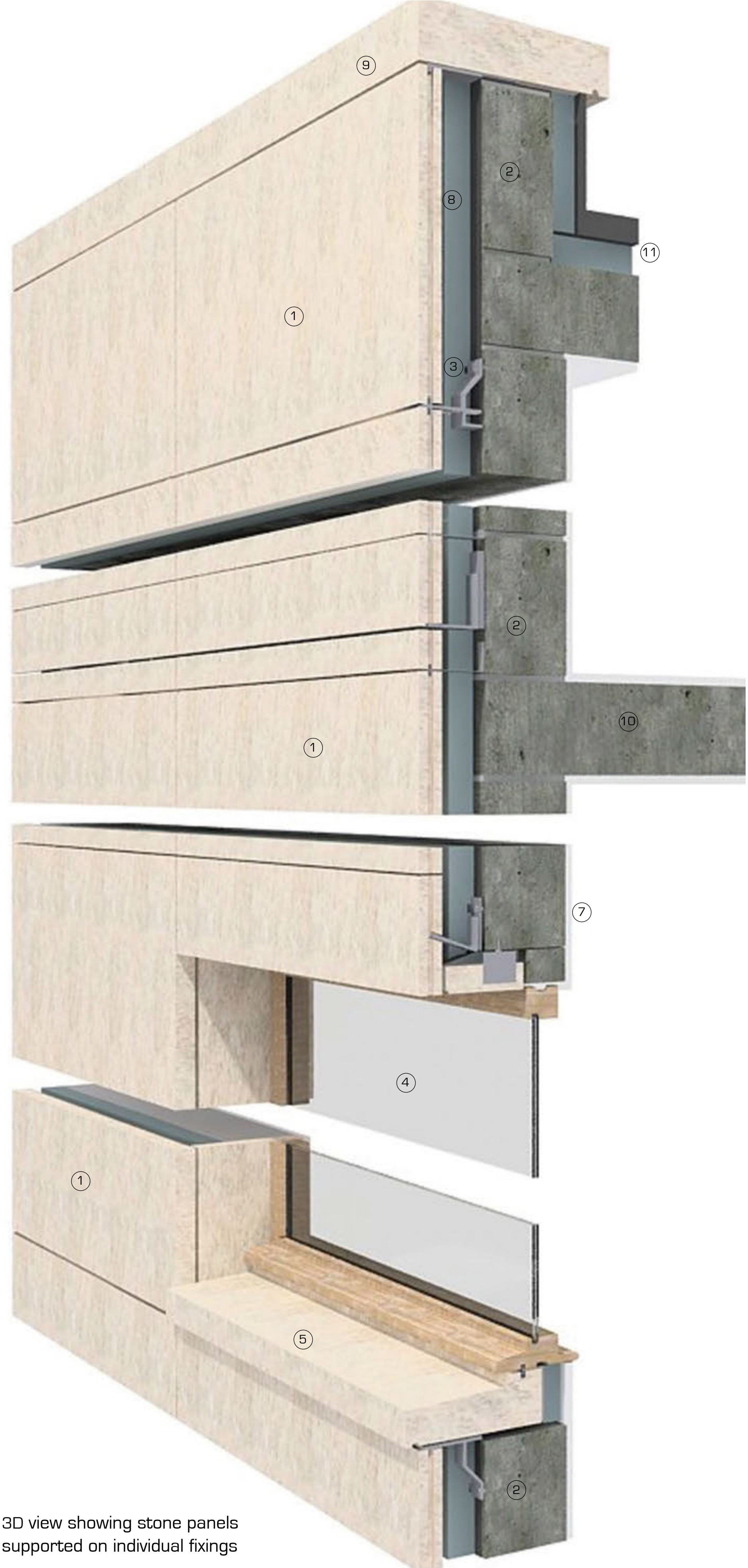
3D view showing stone panels with stainless steel fixing pins



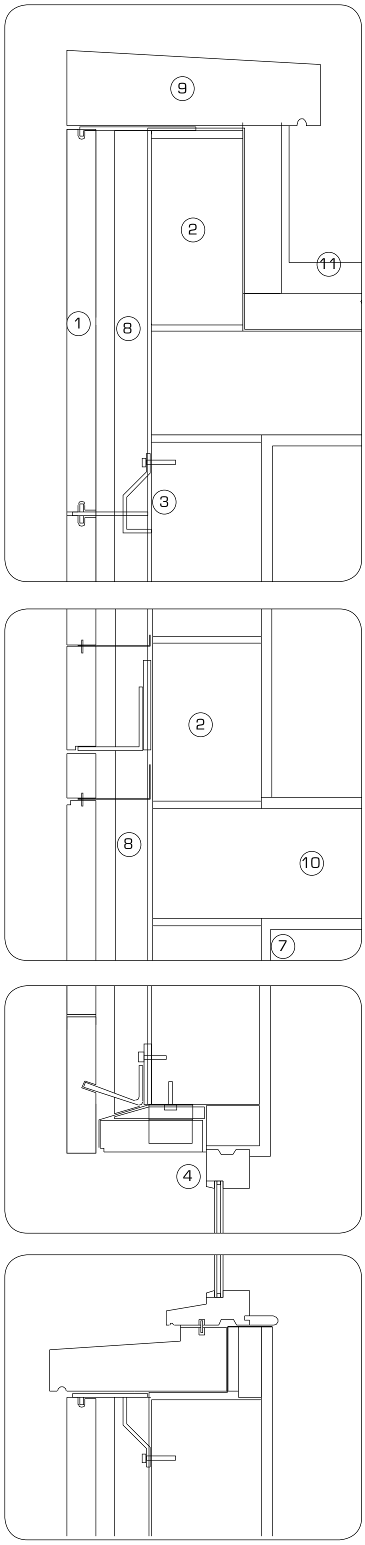
Horizontal section 1:10. Typical stone carrier system made from extruded aluminium section



Vertical section 1:10. Typical stone carrier system made from individual fixings

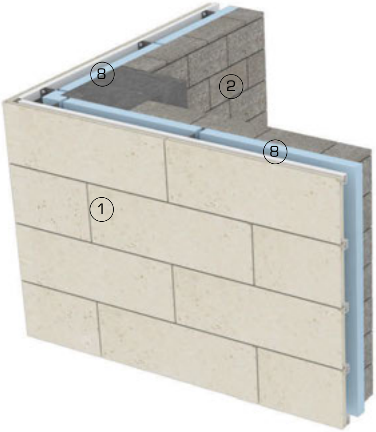


3D view showing stone panels supported on individual fixings



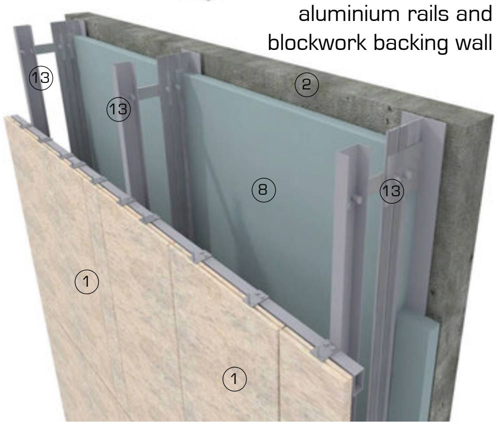
Vertical section 1:10. Stone supported on individual fixings

Details
1. Stone panel
2. Backing wall, typically concrete block
3. Stainless steel fixings
4. Timber framed window
5. Stone cill
6. Timber inner cill
7. Internal plaster finish or dry lining/drywall
8. Thermal insulation
9. Stone coping
10. Floor construction
11. Roof construction
12. Extruded aluminium/steel sections
13. Rainscreen panel support rail

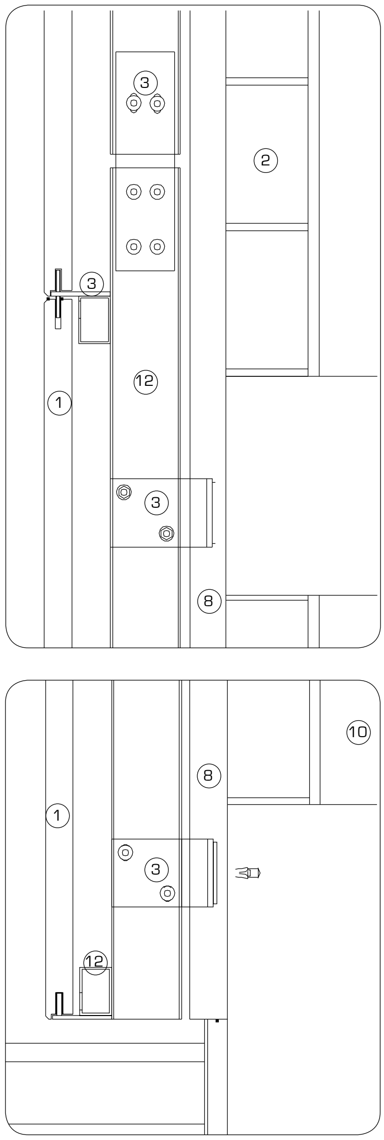


3D view showing stone panels supported on aluminium rails and blockwork backing wall, at internal and external fold

3D view showing stone panels supported on aluminium rails and blockwork backing wall, with window opening



3D view showing stone panels supported on aluminium rails and blockwork backing wall

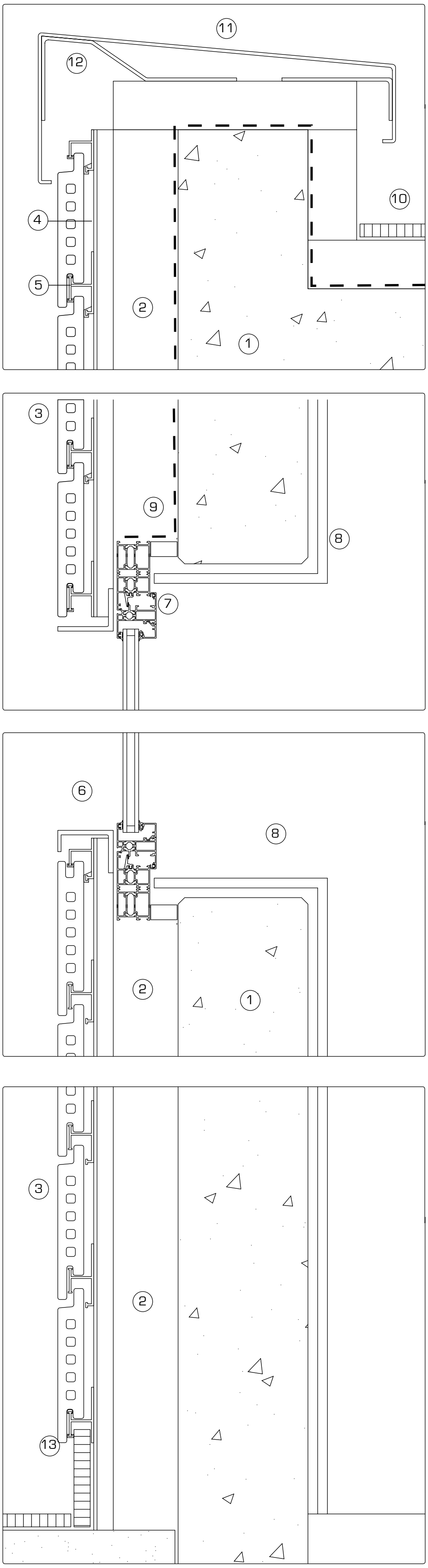


Vertical section 1:10. Typical stone panels on carrier system

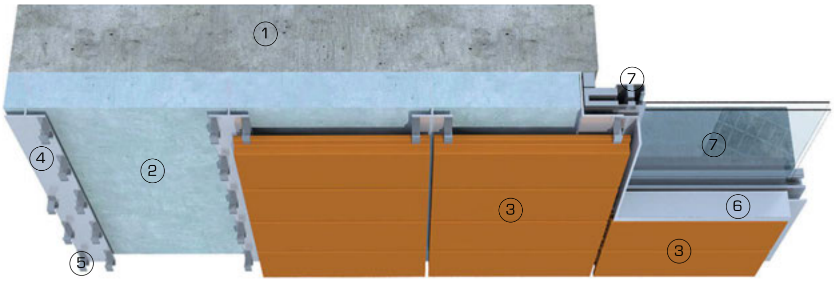
System details

Joints between stone cladding panels are either of open rainscreen type or are closed with mortar or sealant. Closed joints sealed with mortar or sealant are used where the cladding is supported at each floor level on stainless steel angles with jointed stones. With open jointed stones, each panel is individually supported in a rainscreen construction, where rainwater passing through the joints is drained away down either the back of the stones or down the face of the backing wall, which is typically insulated. The choice of joint type is partly a visual decision and partly one that ensures adequate ventilation to the cavity between the stone and the backing wall, allowing stones to dry properly. Closed joints allow the stone cladding to perform in a similar way to a cavity wall, with ventilation provided at the top and bottom to dry the void behind the stones. Joints in sandstones and limestones are usually filled with cement/sand mortar or cement/sand/lime mortar. Granites and slates typically are proprietary sealants such as two-part polysulphide. Mortar used for pointing is made frost resistant when used in temperate climates, and of similar strength to the joining mortar, with the structural mortar behind. The maximum width of mortar filled joints is around 12mm, but sealant filled joints can exceed this, subject to visual requirements. Joint widths are partly a function of the cutting tolerance of the stone, which can vary along its length by up to 2mm, depending on stone panel size and the cutting machine used. Joint widths of 4mm are common, but this can rise to around 12mm when required for visual reasons.

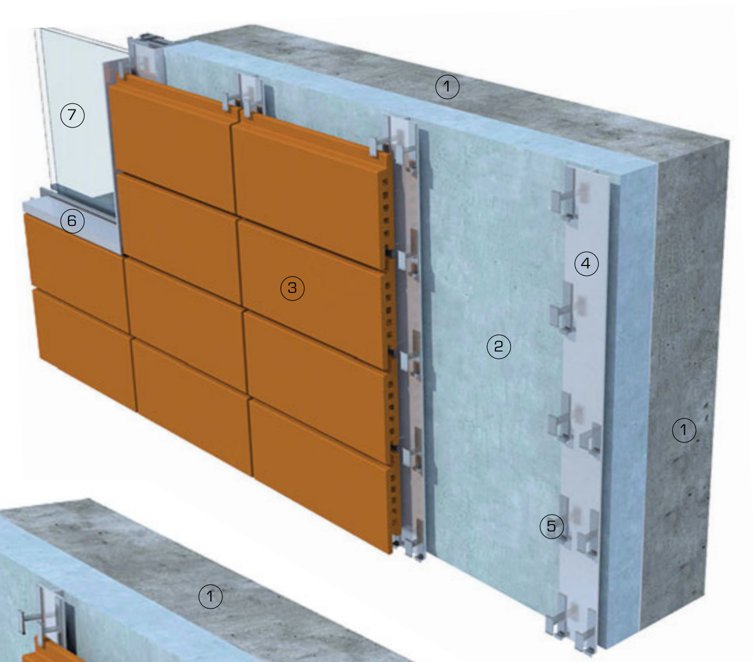
Movement joints are set both horizontally and vertically to accommodate movements in the building structure. Horizontal movement joints are used to deal mainly with structural deflections in floor slabs, and are usually provided at floor level, where the stone cladding is supported from either short lengths of stainless steel angle, or a continuous steel angle. The movement joint is set immediately below the stainless steel angle, where vertical deflection will occur. Horizontal movement joints can be set at intervals of two storeys if a carrier frame is used that will span the full height. The movement joint width is usually around 20mm, formed as an open joint. Vertical movement joints in the facade, located to correspond to movement joints in the building structure, are set immediately forward of these movement joints where they reach the facade. The distance between joints is typically at around 6 metres in a continuous run of stone cladding with closed joints. The joint width corresponds to the expected movement in the cladding, but where sealed joints are used, the joint width is dependent on the amount of movement that the sealant is required to accommodate.

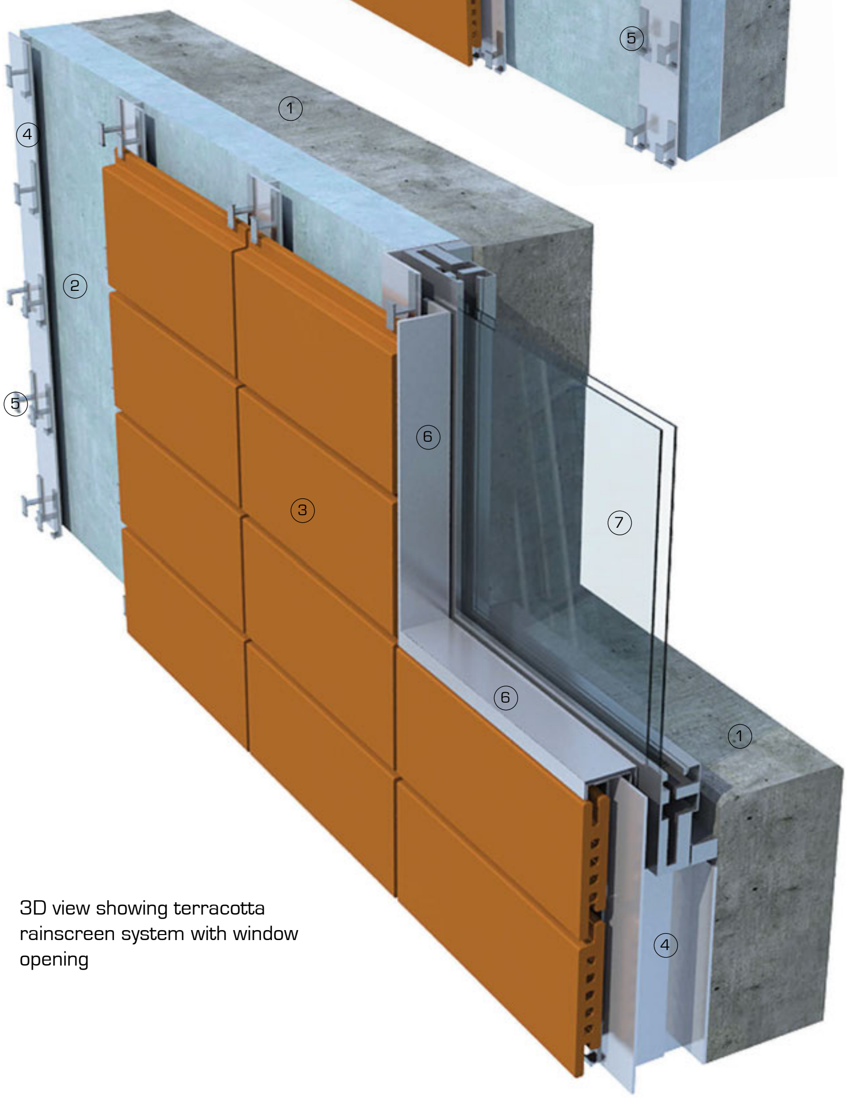


Vertical section 1:10. Terracotta rainscreen fixed to loadbearing concrete wall



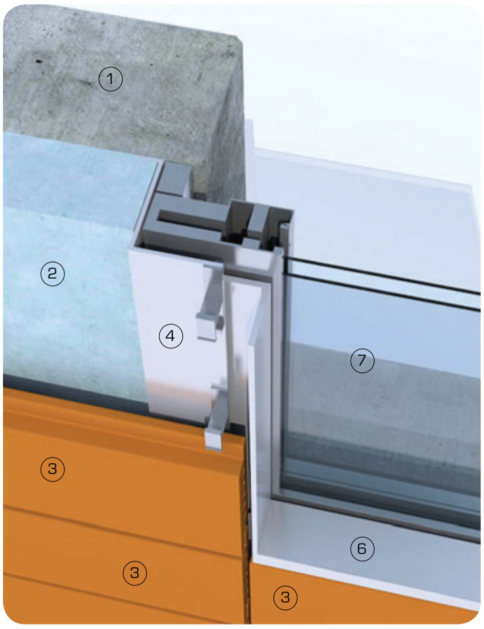
3D views showing terracotta rainscreen system with window opening



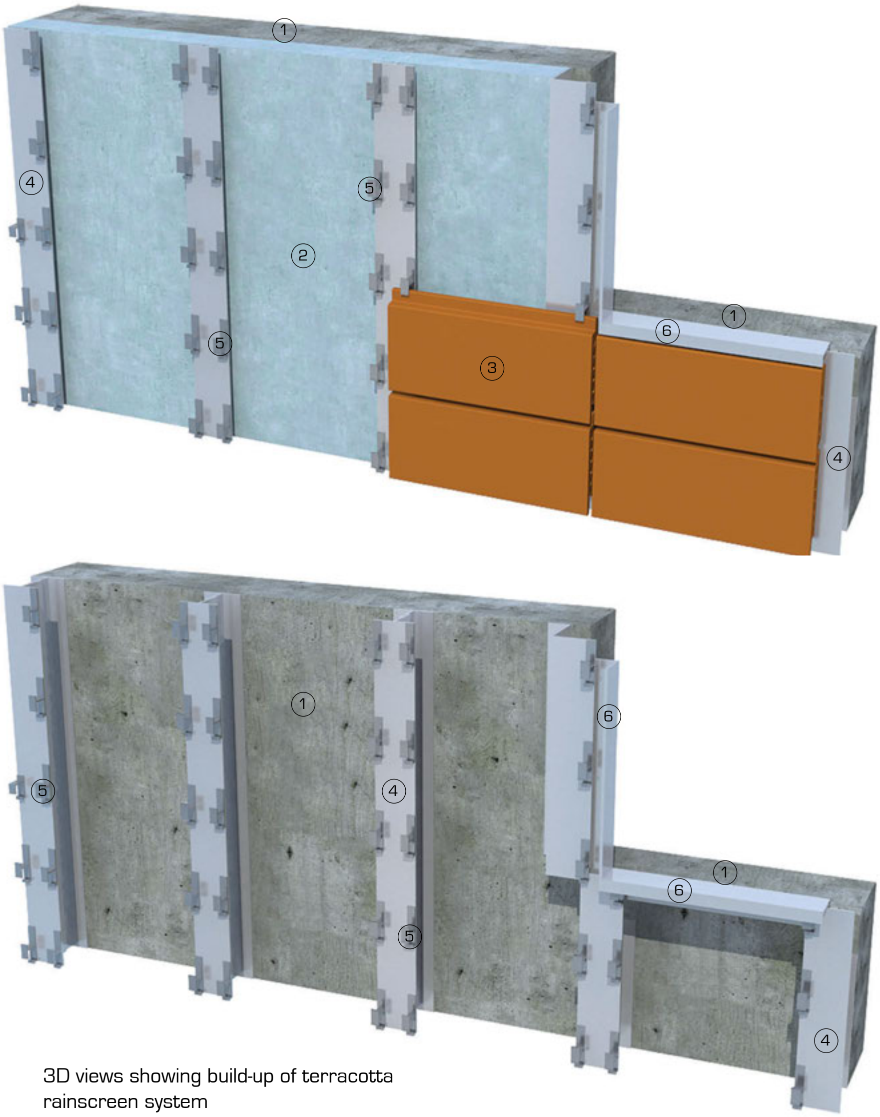


3D view showing terracotta rainscreen system with window opening

Details
1. Backing wall, typically concrete
2. Thermal insulation
3. Terracotta rainscreen
4. Extruded aluminium carrier frame
5. Support clip, typically aluminium
6. Aluminium window surround
7. Metal framed window
8. Internal plaster finish or dry lining/drywall
9. Vapour membrane
10. Roof construction
11. Metal coping
12. Coping support
13. Stone paving



3D detail view showing terracotta rainscreen system at window opening



3D views showing build-up of terracotta rainscreen system

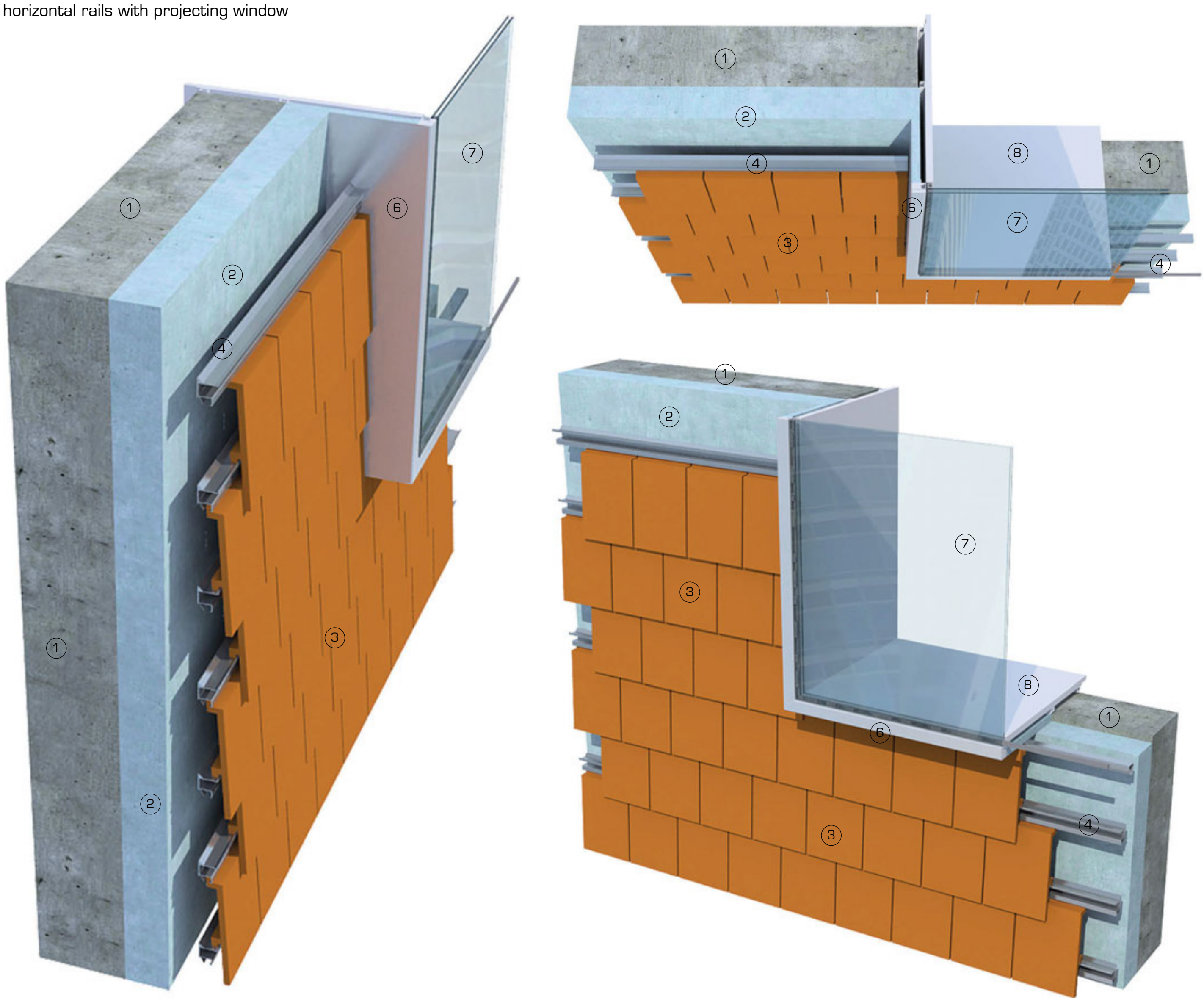
System design

Terracotta rainscreens are a recent development over the past 15 years, and can be seen as a development of brick cavity walls to a fully ventilated version in full rainscreen configuration. Over that time the sizes of terracotta panels have increased and fixing systems have developed, and have also been adapted for use as solar shading louvres to glazed walls, particularly where terracotta is also used as an adjacent wall cladding material. Terracotta louvres typically comprise hollow sections reinforced internally with aluminium sections to form louvered screens that can match with adjacent areas of terracotta cladding. Terracotta rainscreen panels are fixed either on rails, into aluminium or stainless steel panels, or onto individual brackets like masonry cladding with concealed fixings. Vertically-set or horizontally-set rails are used to suit a range of joint arrangements that imitate traditional masonry bonds, or alternatively can be fixed in a stack bonded arrangement. Recently developed systems have interlocking panels to provide visually crisp joints, and panels extruded as twin wall sections to provide long spanning panels. The range of glazed finishes has developed considerably in recent years to give a very wide range of textures and colour mixes derived from contemporary pottery. Terracotta is made from natural clay that is first extruded, then cut to the required length of panel, then fired in a kiln. The use of extrusion dies allows the manufacture of terracotta panels to be flexible from project to project. As with aluminium framed curtain walling, the die creates different heights and depths of block, while maintaining a hollow interior to keep the material relatively light and easy to handle, allowing long panel lengths to be formed.

System details

Terracotta panels have two extruded edges and two cut edges, resulting in panels being arranged on a facade so as to avoid a cut edge being visible at a corner. This arises because the surface finish and colour of the end face will not match that of the front face. The ends of panels are usually concealed with aluminium trims, sometimes at the corners but typically around window openings. Alternatively, special corner shapes can be formed by hand to match the standard extruded tiles, made by a pressing method, usually with a maximum length of 150mm on one leg and 300mm on the other. Large corner pieces are made by hand by joining two sections together, but these currently produce less reliable results that can lack a straight and crisp edge. In addition, manufacturers often provide extruded cill sections for parapets and window sections to suit wall constructions of 300mm to 500mm wide.

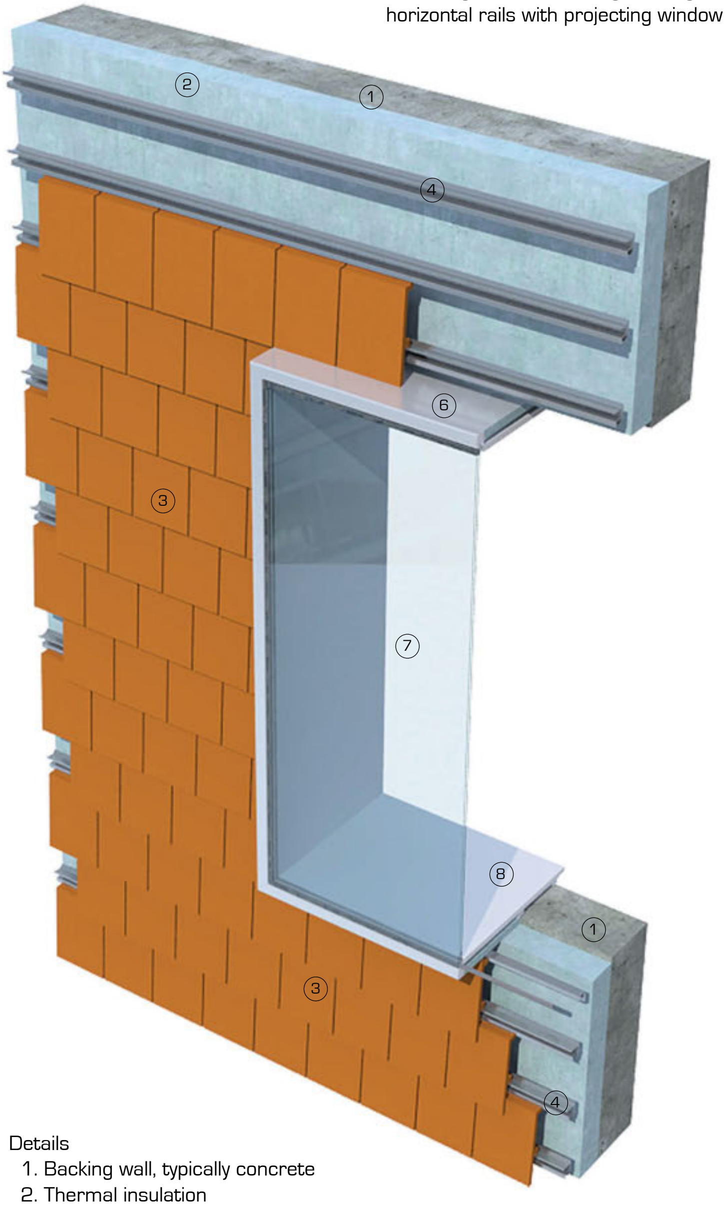
Fired terracotta is either left in its natural colour or is glazed. A glazed finish can give the material a reflective finish which provides better protection from surface staining. However, 3D views showing terracotta shingles hung on horizontal rails with projecting window



water absorption of regular terracotta panels is between 3% and 6%, with a density of around 2000kg/m3, making the use of glazes not essential for excluding rainwater, but important more for visual reasons. Panels are fixed to support rails which are set either vertically or horizontally, made from aluminium for their ability to be formed precisely as extrusions for ease of fixing. Vertical rails are well suited to ‘stack bonded’ terracotta, where joints form a rectilinear grid of continuous vertical and horizontal joints. Horizontal rails are suited to staggered bonds of panels that imitate the stretcher bond used in traditional wall construction where vertical joints are not continuous. At least twice as many vertical rails are needed as those for a stack bond arrangement. Since horizontal joints are continuous, horizontal rails are used to fix courses of terracotta. Joint widths vary from 2mm to around 10mm, depending on the size of panel and type of fixing system chosen.

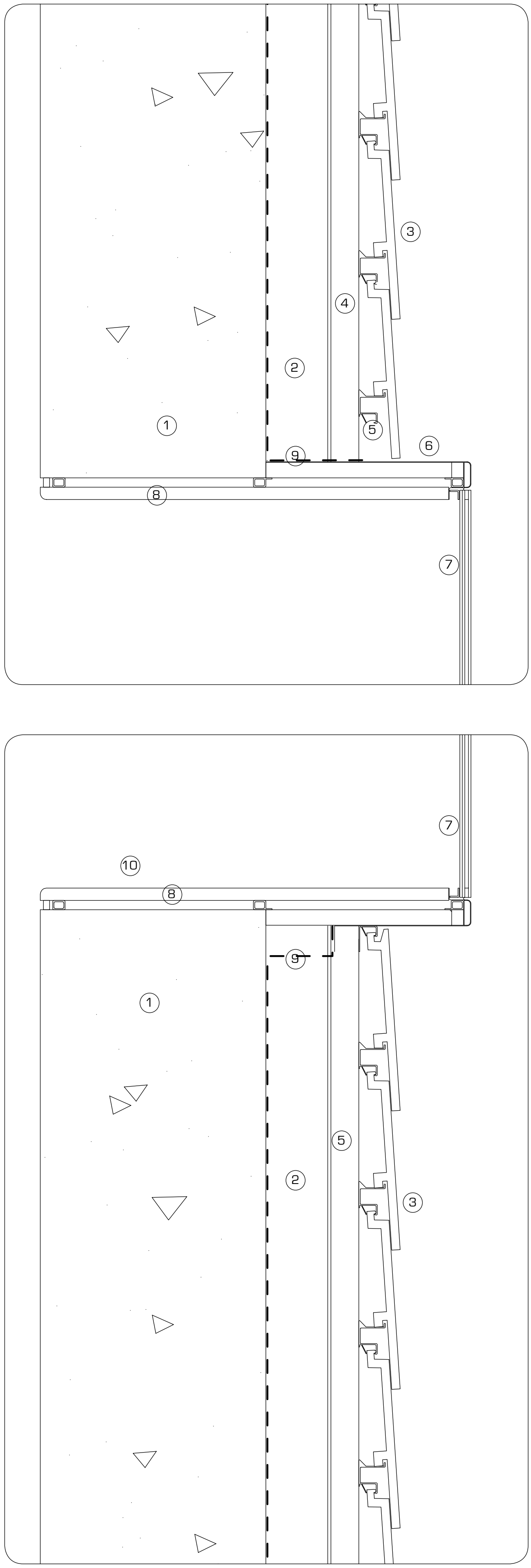
The largest panels are planks up to around 1500mm long x 600mm wide x 40mm thick, requiring a more substantial aluminium support section behind the panels. The aluminium extrusions, set at the ends of each panel, sometimes project forward of the terracotta as structural fins to provide the rigidity to the support framing without requiring greater depth in the cavity zone behind the terracotta. Where used, the projecting fins give the facade a characteristic appearance of vertical bays of panels, where only vertical backing supports are used, divided by the visible edge of the aluminium support. Corner pieces can be made in sizes of 250mm x 300mm high, which often do not correspond with the maximum length that can be manufactured for the planks, but this constraint will no doubt be overcome with the development of this facade system. Thinner terracotta panels of 30mm thickness are used, in sizes with a maximum length of around 800mm and corresponding maximum height of 300mm. These thinner panels have maximum corner panels of 150mm on one leg and 300mm on the other leg. The minimum sizes that can be accommodated with the vertical rail system are terracotta panels around 200mm long x 200mm high, with a thickness of 30mm to 40mm. Windows and doors are set into terracotta rainscreen cladding by fixing them to, and sealing them against, the backing wall. Aluminium trims used at corners and edges of the panels can also be used to close the gap between terracotta and window, with the trim on the bottom edge of window openings used to provide a cill. Windows and doors are positioned to form a continuity of weather proofing, and are typically set back from the face of the terracotta panels, with the trim providing a crisp edge from a visual point of view.

3D view showing terracotta shingles hung on horizontal rails with projecting window

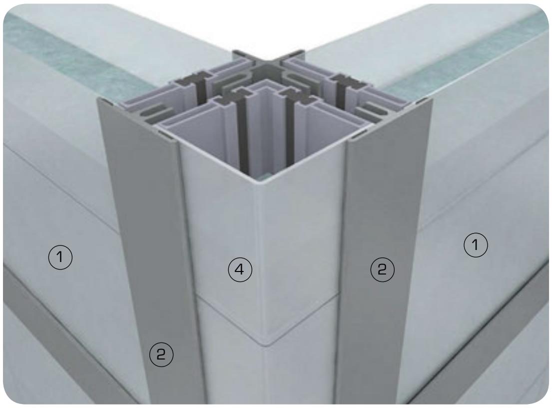


Details
1. Backing wall, typically concrete
2. Thermal insulation
3. Terracotta shingle rainscreen
4. Extruded aluminium carrier frame
5. Support clip, typically aluminium
6. Aluminium window surround
7. Metal framed window
8. Internal plaster finish or dry lining/drywall
9. Vapour membrane
10. Roof construction
11. Metal coping
12. Coping support
13. Stone paving

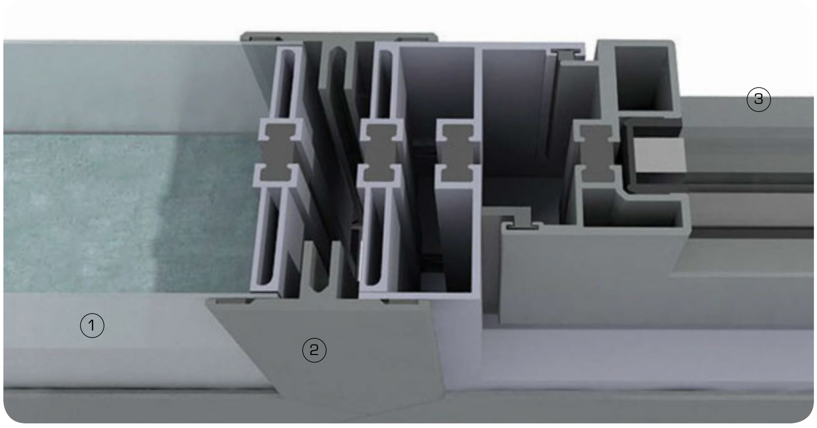
Typically, trims are made from either folded aluminium or rolled steel channels. The flat, planar nature of terracotta has led to the increased omission of reveals around window openings by pushing the window frame forward to align with the face of the terracotta panels, with insulated panels closing the gap between the window and the backing wall. Where terracotta is introduced as the material to form a reveal, corners are mitred with open joints if special corner panels are not used.



Vertical section 1:20. Terracotta shingles fixed to concrete loadbearing wall



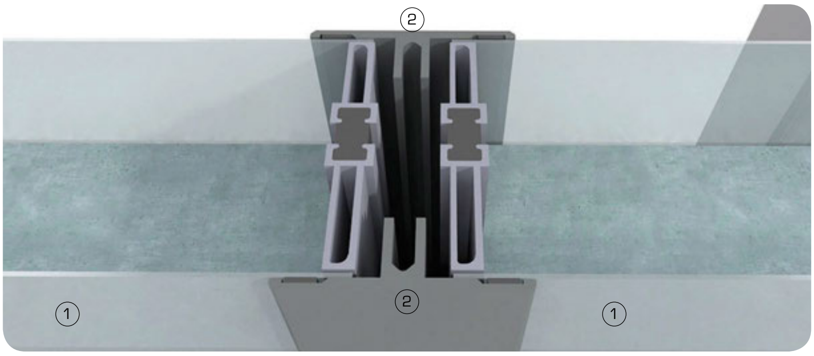
3D detail view showing corner junction of polycarbonate composite panel wall assembly

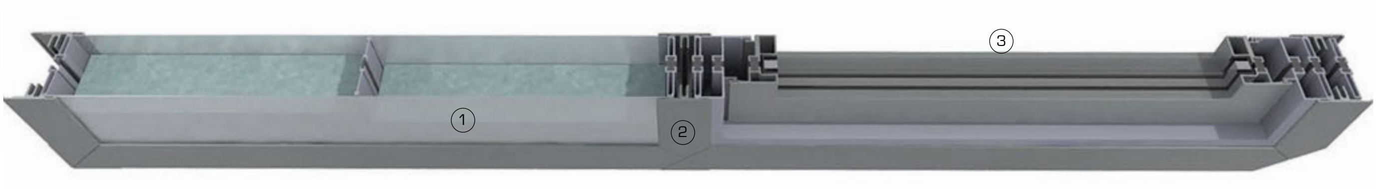


3D detail view showing junction between polycarbonate composite wall panel and window inserted into assembly framing

Details
1. Translucent polycarbonate cladding panel, insulated
2. Thermally broken extruded aluminium framing
3. Window inserted into framing
4. Insulated corner panel
5. Adjacent wall

(Right) 3D detail view showing junction between panels in polycarbonate composite panel wall assembly





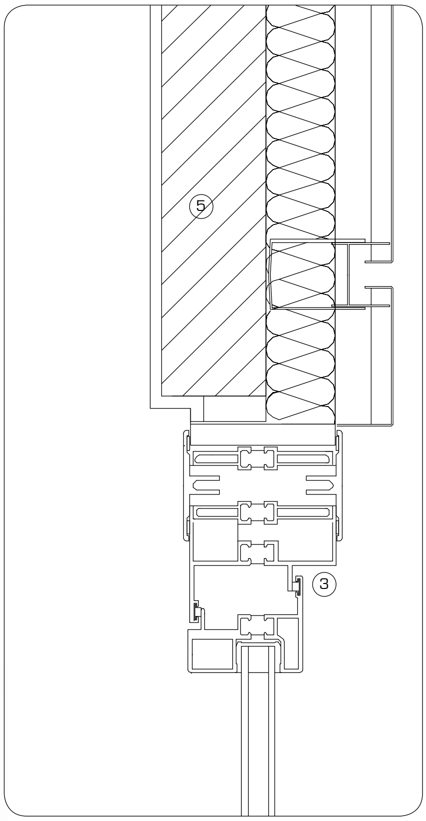
3D sectional detail view showing window assembly within composite panel wall system

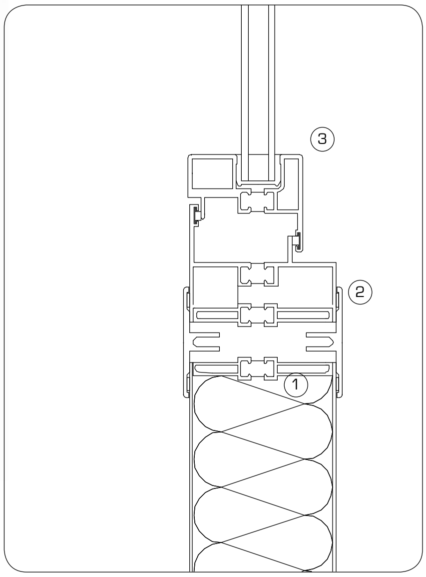
System design
The use of plastics is based on both proprietary systems and those developed by manufacturers for specific projects. Plastics are resinous, polymer-based materials, used in facade systems as the primary material in both sealed cladding panels and rainscreen panels. As sealed cladding panels their use has been enhanced by the successful use of proprietary systems which combine lightness in weight with high levels of thermal insulation with panels of visually elegant appearance. Concerns about the long term weathering aspects of plastics, with their tendency to deteriorate noticeably with time, have been largely addressed by manufacturers. The materials used are principally glass reinforced polyester (GRP), polycarbonate and UPVC. This section discusses the use of GRP in sealed cladding panels which is the most common material used. GRP is a composite material made from thermosetting polyester resins, which set hard and do not melt when re-heated, that are mixed with glass fibre mat. This composite material has high tensile, shear and compressive strength combined with lightness and resistance to corrosion. However, like aluminium it deflects considerably under high loads and requires stiffening, but is more rigid than other plastics. GRP is not combustible and can reach one hour fire resistance in some cladding applications. GRP panels are formed by laying glass fibre cloth into a mould and coating it with resin and catalyst, or alternatively spraying a mixture of glass fibre and resin into a mould. The face of the mould is coated with a releasing agent to allow the GRP to be removed when it has set hard.

GRP panels are characterised by their lightness in weight combined with being manufactured by moulding, allowing them to be made in large panel sizes, up to 6000mm x 1500mm. Panel thicknesses are usually 70-75mm to provide structural stability and high levels of thermal insulation. In common with metal composite panels, GRP panels have undergone much development in the use of adhesives to avoid delamination between the outer skins and the insulation core. GRP cladding panels can be made either as separate panels glazed into an aluminium pressure plate system (in a similar way to glass) with a secondary supporting structure behind, or alternatively by setting thermally broken aluminium extrusions within the depth of the panels. That allows them to be fixed together in the manner of composite metal panels. Panels are also stiffened internally with aluminium I-sections or T-sections where large-scale panels are used. The arrangement of the framing can provide differing amounts of translucency across a panel, where some of the framing is either partly visible, or completely concealed.

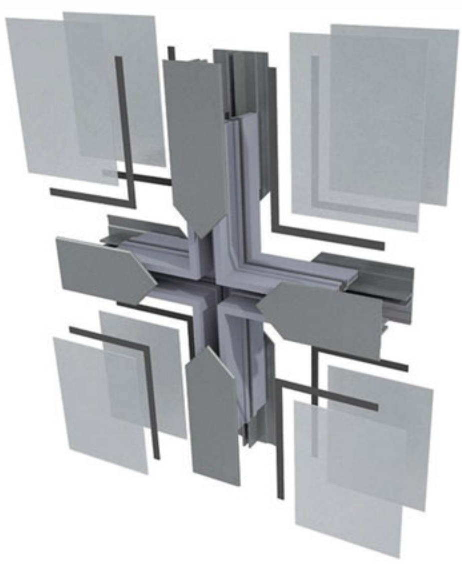
In addition to proprietary panels, GRP and polycarbonate (discussed in the next section) can be used to form larger scale panels which are made by fabricators for individual projects. These typically comprise two sheets of either profiled GRP or polycarbonate fixed either side of metal framing spanning floor to floor, or full height with some additional restraint, to suit individual projects. The main issue from the visual point of view is the choice of thermal insulation, which can provide either translucency or opacity. Where translucent sheet is used, the

3D view showing polycarbonate composite panel construction

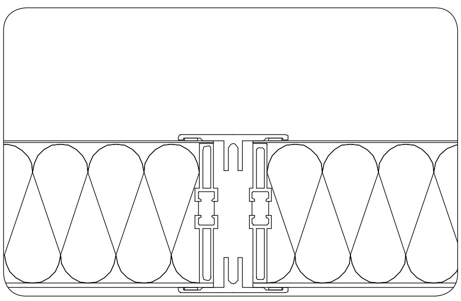


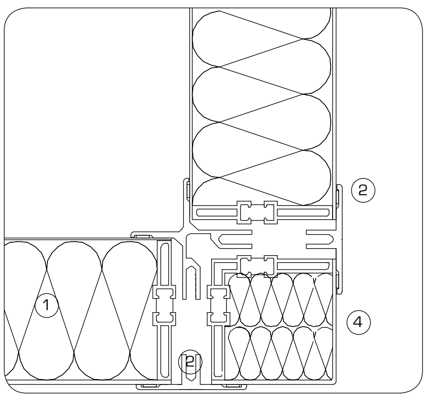


3D view showing polycarbonate composite panel construction

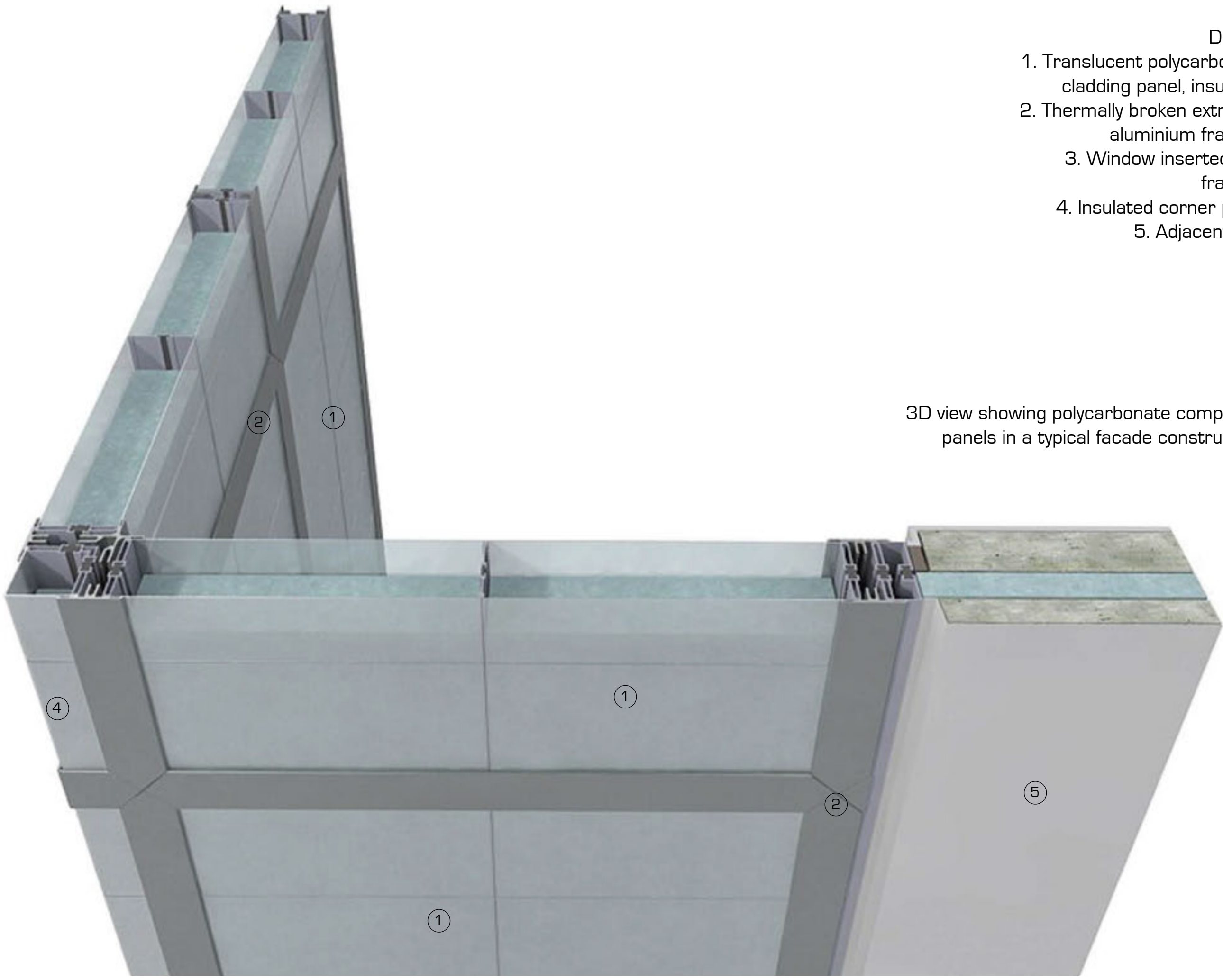


3D exploded detail view showing polycarbonate composite panel construction





Horizontal section 1:10. Wall assembly showing typical details



Details
1. Translucent polycarbonate cladding panel, insulated
2. Thermally broken extruded aluminium framing
3. Window inserted into framing
4. Insulated corner panel
5. Adjacent wall

3D view showing polycarbonate composite panels in a typical facade construction

insulation itself can form the primary visual expression of the facade panel rather than the plastics. Natural materials such as straw bales and wool have been used to this effect.

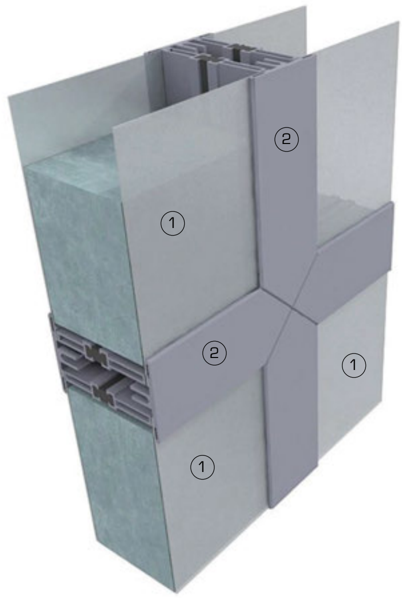
System details

When formed as translucent panels, aluminium framing is set within the panel forming a visible grid resembling that of traditional Japanese Shoji screens. These internal ribs are typically set out on a grid of between around 300mmx300mm to 300mmx600mm centres. The void between the two skins of the panel can be filled with translucent insulation quilt to increase thermal insulation, while still allowing a diffused light to pass through the panel. Light transmission without additional thermal insulation is typically around 15%, with a U-value of 1.5W/m^2 ºK, similar to an argon filled double glazed unit, and a shading factor of 20%, which provides a high level of shading for a glass-based wall. Windows can be glazed into the panels, giving the possibility of a rich mix of windows, doors and translucent panels without the need for complex framing. Window frames can form part of the T-section extrusion around a window. Integrating the window frame into the extrusion that supports the GRP panels avoids the risk of leaks associated with single silicone-sealed butt joints when a separate window frame and panel frame are fixed together. The integrated window frame allows water to be drained from the frame. GRP panels can be glazed into large structural openings, from floor to ceiling for example, or can form a complete glazed wall, restrained by a secondary steel frame. When glazed into an opening, the edge T-section aluminium profiles are sealed against the adjacent concrete floor slab with silicone, at both top and bottom. When fixed to a secondary support frame, panels are supported at each floor level on metal brackets in either aluminium, mild steel (if internal) or stainless steel (if exposed to the weather). Cills and copings are formed with the methods described in the section on metal composite panels.

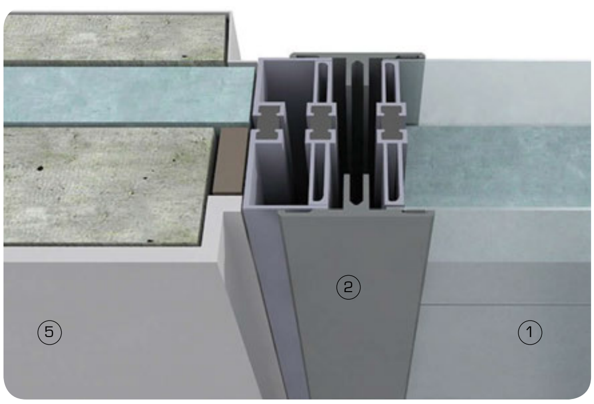
Where twin wall polycarbonate is used in conjunction with other plastic-based panels, the material is fixed with either conventional aluminium framing for windows or, alternatively, framing for stick glazing curtain walling. Some manufacturers provide extruded I-sections, similar to those used in GRP cladding, to clip the twin wall sheets to provide a completely lightweight system. This is a very economic form of cladding which can be screen printed to create visually dramatic translucent facades. As with profiled polycarbonate sheet, other standard components are not usually manufactured, and folded aluminium sections are used for drips and parapet copings instead of polycarbonate sections, which are expensive to produce as new profiles. Although plastic-based panels are usually made as panels fabricated in a factory and fixed together on site in an extruded aluminium glazing system, they can also be formed on site by fixing plastic-based sheet on either side of metal framing supports. The cladding may be formed into panels or as a continuous wall structure. The use of translucent insulation as an infill material that is not fully bonded to the supporting plastic skins provides considerable possibilities for innovation.

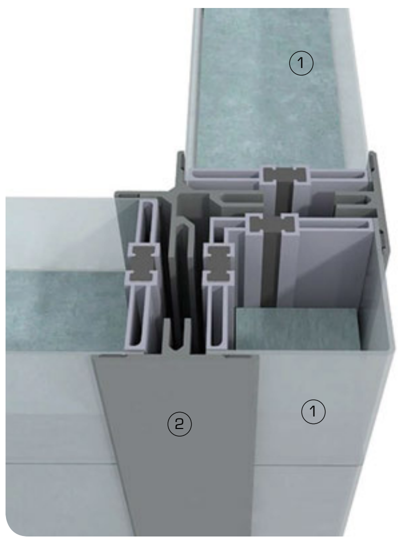
3D view showing polycarbonate composite panels in a typical facade construction

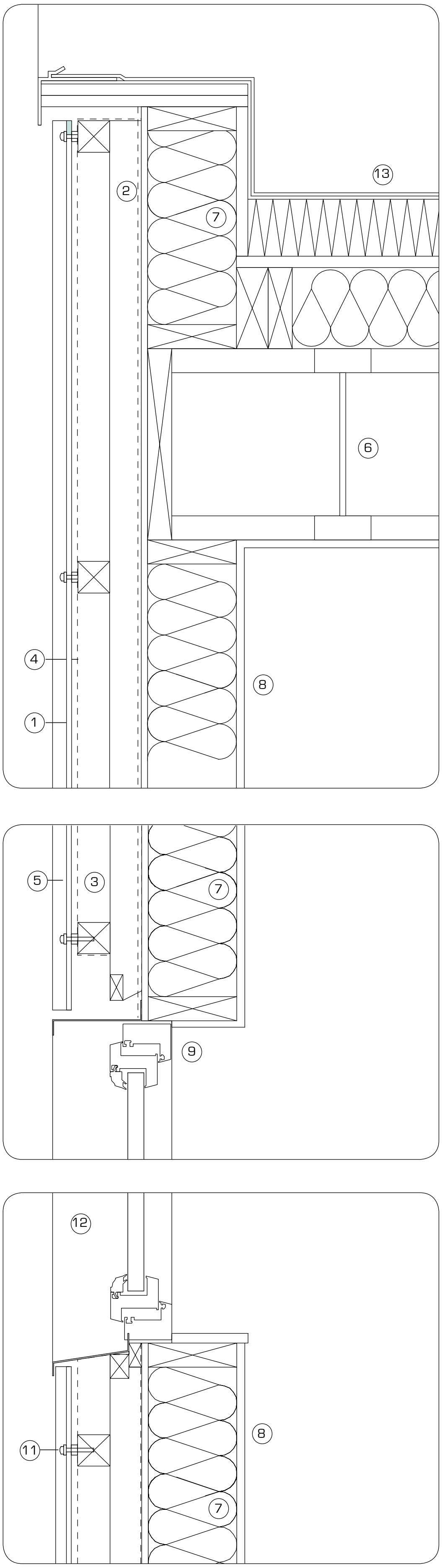
3D detail view showing polycarbonate composite panel construction



3D detail view showing polycarbonate composite panel construction

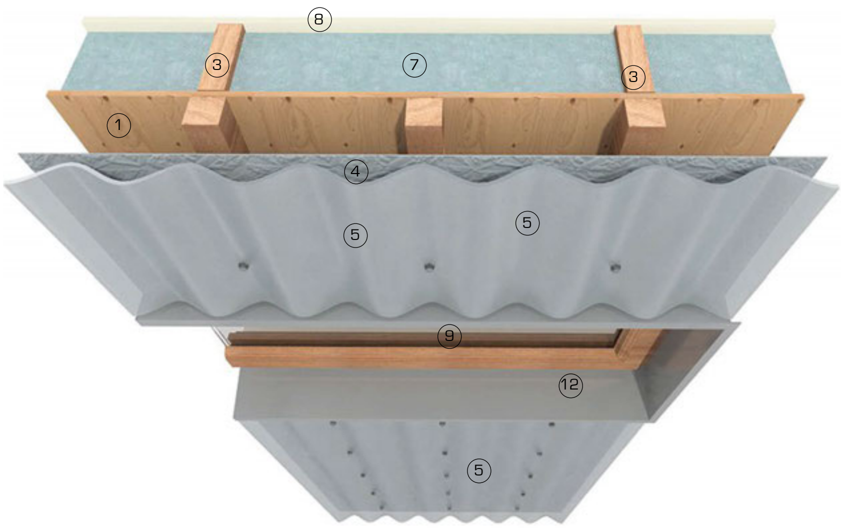


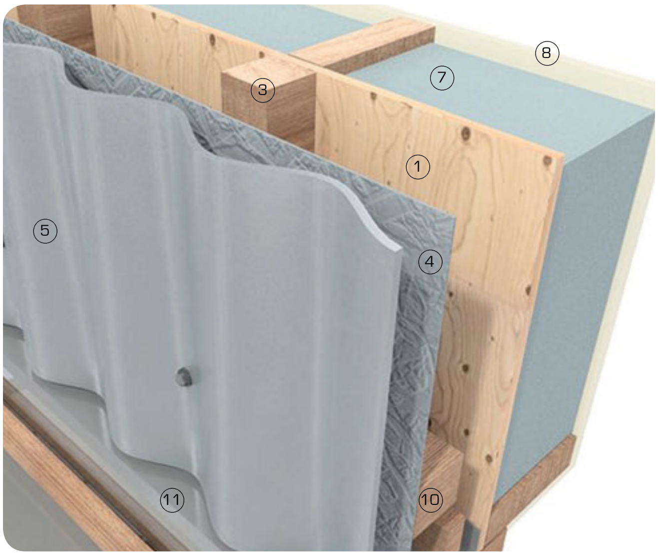


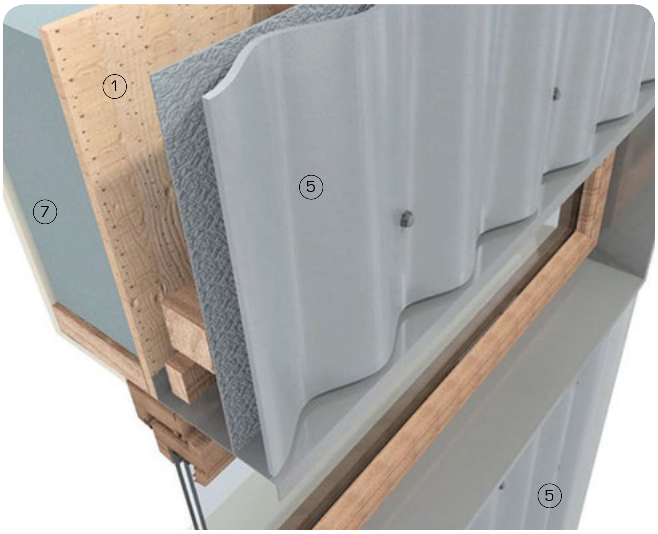


Vertical section 1:10. Polycarbonate rainscreen cladding

3-D views showing section through polycarbonate rainscreen







3D detail view showing cutaway through polycarbonate rainscreen

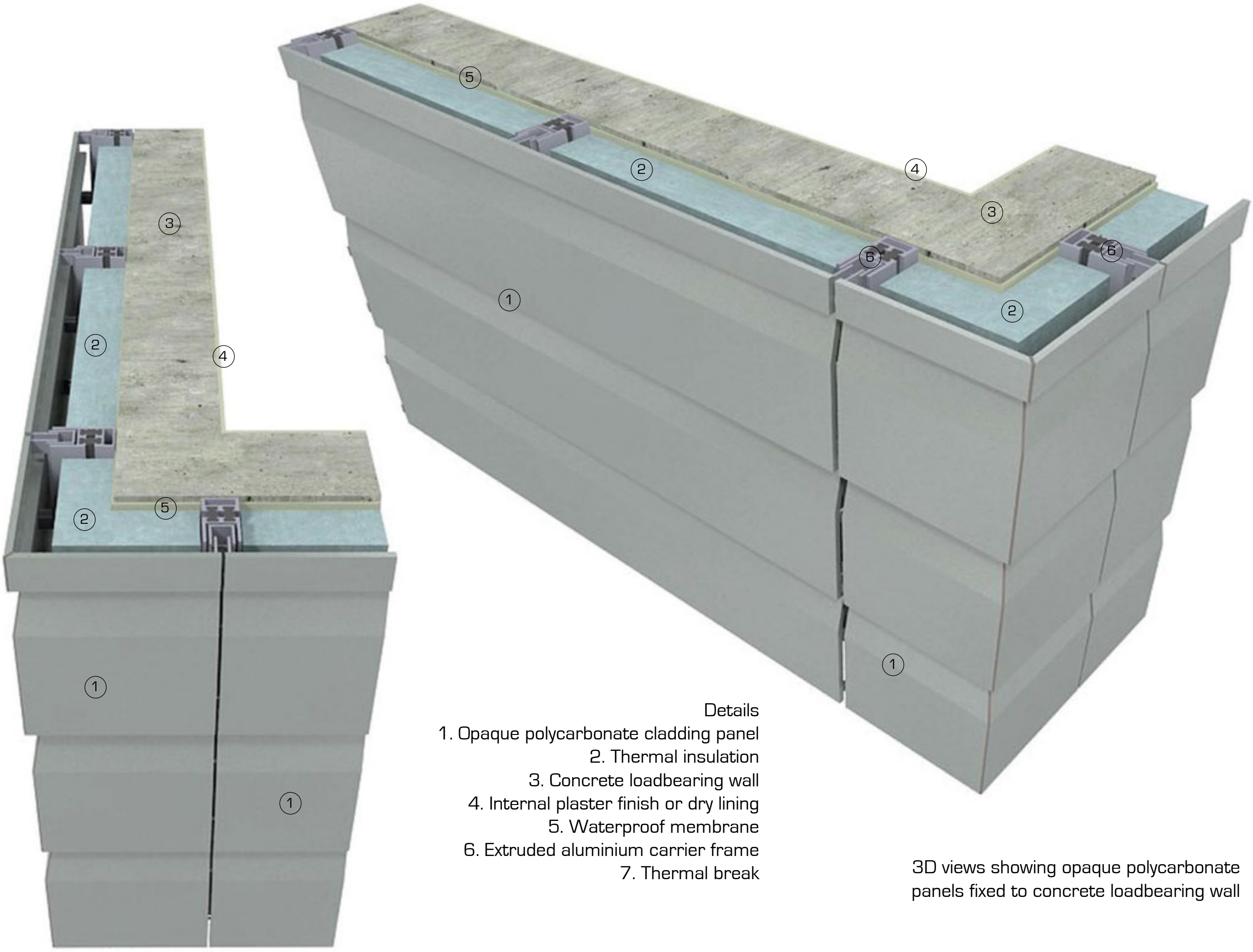
Details
1. 10mm plywood sheathing
2. Breather membrane
3. Vertical timber battens
4. Reflective foil breather membrane
5. Profiled polycarbonate cladding (orientated vertically)
6. Composite timber joist
7. Thermal insulation
8. Internal dry lining
9. Timber framed window
10. Horizontal timber battens
11. Screw fixing with plastic spacer
12. Aluminium window surround
13. Roof construction

System design

Plastic-based rainscreens are use in a variety of types reflecting the overall range made in other materials: flat panels, cassette panels, profiled sheet and shingled tiles. Plastic panels are used as either outer screens to glazed walls, typically as solar shading, or as rainscreen panels to an opaque wall. The materials used are either polycarbonate or glass reinforced polyester (GRP). The use of GRP is discussed in the previous section. Acrylic and UPVC, while softer than both these materials, are used for window frames and special moulded elements. In addition, composites are used for cladding panels, made from thermosetting polymer resins mixed with cellulose fibres to provide sheet materials with high durability which fade little in sunlight. In common with rainscreens in other materials, panels or sheets are fixed with either visible point fixings, vertical/horizontal rails with partially concealed framing members, or partially interlocking panels where there is no view through the joints. Polycarbonate is a thermoplastic, that is to say it melts at high temperatures, which is used in cladding for its translucency and transparency, achieving up to around 90% light transmission. The material is extruded or moulded (from polymer-formed granules) to form sheet materials that are flat or profiled. Polycarbonate has a tendency to yellow with age, which can be overcome with an acrylic coating. It is also used for its high strength and impact resistance, ductility and lightness in weight. However, because the material is combustible, its use in facades is limited. It is also less durable than glass, scratching easily which makes the surface dull with time, and has high thermal expansion, up to 20% more than glass. Opaque flat sheet is fixed as rainscreen cladding panels, made in a wide range of colours, Sheets are fixed either at their corners with an aluminium clamp on both sides, or with visible point fixings. Generally, plastic panels can be used with the full range of rainscreen configurations of other materials, including the lapped construction of timber boards and shingles. Like sealed plastic panels, plastic rainscreen panels have the benefit of translucency, though the visual effects of dust settling on the rear face of the rainscreen, and any periodic cleaning they may require, varies between facade applications.

System details

Single layer polycarbonate sheet sizes are around 2000mm x 3000mm and 2000mm x 6000mm, in thicknesses from around 3mm to 8mm. Profiled sheets are produced in lengths up to around 10 metres, around 1200mm wide, with thicknesses around 1mm. When opaque colours are used, rather than the translucent or clear types, hook-on fixings can be secured to the rear face of the panel, secured to vertically- or horizontally-set rails without the fixings being visible. Profiled sheets are fixed with self tapping screws sealed with a weathertight washer and lapped on all sides, in the manner of profiled metal sheet. This technique creates a shadow where they lap, which can be masked by the support structure behind, or may even contribute to the overall visual effect. Cill, drip and coping profiles are made



Details
1. Opaque polycarbonate cladding panel
2. Thermal insulation
3. Concrete loadbearing wall
4. Internal plaster finish or dry lining
5. Waterproof membrane
6. Extruded aluminium carrier frame
7. Thermal break

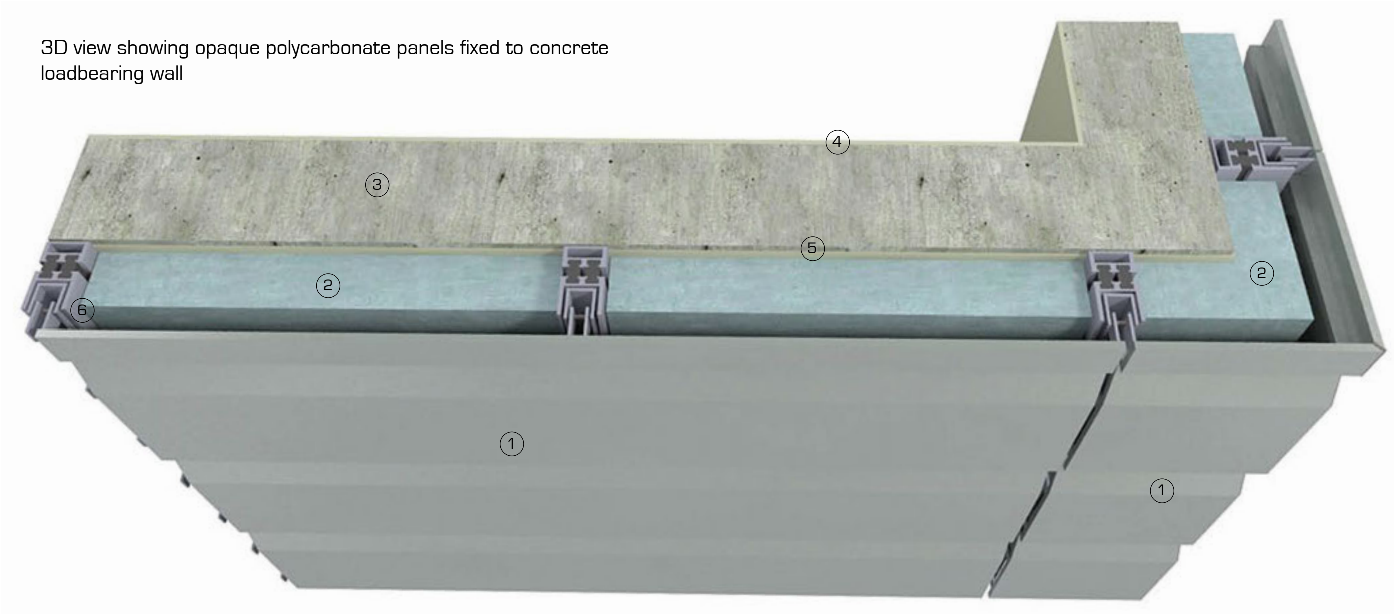
3D views showing opaque polycarbonate panels fixed to concrete loadbearing wall

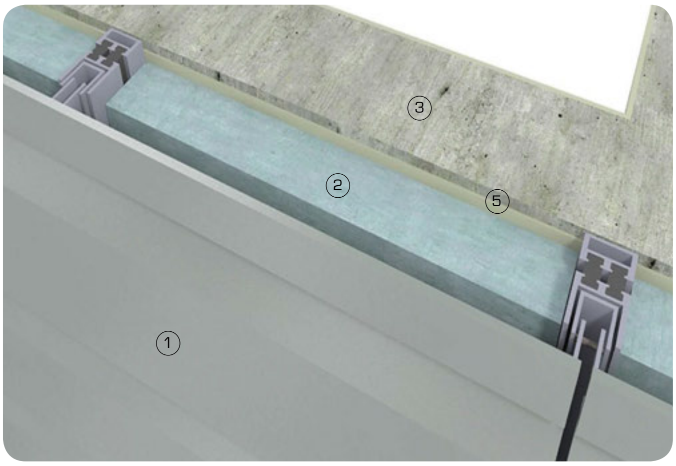
from any of the typical materials used: extruded aluminium, extruded UPVC or GRP. Profiled sheet can be curved to a minimum radius of around 4000mm for a sheet of 50mm thickness, making it possible to create complex geometries with an economic translucent material. Profiled polycarbonate sheet is also made in a translucent white colour to provide a light transmission of around 45% and in grey colours with light transmission of around 35%. Multi-wall polycarbonate sheet can also be used for rainscreens, where its main advantage is the ability to provide large, flat panels as well as its inherently high level of thermal insulation. Thicknesses range from 4mm to 32mm in sheet sizes from 1000mm x 6000mm to 2000mm x 7000mm. The material can be screen printed or coated to provide a wide variety of colours on a large format sheet. As with flat sheet, the material can be coated to give UV protection on one side or both sides to avoid yellowing. The sheet material is used in increasing numbers of walls, from twin wall to five or six walls thick. Panels are fixed using the same methods as flat sheet, with thicker sheets being supported up to around 1800mm centres. Panels can be curved by setting them into a pre-formed aluminium edge frame, when the material can be curved to a minimum radius of 1500mm for twin wall sheets and around 4000mm for the thickest sheets.

Plastic-composite flat panels typically have a mixture of around 70% softwood fibre and 30% resin, manufactured at high temperature and pressure to provide coloured panels of smooth and almost impervious surface. Although the finish colour is formed by using pigmented resins as a top coat in the mould, the colour extends all the way through the material, allowing cut edges to be visible. Plastic-composite panels have high UV resistance, high colour stability, high fire resistance and can be cut and drilled easily, allowing them to be used as overlapping shingles. Their high impact resistance makes them well suited to conditions susceptible to damage. The material is made in sheet sizes from 3600mm x 1800mm, 3000mm x 1500mm and 2500mm x 1800mm in thicknesses from around 5mm to 12mm. Corner panels and parapets are also manufactured in the same material. Plastic-composite flat panels can be fixed with visible fixings or concealed point fixings.

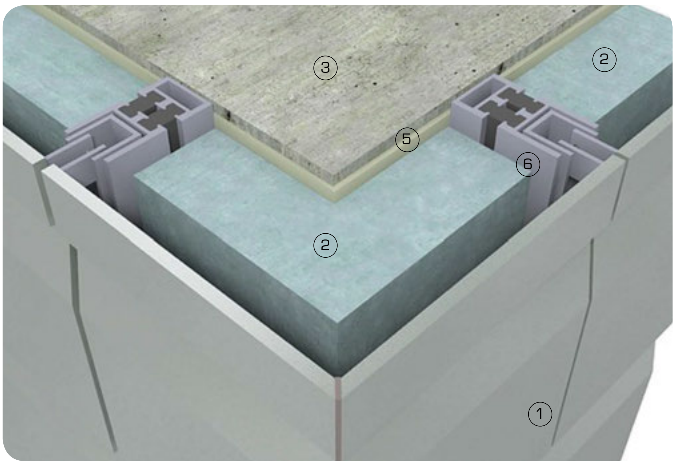
Polycarbonate is generally a more expensive material than GRP, making GRP more suitable for lower cost applications. However, GRP has one advantage over all the other plastic-based materials, which is its ability to be moulded easily and economically for small scale applications. When used as rainscreen panels the material needs a top gel coat to avoid its fibres being seen. The ability to see the fibres through the material makes it very unsuitable for transparent or translucent panels, but for moulded rainscreen panels it is possible to introduce some 3-D modelling into the facade panels. GRP can be bonded to honeycomb panels formed in the same material to produce large panels with high fire resistance.

3D view showing opaque polycarbonate panels fixed to concrete loadbearing wall





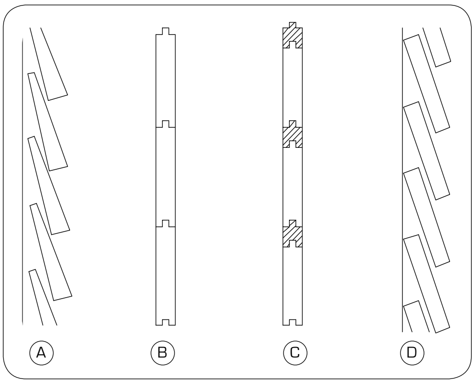
3D detail view showing vertical rail fixing opaque polycarbonate panels to concrete loadbearing wall



3D detail view showing corner fixing of opaque polycarbonate panels to concrete loadbearing wall

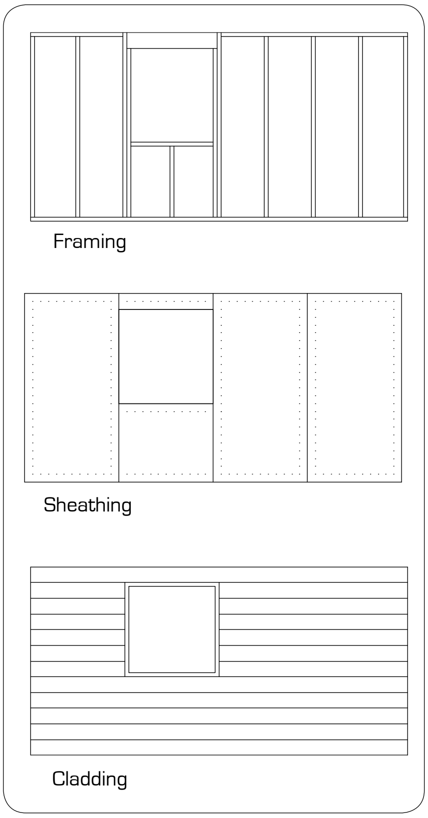
3D views showing opaque polycarbonate panels fixed to concrete loadbearing wall

3D view showing cutaway section through typical wall construction



Boarding arrangements
A. Feather edge boarding
B. Tongue-and-groove boarding
C. Tongue-and-groove boarding with inserts
D. Shiplap boarding

Details
1. Timber boards
2. Timber battens
3. Plywood sheathing
4. Timber studs
5. Timber rail
6. Breather membrane
7. Engineered floor joist
8. Damp proof course
9. Vapour barrier
10. Timber floor
11. Concrete ground slab
12. Internal plaster finish or dry lining/drywall
13. Thermal insulation quilt set within timber frame
14. Timber framed window
15. Timber cill
16. Air gap
17. Roof buildup



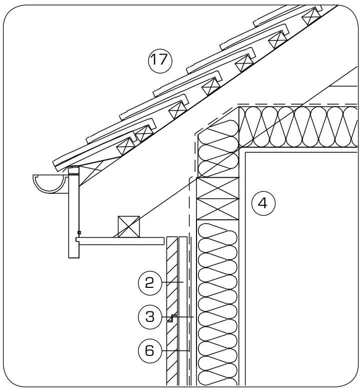
Assembly sequence

System design

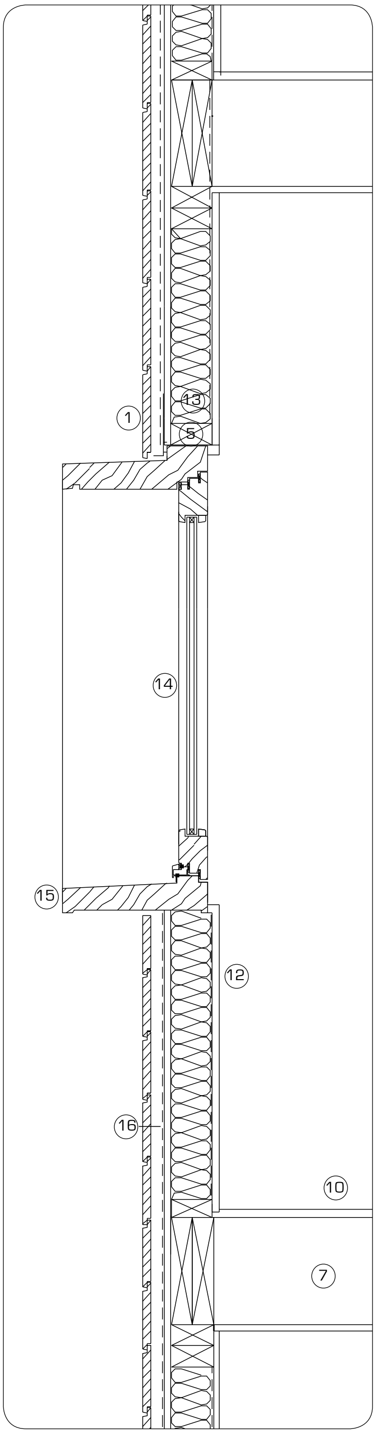
There are two enduring generic forms of loadbearing timber frame that use small section timbers to form framed loadbearing walls: the platform frame and the balloon frame. Both the platform frame and the balloon frame are based on softwood sawn timber sections. The platform frame comprises studs spanning from floor to floor, with the timber floor structure being supported at each storey height set of timber frames. The balloon frame, which is now used to a much lesser extent, is enjoying a revival in light-gauge steel sections. This method has vertical framing members which are continuous, with the intermediary floors being supported by the wall running continuously past it. A recent development has been in 'solid' construction rather than the framed type. Laminated structural timber has been developed to make wall panels as complete proprietary systems where the material is glued together to make full timber panels. Thermal insulation is added to one side of these panels, with the possibility to expose either the outside or inside, depending on exposure and location, but mostly these panels are clad with an additional material on the outside to provide weather resistance. Another system, where plywood is bonded to each side of a rigid insulation panel, called structural insulated panels, or 'SIP' panels, provides a solid panel where the insulation holds the structural plywood sheets in place, allowing timber wall construction to be thinner and lighter.

Timber frames comprise studs (vertical sections) fixed to rails (horizontal members) which are clad with plywood sheathing to provide lateral bracing, typically 12mm-18mm thick, depending on panel size and loads. Timber boards can also be used as sheathing, but this is an expensive solution. Framing members are typically formed from 100x50mm softwood sections at 400mm vertical centres which are nailed together. Voids between the framing members are filled with thermal insulation. A breather membrane is then fixed to the face of the sheathing layer. This provides a waterproof barrier which also allows the vapour to escape, allowing the timber wall to release and absorb moisture with changes in the weather. Outer timber cladding boards are then fixed on the outside of the breather membrane. Traditionally, timber cladding was used to stiffen the structural frame by fixing the boarding directly to the frame, with a breather membrane set between the frame and the timber boards as a weatherproof layer. More recently, the timber cladding is fixed to battens set forward of the breather membrane, or waterproofing layer, to ensure that the timber is ventilated on both sides. The inside face of the timber framed wall has a continuous vapour barrier set (in temperate climates) on the warm-in-winter side of the wall. The inner face of the wall is then finished with a dry lining.

Solid laminated structural timber is made in panels up to approximately 16000mm long, 3000mm wide and to a maximum thickness of around 500mm, varying between proprietary systems. The main benefit of the system is that it provides an alternative to steel and concrete frames for larger scale projects. This panel system has recently been used for

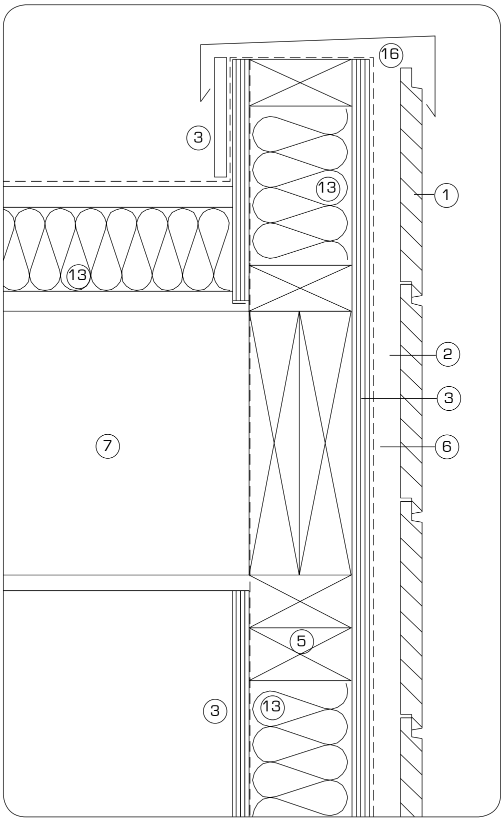


Vertical section 1:20. Roof junction



Vertical section 1:20 showing typical details

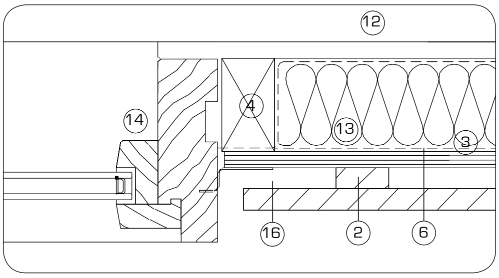
3D view showing cutaway section
through typical wall construction



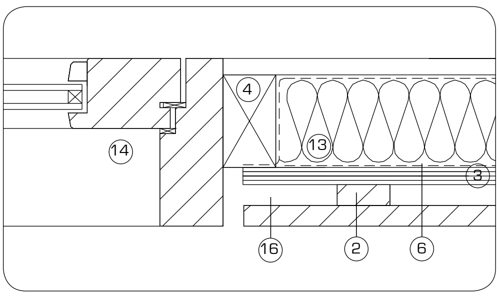
Vertical section 1:20. Flat roof connection

Details

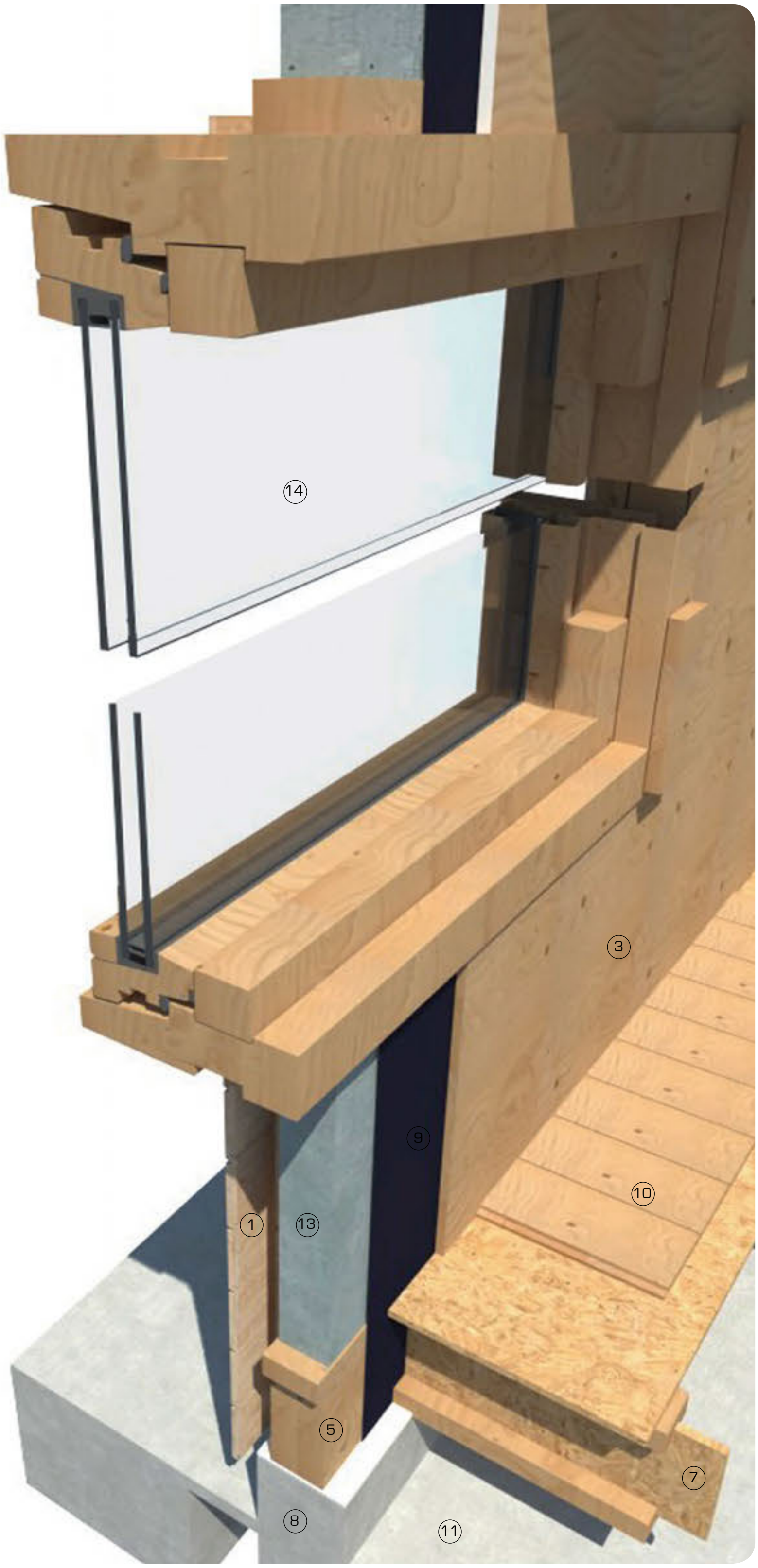
1. Timber boards
2. Timber battens
3. Plywood sheathing
4. Timber studs
5. Timber rail
6. Breather membrane
7. Engineered floor joist
8. Damp proof course
9. Vapour barrier
10. Timber floor
11. Concrete ground slab
12. Internal plaster finish or dry lining/drywall
13. Thermal insulation quilt
14. Timber framed window
15. Timber cill
16. Air gap



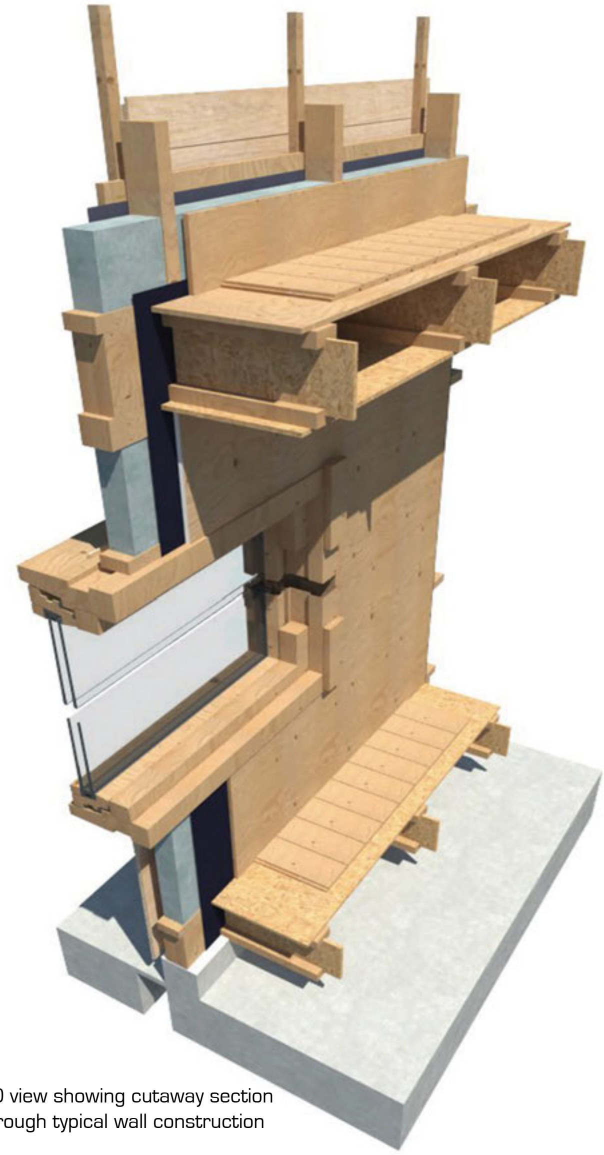
Horizontal section 1:5. Outward opening window



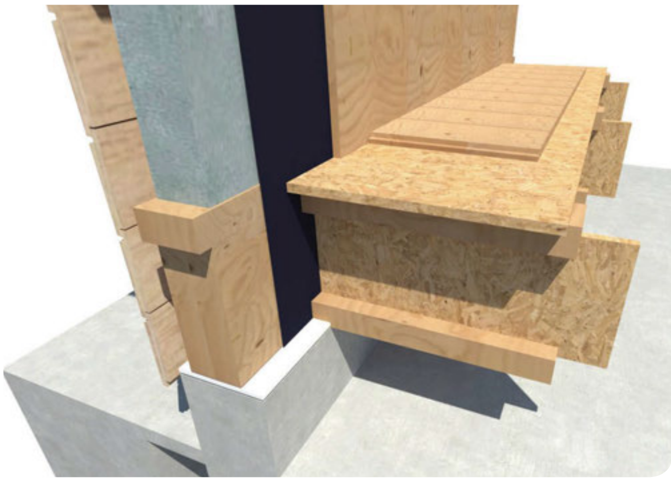
Horizontal section 1:5. Inward opening window



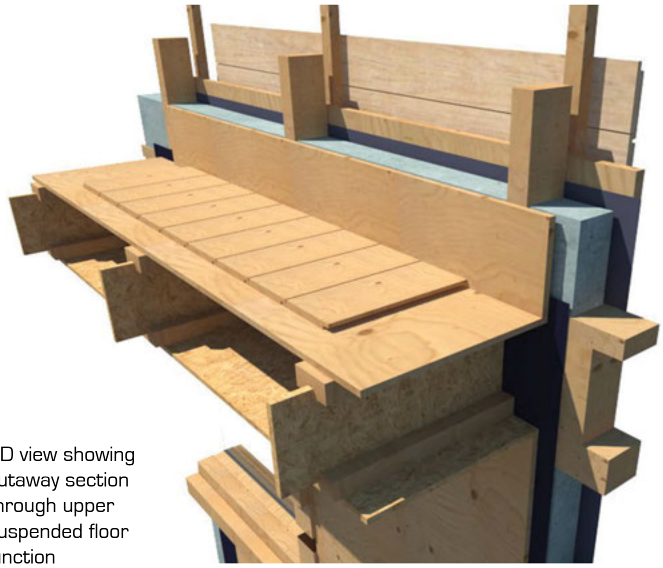
3D view showing cutaway section through typical wall construction



3D view showing cutaway section through typical wall construction



3D view showing cutaway section through ground floor junction



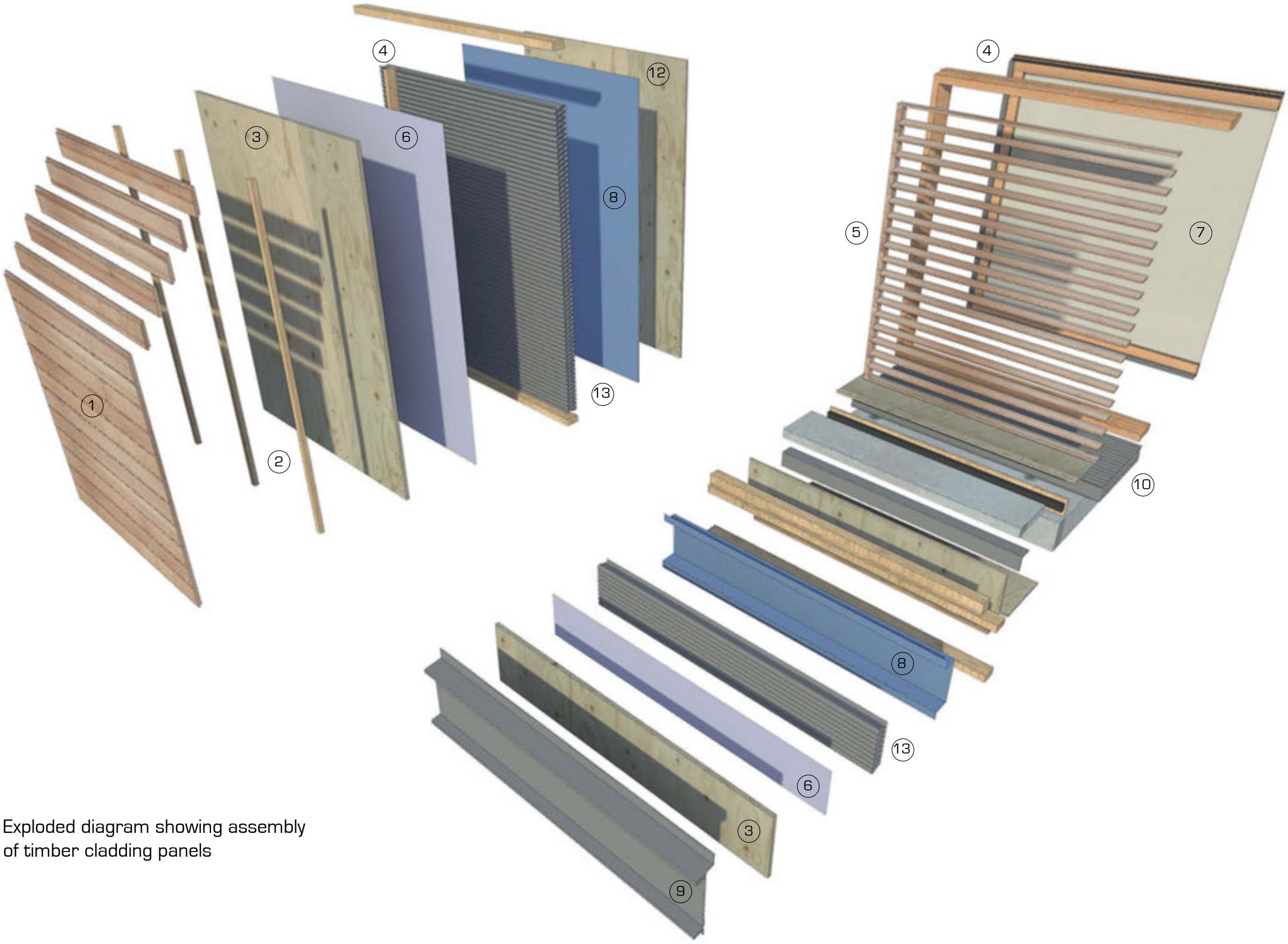
3D view showing cutaway section through upper suspended floor junction

buildings up to eight storeys high, providing loadbearing walls in a single material which is light in weight. Structural insulated panels, with integral insulation, are made in panels up to approximately 6500mm long, 1200mm wide and in thicknesses up to around 150mm, depending on the manufacturer. Curved wall panels are made to shallow radius. They are used typically as a direct alternative to traditional timber framed construction, and like laminated timber panels, are set to become more widely used in timber construction.

System details

For all these timber wall types, the timber cladding is terminated at ground level at a minimum of 150mm above external ground level. The cladding is usually supported at ground level on a concrete slab or edge beam that forms part of the concrete wall. Alternatively, the wall can span between concrete pads at 3000mm–5000mm centres, with timber beams at the base of the wall to provide support between pads. Where an expression of a concrete floor slab is required, the edge of the slab is covered with thermal insulation, with an additional outer protection, typically a thin concrete facing panel. The timber wall frame is usually set on a continuous timber section at ground level, which is first fixed to the concrete slab to provide a level surface to set the timber in place. A damp proof course (DPC) is set beneath the continuous timber base plate usually extending down the vertical face of the concrete slab where it connects with the damp proof membrane (DPM) beneath the concrete slab or the vertical face of the basement wall. The DPC is also made continuous with the DPM set on top of the concrete slab. Where concrete foundation pads are used, the timber beam is set into stainless steel shoes fixed to the pads. Timber can also be supported on brick walls set at a minimum of 150mm above external ground level and be supported on a concrete strip foundation or ground beam. An insulated raised floor is then set into this brick wall. The void beneath the timber floor is ventilated with air bricks that encourage cross ventilation. This avoids stagnant air in the void from damaging and eventually rotting the timber floor.

Corners, both external and internal type, are formed typically with a timber bead set so that the timber boards on both sides butt into it. If a breather membrane is used behind the cladding, then an additional waterproof flashing is added to the corner. This is formed in a durable polymer-based sheet or metal sheet. Alternatively, the boards can be allowed to make a corner with a butt joint, and an additional L-shaped timber trim, formed from two separate timber sections, is added on the face of the corner to protect the exposed end grain of one of the sides forming the corner. Boards can be joined with a mitred joint (45º) without any cover strip but the timber used must be of the highest quality to avoid the joint opening up with moisture movement. A waterproof layer or flashing is set behind the mitred joint.



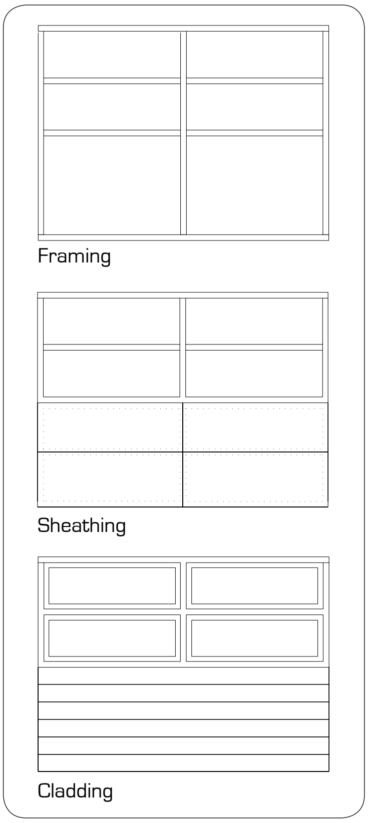
Exploded diagram showing assembly of timber cladding panels

System design
Timber cladding panels have been more widely used in recent years as a method of cladding steel and concrete frame buildings with prefabricated, factory made panels that have a natural finish. They are also used in twin wall facades, or 'double skin facades' where an inner timber wall with window openings has an additional glazed screen set approximately one metre in front of it to provide a thermal buffer to reduce the effects of heat and cold at different times of the year, as well as allow the windows to be opened in taller buildings. Where timber cladding panels are fixed to a timber frame, or structural laminated frame, the cladding panels can be set between timber columns as well as in front of them to give a combined timber frame and panel building using a single primary material system. These cladding panels are typically faced in timber boards in rainscreen configuration. A recent addition to the language of timber rainscreens has been the use of thin slats to create a degree of translucency in timber screens, particularly when set forward of windows set into the panel behind. This can create a visually rich mix of timber panel assemblies that use a single timber species. However, the higher moisture movement associated with timber has the consequence of requiring junctions between cladding panels to provide an allowance for both structural movements and moisture movements both between cladding panels as well as within the panel itself.

Where timber cladding panels are set forward of floor slabs in the manner of glazed curtain walling, panels extend from floor to floor, either hung from a floor slab or, more typically, supported on it at floor level. Vertical joints between cladding panels have a stepped joint to allow for deflections in floor slabs between panels, following principles of glazed curtain walling. This stepped joint is covered on the outside with timber boards, set forward of the face of panels on battens in rainscreen configuration. The construction of panels follows the same principle of timber cladding described in the previous section. Horizontal joints have an inner chamber formed between two adjacent panels. Any rainwater that penetrates the outer seal, which is also kept open in some designs, is drained down an inner chamber where the water is discharged through the horizontal joint at the bottom of the panel. Where timber cladding is used in twin wall construction as an inner wall to an outer glazed wall where the outer wall provides a thermal buffer, the outer screen provides protection by allowing the material to maintain its appearance without full exposure to outside conditions, other than the effects of the sun which cause the timber to change colour.

When cladding panels are set onto floor slabs, and restrained at the slab above, timber posts that may form part of the structure can also be set between panels rather than inside the building, since there is no significant thermal bridge from

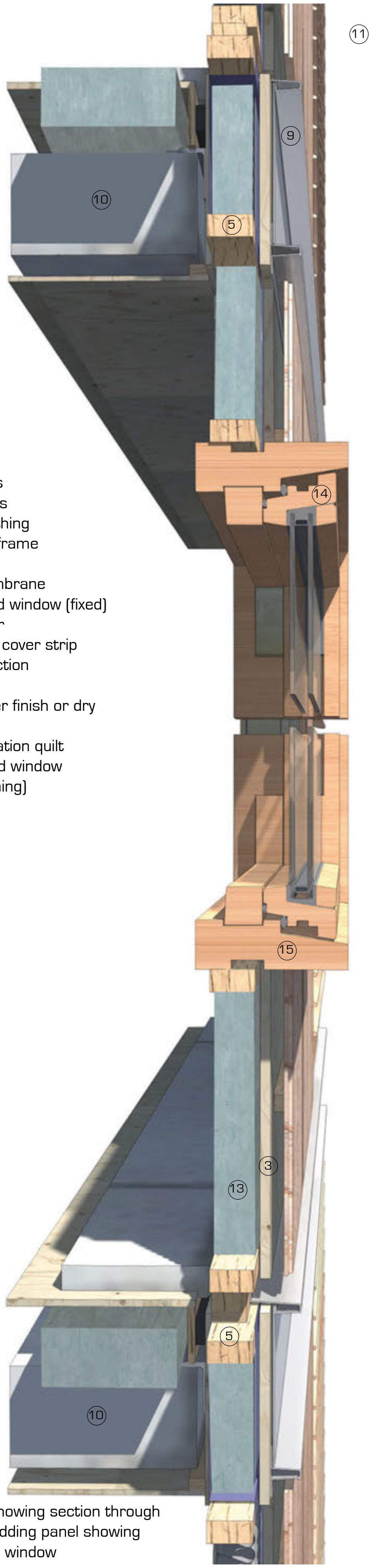
Elevation of timber cladding panels showing relationship with structural frame



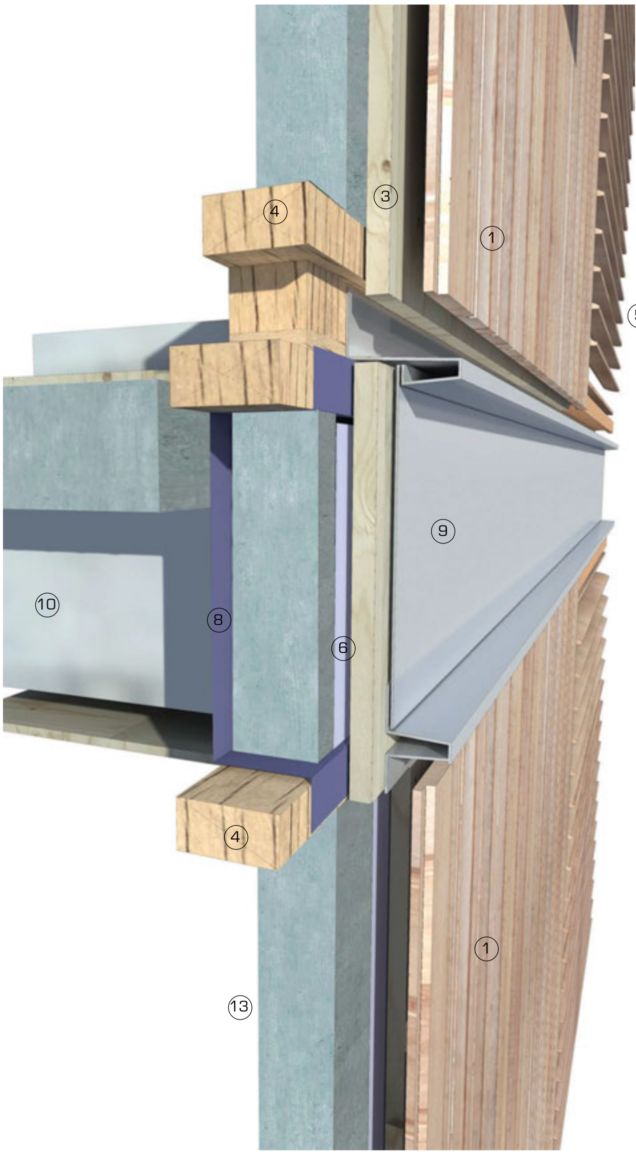
Assembly sequence

Details

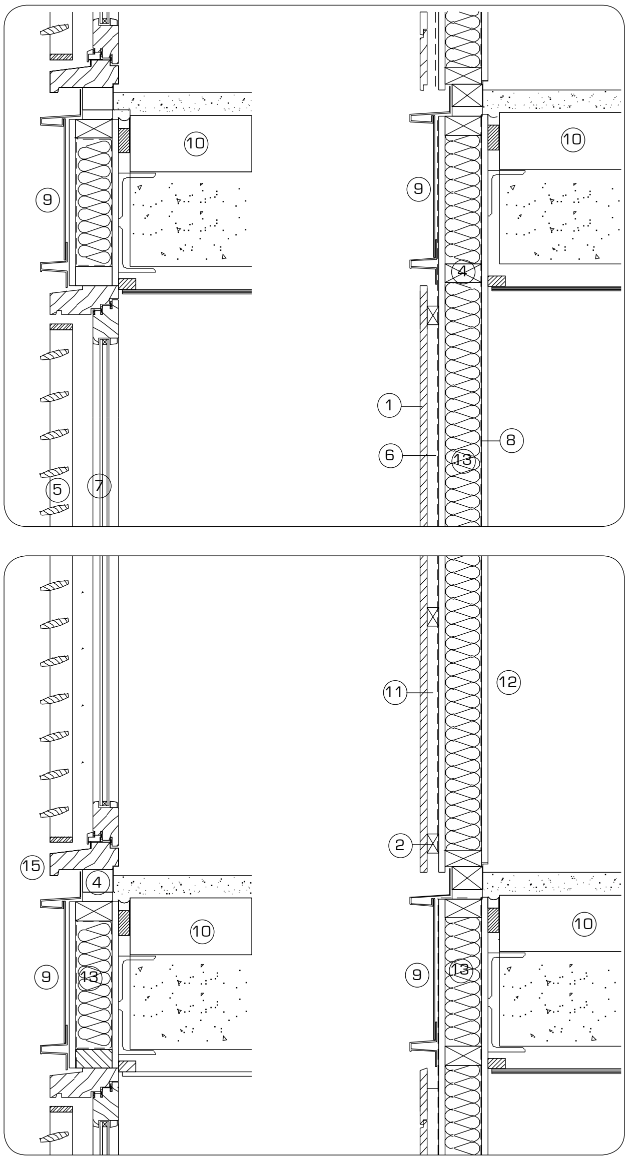
1. Timber boards
2. Timber battens
3. Plywood sheathing
4. Timber panel frame
5. Timber louvre
6. Breather membrane
7. Timber framed window (fixed)
8. Vapour barrier
9. Profiled metal cover strip
10. Floor construction
11. Air gap
12. Internal plaster finish or dry lining/drywall
13. Thermal insulation quilt
14. Timber framed window (outward opening)
15. Timber cill



3D view showing section through timber cladding panel showing integrated window



3D view showing connection between timber cladding panel and supporting frame



Vertical section 1:10 through timber cladding panels showing typical details

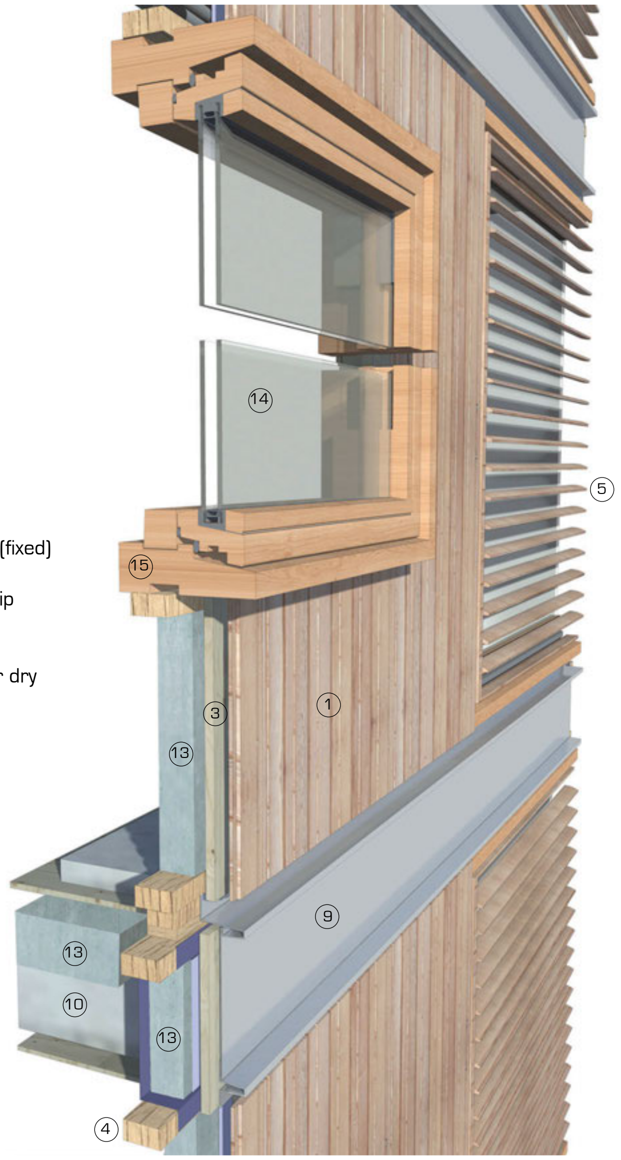
outside to inside, allowing the structural frame to be exposed on the outside. Cladding panels are set into openings in laminated timber frames, with panels supported at their base on the beams set beneath. Floor decks in timber are then fixed to the side of the laminated timber beams. Timber panels are fixed at their base to the beam beneath, but have a lateral restraint at the top to allow the slab and panel above to deflect without damaging the panel below. A metal flashing at the base of the panel drains water and throws it clear of the beam beneath in order to avoid staining of the timber beam. The outer timber rainscreen cladding is set flush with the outer face of the laminated timber frame to avoid any views into the waterproofing layer behind.

System details

Both softwoods and hardwoods are used for cladding panels, with durable hardwoods being more commonly used for rainscreen applications. Where less expensive, less durable timbers are used, higher levels of both protection and maintenance are required. Softwood boards are made usually in 250mm widths, with trimmed boards with profiles routed into them usually trimmed down to 150 - 200mm widths. All timbers vary in moisture content with changes in temperature and air humidity, this being one of the essential aspects to be considered in timber detailing. Most timbers used in cladding will have a moisture content from around 5% to 20% when in use. Similar levels are found in timbers from timber suppliers, and are classified as 'dry', 'kiln dried' or 'seasoned'. The most common types of jointing of boards is 'ship lapping' where timber boards are set horizontally and lapped over one another with the upper board lapped over the top of the board below to protect it from rainwater ingress. Ship lapping can be assisted by the use of 'feathered' or wedge-shaped boards to give the lapping a more elegant appearance. Tongue and groove boards are used to give a continuous flat appearance, while having the advantage of locking boards together into a continuous plate-like structure. Boards are typically around 20mm thick, made as long as possible at around 3000mm – 3500mm, to avoid vertical joints which are a potential source of rainwater penetration except in rainscreen configuration. Timber cladding is finished with the timber being left either as supplied, with preservative applied or injected by the supplier, or alternatively is given coats of preservative in clear, stained or opaque finish on site with preservatives that repel rainwater, or wood stains and paint. Paints can be oil-based or acrylic, while preservatives

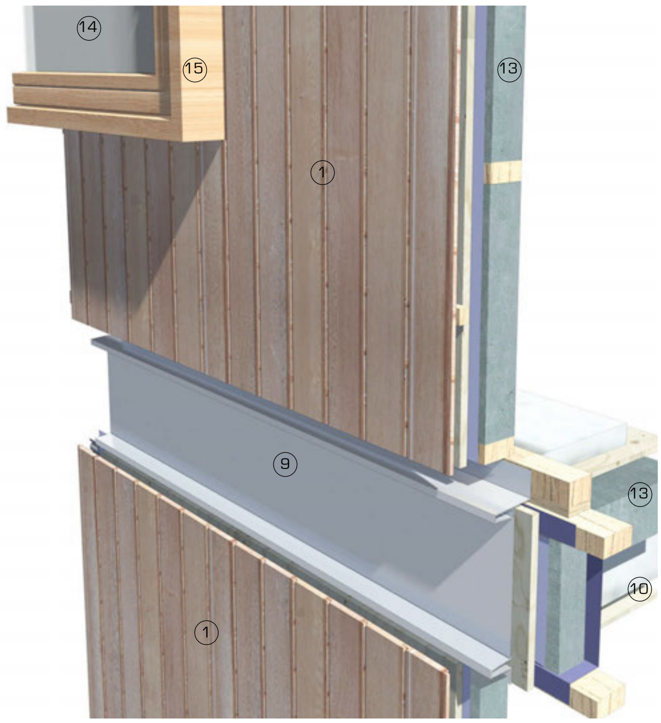
3D view showing timber cladding panel consisting of fixed glazing and louvre screen

Details
1. Timber boards
2. Timber battens
3. Plywood sheathing
4. Timber panel frame
5. Timber louvre
6. Breather membrane
7. Timber framed window (fixed)
8. Vapour barrier
9. Profiled metal cover strip
10. Floor construction
11. Air gap
12. Internal plaster finish or dry lining/drywall
13. Thermal insulation quilt
14. Timber framed window (outward opening)
15. Timber cill



3D view showing cladding panel assembly with built-in opening window

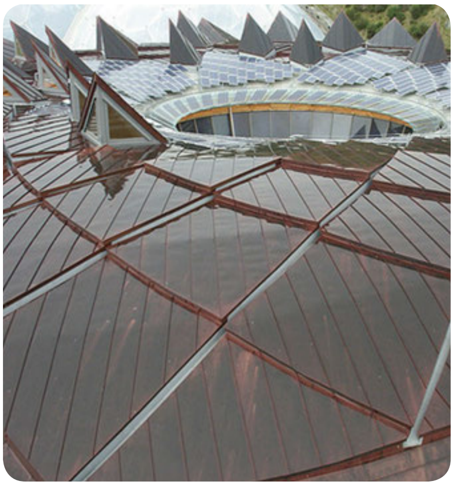
are clear and can be used as a finish that does not appreciably change its appearance. It can also be used before staining or painting the timber. Preservatives help to prevent moisture absorption as well as reduce fungal growth, enhancing the life of the timber but not preventing the material changing colour and fading to its characteristic silver grey appearance. An essential issue in the use of timber cladding panels and rainscreens is the coordination of timber types and finishes used for windows, doors, visible panel framing and rainscreen cladding, in order to give a controlled visual appearance that will weather consistently together.



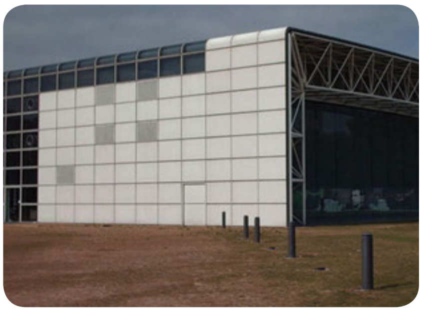
3D view of timber cladding panel assembly

3

ROOFS



metal standing seam: The Core, Eden Project, U.K.
Architect: Grimshaw Architects



top left: metal composite panel:
Sainsbury Centre for Visual Arts, Norwich, U.K.
Architect: Foster Associates.
top right: metal standing seam:
Walt Disney Concert Halll, Los Angeles, U.S.A.
Architect: Frank Gehry
bottom right: profiled metal sheet:
Atelier and House, Bwa-Cho, Japan.
Architect: Shuhei Endo

An overview of roof systems

Where roofs were once considered to be either of traditional appearance, as with tiled and slated pitched roofs, or else completely concealed as flat roofs, they are now increasingly considered to be a part of a completely visible envelope design which is as visually important as the external walls, both in their appearance and their technical performance. In recent projects, walls and roofs are taking on a single form, with the same construction methods, materials and detailing used on both walls and roof. The increased technical performance and long term reliability of roofing materials of all types has led to a much more ambitious design approach. However, an essential difference between facades and roofs is that facades have rainwater running across their surface, but roofs can be submerged in water during rain. A roof has to be completely sealed in areas where water can collect, such as parapet gutters, with the assumption that rainwater will be expected to remain on the roof if the rainwater outlets become blocked.

Metals

The increased reliability of jointing together with the increased use of aluminium sheet, with its increased flexibility, instead of steel sheet has led to more adventurous roof forms without affecting the waterproofing performance. By the early 1990s profiled metal roofs were using standing seam joints, which combined the long span capability of profiled sheet with the visually refined and very water tight standing seams which are 'zipped' together by machine on site. Since the introduction of 'zip up' sheeting, the difference between profiled metal and standing seam systems has reduced, with new hybrid systems having a lining panel system which can be fixed with metal sheets, some of which are being hung down from the roof level without scaffolding. This makes large roof spans, particularly at high level, such as in covered sports halls, much easier to construct since scaffolding is not required.

Composite roof panel systems have been in development since the 1980s, with panels that provide an internal ceiling finish and outer roof covering in single panels that are semi-interlocked, with either a lapped metal joint between panels or a metal capping that clips over a standing seam-type joint. Composite panels are now being used as an insulated structural deck to a separate waterproof membrane set on top. While lacking visibility of metal faced panels, they are very adaptable and economic, with thermal insulation not only filling the voids between peaks and troughs of the metal sheet on its underside but also providing some structural stability.

Metal rainscreen panels are a recent addition to metal roofing systems. They do not use the outer seal as a first line of defence against rainwater penetration but rather as a protection to the membrane beneath against the effects of the sun as well as foot traffic. Metal rainscreen panels are required to be sufficiently rigid and resistant to impact damage from occasional access. Composite sheets with a plastic core and thin metal outer facings are popular in this regard since they achieve high levels of flatness and are flexible enough to withstand foot traffic, usually when aluminium sections are silicone-bonded on the underside of panels. Perforated and slotted metal sheets are also being used as metal rainscreen panels, partly shaping the expression of the building envelope in forming a continuity between different parts of a roofscape, ranging from covering air extract terminals, rooflights and gutters to producing a (seamless) smooth continuation of the facade below. These rainscreen panels can also accommodate complex geometries without having to make individual composite panels to achieve the same visual effect. Although such panels are an additional roof covering rather than being formed entirely from metal, they can provide varying amounts of translucency and transparency in a single metal layer that can reveal its depth both from inside the building and from outside.

A change over the past 10 years which has influenced all types of metal construction is the increased quality of the finishes. The quality of powder coating has improved enormously, with greater durability and colour-fastness, so that it competes strongly with the more expensive PVDF finishes. Consequently, the main constraint in the design of metal roofs in any of these systems is that metal sheet is produced in widths of around 1200mm or 1500mm, from which most metal panels in

top left: concealed membrane: Persistence Works, Sheffield, U.K.
Architect: Fielden Clegg Bradley Studios
top middle: exposed membrane: Tenerife Concert Hall, Spain.
Architect: Santiago Calatrava
top right: greenhouse glazing: The Glasshouse, RHS Wisley, U.K.
Architect: Peter van der Toorn Vrijthof
bottom left: silicone sealed glazing: Dulwich picture gallery, London, U.K. Architect: Rick Mather
bottom right: capped glazing: House in London, U.K.
Architect: Gianni Botsford Architects

facades are made, but is usually available in long lengths where coil material is used, that is, where the metal is rolled into a long coil in the factory. Thicker plate, at 4mm thickness and above, is made in flat sheet form, at around 1000mm x 2000mm in size, with larger sheets being more difficult to obtain easily in large quantity. Working with the width of the coil in forming joints, and allowing for the folding or turning of the material at the joints, is the main constraint, but the material can be curved and folded economically in a durable material.

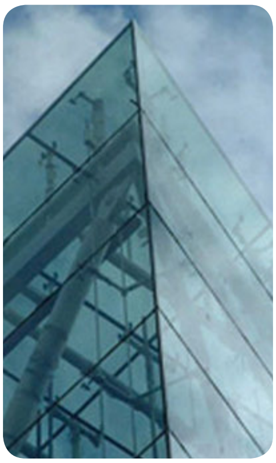
Glass

Although drained and ventilated systems have been in use for the past 25 years, the issue of the water tightness of the horizontal joint, running perpendicular to the fall of the roof, has been undergoing continual development. Glazing bars have been used to support glass down the slope of the roof where they do not impede the passage of rainwater. Horizontal joints have been supported with stepped joints where water runs off the top of the upper glass down onto a lower glass. The glass is traditionally secured with clips and is sealed with a proprietary sealant. This joint is difficult to seal reliably in order to achieve water tightness for higher wind pressures, and is difficult to adapt to a drained and ventilated system. This issue has been resolved over the past 20 years with the development of silicone sealed glazing that was originally used in glazed curtain walls. In this method, a metal channel is set into the edge of double glazed units, with the units being set flush with one another along the horizontal joints. The units are then secured with metal 'toggles' held to the metal channels within the depth of the joint, and fixed to an aluminium frame below to provide a mechanical fixing. The flush horizontal joint between units is then sealed with silicone. The aluminium frame onto which the glass is fixed has ventilated drainage channels to take away any water that passes through the outer silicone seal. With the development of silicone bonding techniques, the double glazed unit can also be bonded to aluminium profiles which are mechanically fixed with screws to a supporting frame. The joint between the glass units is then sealed with silicone in the same way as the previous example. An alternative approach has been to introduce horizontal glazing bars with pressure plates that are shaped to allow as much water to drain down the roof as possible, and accepts that the same water will be trapped behind the upper edge of the pressure plate. Small amounts of water that find their way through the outer seal are drained away within the system back to the outside. Both the recessed fixing method with a silicone seal, and the modified pressure plate 'toggle' system have been proved reliable in their performance.

Bonded glass rooflights are a recent development in glazed roofs, where double glazed units are bonded directly onto a lightweight metal frame that has no visible fixings on its external face. While bolt fixed glazing can conceal the fixing bolt within the double glazed unit on one side, structural silicone glazing has no visible structure at all, with supporting glazing bars being concealed within the width of the joint behind the external seal. This has led to greater freedom in the forms used for rooflights in this technique, where the position of the glazing bars, and how they intersect, does not have to be considered in rooflight design. Bonded glazing has encouraged the use of structural glass beams, which suit well a structurally glazed rooflight. Most bonded glass rooflights with a gently sloping, but planar surface are derived in part from examples of glass floor decks and staircases used in buildings that have been developed over the past 15 years. A new addition is to bond point fixings directly to the inside face of the glass, with brackets and support systems used for regular bolt fixed glazing.

Concrete

Developments in waterproofing membranes for concrete roofs over the past 25 years have focused on increasing the flexibility of the material used. Asphalt, a well established material for concrete decks, suffered traditionally from an inability to take up movement from either the building structure or from solar gain when exposed to the effects of the sun. A solution to this problem has been the 'inverted' roof configuration, where thermal insulation is fixed above, rather than below, the waterproof membrane in order to keep its temperature cool and relatively constant. Pebbles or paving slabs are set onto the insulation. In addition, the introduction of polymers into asphalt to provide greater flexibility has led to the material being easier



bolt-fixed glazing: Tower Bridge House, London, U.K.
Architect: Rogers Stirk Harbour + Partners

top left: bolt-fixed glazing: Louvre gallery, Paris, France.
Architect: I M Pei
bottom left: exposed membrane: Canary Wharf underground station, London, U.K. Architect: Foster and Partners
top middle: timber flat roof: Private residence, London, U.K.
Architect: Lynch Architects
top right: timber pitch roof: The Lighthouse, Watford, U.K.
Architect: Shepherd Robson Architects

to apply on site, particularly as torch-on membrane sheet rather than in liquid applied form. However, polymer materials, mainly thermoplastics and elastomers, are becoming more economic. Polymer materials have the advantage of increasingly being able to be exposed to sunlight, which is leading to roofs being covered in a few of these materials as a self-finish, with some buildings taking the membrane down the facades to form a complete building envelope. Where a smooth or level insulated substrate can be formed, these waterproofing layers can be fixed in a similar way to fabric membranes, welded together in the factory to form a membrane with straight and crisply formed joints that can form a visible self-finish to a roof, with an appearance similar to that of fabric 'tent' membranes. This change from roof membranes which are kept concealed, due to their poor visual aspect, to ones that are now capable of being a visual part of the design.

On pitched roofs, visually exposed polymer-based membranes, or polymer modified asphalt sheet, are beginning to be used as materials in their own right rather than imitating the appearance of traditional roof tiles or shingles. The more refined fixing techniques that are being made available by manufacturers will assist in this change. Waterproof membranes are increasingly being used on substrates such as folded steel sheet decks and foam insulation-clad roof decks where there is a strong modelling of the form of the roof structure seen either from inside or from outside the building. Membranes are required to accommodate more structural movement and higher temperatures combined with an external wearing surface that can be walked upon without reasonable risk of damage, for maintenance access.

Timber

Timber-based roofs have developed over the past 20 years to improve their thermal insulation performance. So-called 'cold' roofs, with the insulation set at ceiling level with the roof void being ventilated, continue to be used, however 'warm' roofs have undergone much development in order to properly deal with the needs of ventilation to avoid condensation occurring within the roof construction. Some manufacturers prefer to have no ventilation within the roof construction where it cannot be easily provided by using a high performance vapour barrier on the inside face of the wall construction immediately behind the internal finishes. Manufacturers also provide increasingly better performance vents to ensure that air can be drawn through the void between the roof tiles, slates or shingles, and the breather membrane or roofing felt that is set above the thermal insulation. Most of the effort in ventilating pitched roofs of this type is in trying to retain the appearance of traditional roofs, where ventilation ducts and boiler flues did not, until recently, play a part. Modern tiled, slated and shingled roofs use two lines of defence against rainwater penetration, where the outer layer is the outer line of defence to, and protection for, a waterproof membrane or breather membrane beneath.

The use of metal shingles has been a recent development. This technique is a hybrid of lapped tile roofing and standing seam facades, and can be used to form both wall and roof in a single system that is both economic and able to deal with a variety of fixing angles. While shingles or tiles are hung from their top edge, metal shingles are folded over into a seam on their sides and lower edge, or edges, if the shingles are not rectilinear, but are set at 45° to the vertical, for example. The top edge or edges are fixed with nails or screws with the shingle immediately above being lapped over the top of the nailed fixing in the manner of tiling. This fixing method secures the shingles on all sides while retaining a visual lap, allowing the shingle to be fixed in any position, even in a soffit condition. The fixing method usually follows rainscreen principles by assuming that rainwater will pass through the joints, which are drained in a ventilated cavity behind. Metal shingles are economic to fabricate, since they can be cut easily from sheet metal, aluminium, mild steel, copper or zinc. In addition, tiles can be formed to a curved shape in a press to give a very textured facade with a three-dimensional quality that has yet to be explored.

Plastics

Translucent plastics are used mainly both to imitate the appearance of glass rooflights as flat sheet materials and to form composite panels. This is gradually changing as plastics are no longer seen as economic substitutes for other materials but

top left: GRP roof: ARC, Hull, U.K.
Architect: Niall Mclaughlin Architects
bottom left: fabric ETFE cushions: Kingsdale school, London, U.K.
Architect De Rijke Marsh Morgan
top middle: fabric single membrane: Whitlingham Park Water Activities Centre, Norwich, U.K.
Architect: Snell Associates
top right: GRP panels: Bus Station, Hoofddorp, The Netherlands.
Architect: NIO architecten
bottom right: single membrane fabric: National Tennis Centre, Roehampton, U.K. Architect: Hopkins Architects

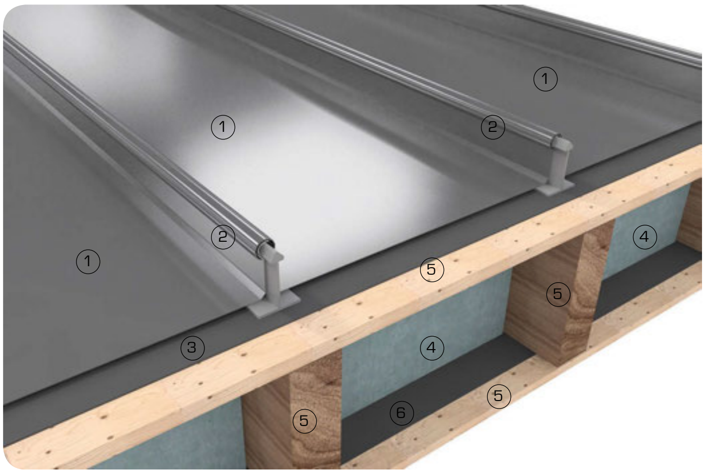
as construction materials in their own right. Earlier examples of plastic rooflights suffered from the effects of colour fading or of yellowing in transparent / translucent rooflights. The materials and finishes used in bonding are superior to those used previously, ensuring that colour fading is far less pronounced than it was. A greater acceptance of plastics as durable and capable of being moulded economically to complex shape has prompted a revival in roof design. Some panels have been used as translucent rainscreen panels with lighting or graphic displays set beneath the outer plastic skin. The essential difficulties for plastics remain in their perception as being less durable than either glass or metal, for which polymer materials are seen as economic substitutes. This perception will change only when more complex geometries of external envelopes are demonstrated in buildings which could not otherwise have the budget available for such work in other materials. Working with plastics and composites is still undertaken in relatively small-scale workshops, where mock-ups can be produced easily and economically, allowing an interaction between designer and fabricator that is more difficult in larger scale factory-based methods where repeatability of large numbers of identical components still dominates production methods.

Fabrics

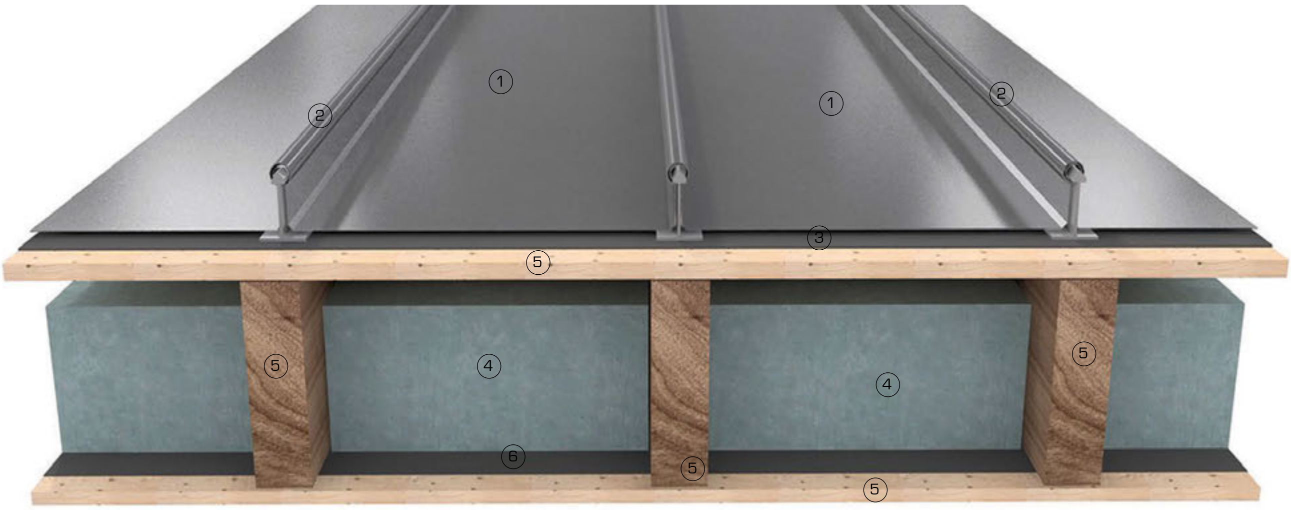
The use of woven textiles made from polymers has been focused on its application to form tent-like roof forms. Tent-based structures stretch a single membrane sheet, which is waterproofed on its external face, over a supporting structure that may use a mast to support the tent, and cables to hold the membrane in position, in the imitation of a traditional tent. This has led to developments in the connection of membrane to cable and restraint of cables to adjoining structure. Alternatively, membranes are stretched over more sculptured supporting frames, which are derived more from the established language of building construction rather than from the masts and cables of tent-based roofs. The design life of these roofs is gradually increasing as both a result of observing earlier examples and developing them, as well as an improvement in the performance of the protective coatings applied. The introduction of double layer membrane roofs will no doubt change their use from purely weather barrier to a thermally insulated roof, making them more attractive for roofs to internal spaces than shelters for external spaces. More translucent insulation materials reduce the amount of light transmission lost through these roofs, with research being undertaken to form an economic and highly translucent thermal insulation material that would suit double layer membranes. An alternative method of insulating membranes is to fill the gap in a double layer membrane roof with air to form an inflatable roof. The concern with this approach is that it relies on a constant supply of air to hold the roof in place rather than by a supporting frame. This method has been adapted as small 'cushions' or 'pillows' filled with air to provide an insulated fabric membrane roof. The most visually striking examples use ETFE foil which is both very durable when compared to other polymer fabrics, and also highly transparent. While this can be a disadvantage in rooflights, where some amount of solar shading is usually required, it is ideal for many facades and is finding use in complete building envelopes, where wall and roof are formed from a mixture of transparent and translucent panels. These panels are inflated and fixed to a permanent air supply that periodically refreshes the cushions with more air to maintain the pressure required to give them structural stability. The use of fabric is set to grow, with air cushions that can be used in conjunction with external solar shading or internal screen walls in a variety of twin roof or twin wall applications. Like sheet plastic materials, ETFE cushions are becoming liberated from the design language of glass rooflights, with more complex geometries to form curved roofs. Loadbearing air cushions, which do not require any supporting structure, are in their early stages of development and application, and we are likely to see much of this development in roof structures and self-supporting envelope structures in the coming years.

Details

1. Metal sheet
2. Standing seam joint
3. Breather membrane
4. Thermal insulation
5. Substrate, typically timber/metal rafters with plywood facing
6. Vapour barrier
7. Drywall/dry lining if required
8. Outer standing seam sheet
9. Inner lining sheet
10. Clips at centres
11. Folded metal gutter
12. Curved eaves sheet
13. External wall
14. Structural frame
15. Outersheet fixing bracket
16. Rooflight
17. Metal flashing
18. Ridge piece



3D detail view showing section through metal profile roof on timber structure



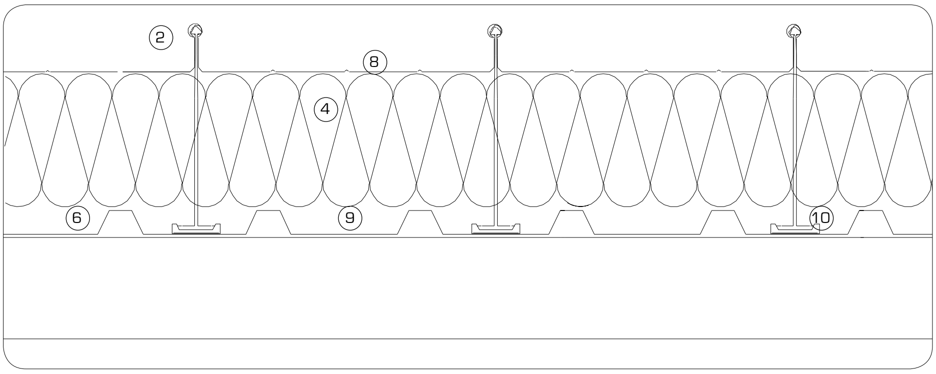
3D sectional view showing section through metal profile roof on timber structure

System design

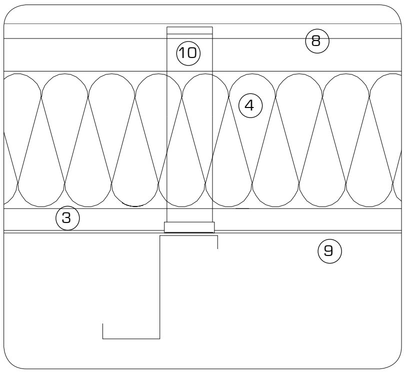
Standing seam roofs are increasingly being used for industrial and commercial buildings where concealed fixings and low roof pitches are required for visual reasons. The main advantage of standing seam roofs over profiled metal roofs is that almost no fixings pass through from outside to inside the construction. This gives the roof surface a visually crisp appearance with very few visible fixings. The standing seams allow the technique to be used on very low pitch roofs. The traditional method of forming a standing seam roof is to set the sheet onto a timber substrate, and to fold the long edges of the metal upwards to form a standing seam joint. However, this method is increasingly giving way to prefabricated systems where the sheet metal is folded to a specific profile either in a factory or on site with a rolling machine. The folded metal is then secured with a clip-based fixing system rather than onto a continuous substrate.

The site-based method of fixing sheet is well suited to smaller-scale applications, or where complex geometries are used. These applications make the use of prefabrication both unnecessary and uneconomic, due to the time saved by forming junctions and edges on site. The use of a single sheet metal profile and angle support clips used in prefabricated methods is typically too inflexible for such conditions. This traditional method of forming standing seam roofs has timber boards or plywood sheet used to form a continuous substrate, or supporting surface. Standing seams are formed by timber strips of rectilinear or curved section which are set at 450-600mm centres down the slope of the roof, corresponding to the width of the sheet metal used. Sheet metal is laid along the length of the roof from top to bottom, with the sides of the sheet folded up and over the timber battens. Successive strips of metal sheet are lapped over the next to form a continuous sealed surface. The standing seam joint is produced by folding the metal together to create a seal. Because the roof is formed, effectively, as a series of linked gutters, the standing seam between each gutter is above the level of the water draining down it. Rainwater is avoided being drawn through the joint by capillary action by one of two methods, where the joint is either sealed or ventilated. In a sealed joint the seam is pressed tight, as in a traditional lead or copper roof, either by folding the metal over itself to form a thin seam, or by forming the metal over a timber roll or section. In a ventilated joint, a small gap is left between the folded sheets to allow air to pass through but not rainwater.

For prefabricated standing seam roofs, the most common configuration is to fix the brackets supporting the outer sheet to a set of metal purlins. A metal liner sheet is set below the purlins to support the thermal insulation quilt, set between the purlins. A vapour barrier is set between the insulation quilt and the liner tray on the warm (in winter) side of the thermal insulation. An alternative configuration is to have a full structural deck with insulation set on top and an outer (upper) sheet supported on brackets set onto the structural deck. In hot, humid countries an additional vapour barrier is set on top of the insulation where

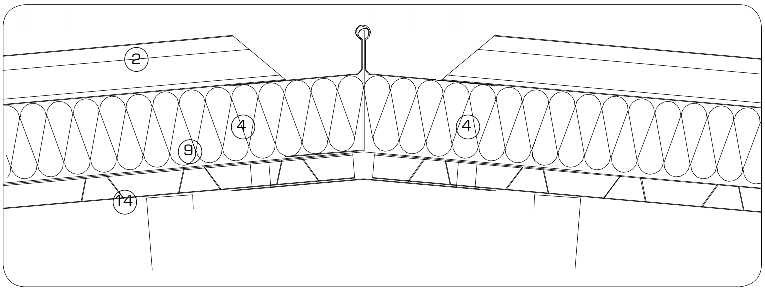


Vertical section 1:10. Typical roof assembly without acoustic layer

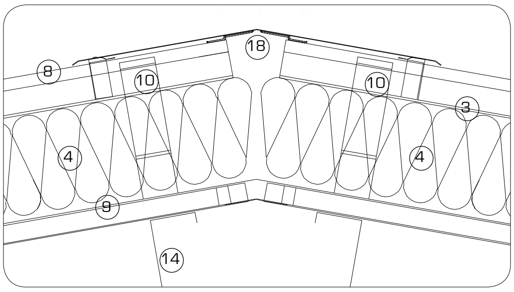


Vertical section 1:10 Typical roof assembly without acoustic layer

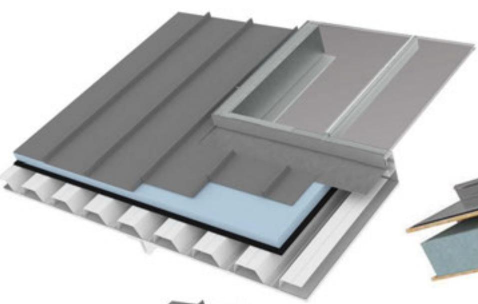
3D cutaway view showing typical roof assembly

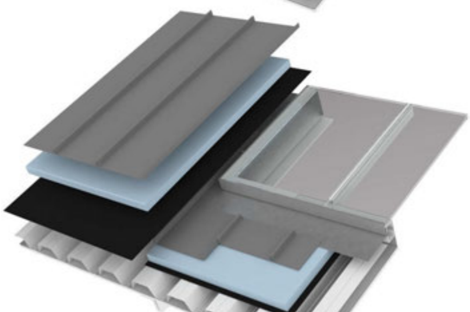


Vertical section 1:10. Ridge with recessed flashing

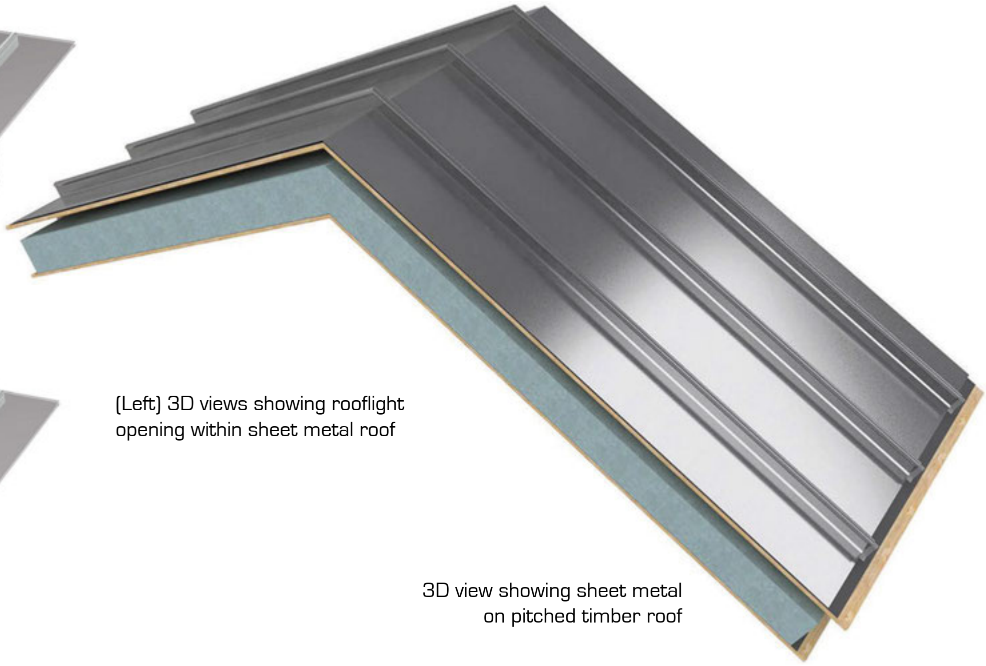


Vertical section 1:10. Ridge with flashing



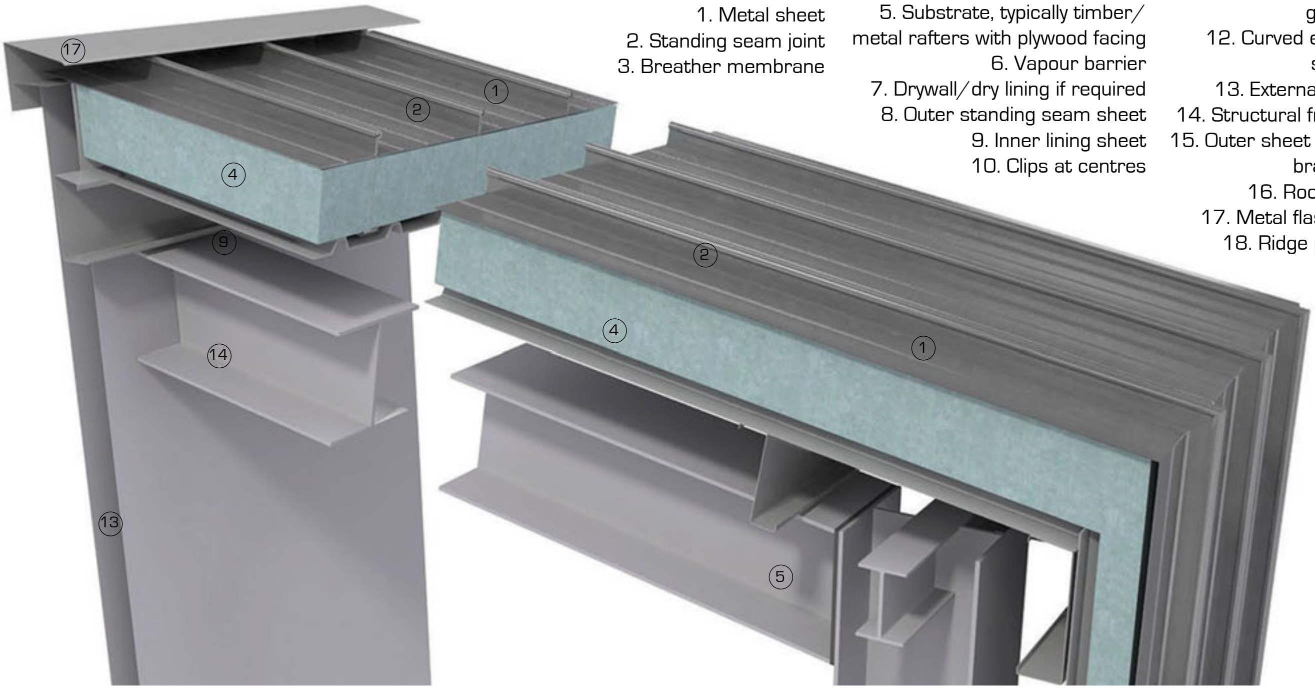


(Left) 3D views showing rooflight opening within sheet metal roof



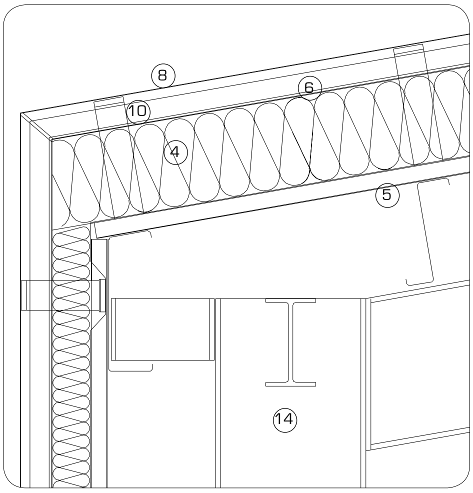
3D view showing sheet metal on pitched timber roof

Details
1. Metal sheet
2. Standing seam joint
3. Breather membrane
4. Thermal insulation
5. Substrate, typically timber/metal rafters with plywood facing
6. Vapour barrier
7. Drywall/dry lining if required
8. Outer standing seam sheet
9. Inner lining sheet
10. Clips at centres
11. Folded metal gutter
12. Curved eaves sheet
13. External wall
14. Structural frame
15. Outer sheet fixing bracket
16. Rooflight
17. Metal flashing
18. Ridge piece

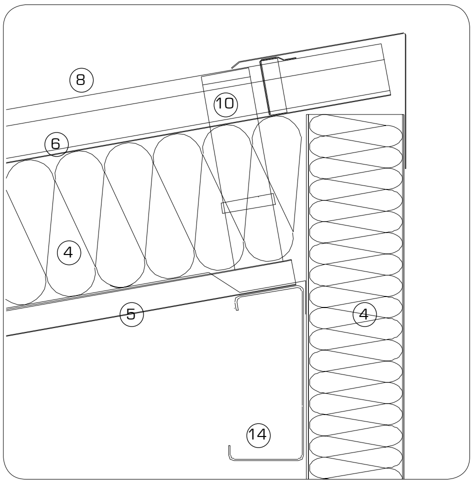


3D view of folded eaves and ridge junction

(Below) 3D sectional view showing metal standing seam roof construction



Vertical section 1:10. Folded eaves

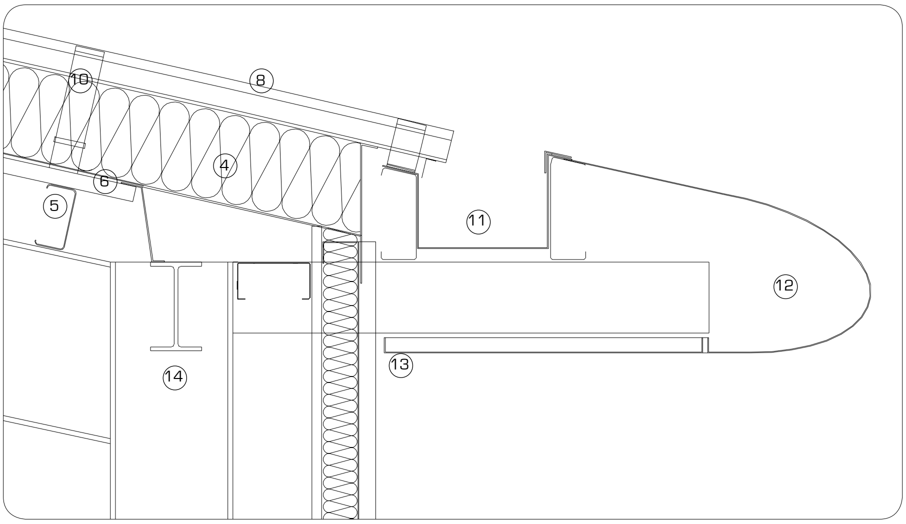


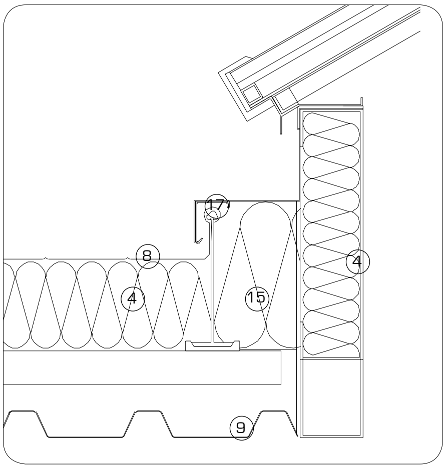
Vertical section 1:10. Monopitch ridge

the risk of interstitial condensation is from the outside as well as the inside.

For both site-based and prefabricated construction methods, the roof pitch can go down to 1°, after taking into account any structural deflections that would further reduce this angle. Metal sheets can be made up to 40 metres in length, but road transport is difficult, being considerably longer than a trailer length. For larger projects, long sheets are formed on site with a rolling machine that can form the profile of the standing seam sheet to any length required, the profile being formed from metal coil.

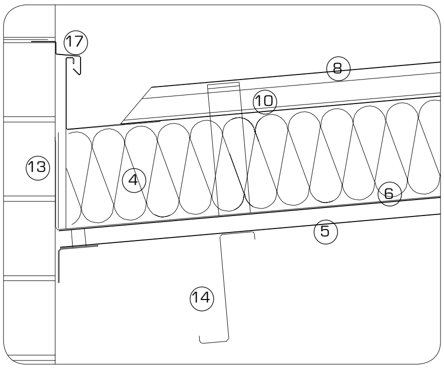
System details
Support brackets are usually T-shaped and are fixed either to the structural deck or to purlins with self-tapping screws. The brackets are usually made from extruded aluminium in order to provide a profile that is both thick enough to form a rigid connection and sufficiently precise in section to retain a given standing seam profile in place. Metal sheet is formed in long lengths of folded trays which are then fixed onto the support brackets. Finally the standing seam joints are crimped to form a seal, usually with a ‘zip up’ tool that travels along the joint and across the roof, sealing the joint as it moves along.



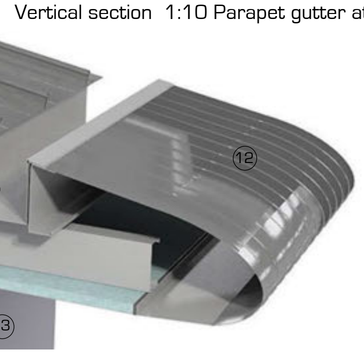


Vertical section 1:10. Junction with rooflight

Vertical section 1:10. Eaves with curved gutter



Vertical section 1:10 Parapet gutter at abutment

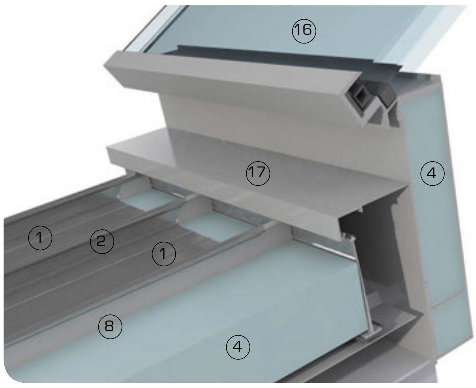



3D detail view showing metal roof
showing eaves with curved gutter

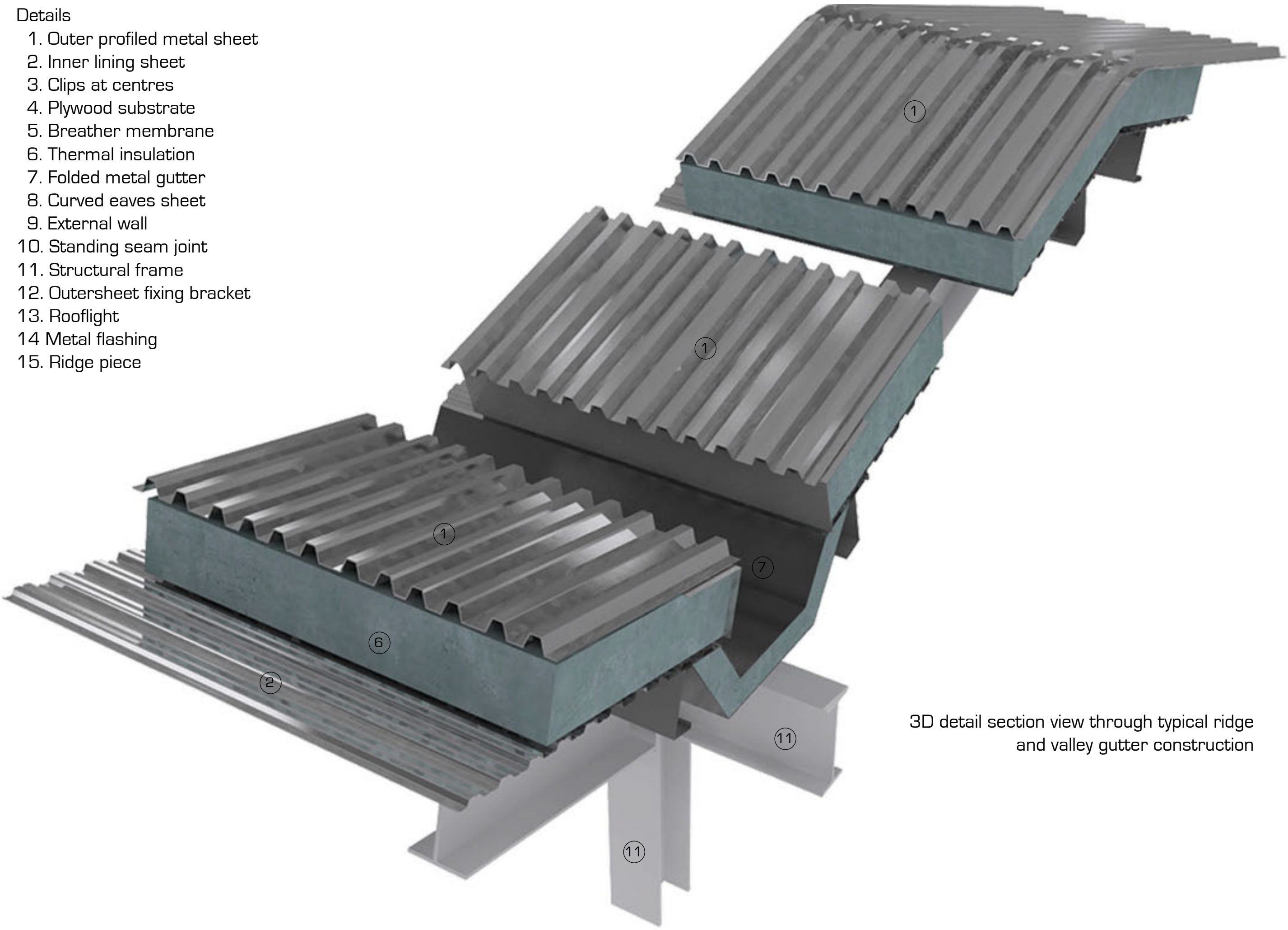
(Below right) 3D detail view showing
metal roof at abutment
3D detail view showing eaves with
curved gutter

Standing seam sheets can form shallow curves by gently bending the metal on site, or alternatively by curving the sheets in the factory, to give a smooth appearance. Small radius curves are formed by crimping the sheet in the factory, where the material is mechanically formed with small local folds. Sharp folded corners are made by welding two sheets together along the fold line.

Ridges are formed by a variety of methods, the visually sharpest being a ridge line formed as a standing seam joint, with the seams meeting the ridge being terminated to avoid the need for visually bulky filler pieces which could be seen from below. Valleys are formed by lapping the ends of the standing seam roof into a folded metal tray forming a continuous gutter. Eaves are formed in a similar way, with a gutter set at the edge of the roof. Increasingly, gutters are being integrated into roof forms in order to avoid a weak visual line formed by a gutter which is not continuous with the smooth lines of the roof. When additional closer pieces are used, such as bull nose profiles, the metal panels are usually designed to be drained and ventilated to the exterior, and the line of waterproofing continues up the external wall to the underside of the standing seam roof.



Details
1. Outer profiled metal sheet
2. Inner lining sheet
3. Clips at centres
4. Plywood substrate
5. Breather membrane
6. Thermal insulation
7. Folded metal gutter
8. Curved eaves sheet
9. External wall
10. Standing seam joint
11. Structural frame
12. Outersheet fixing bracket
13. Rooflight
14 Metal flashing
15. Ridge piece



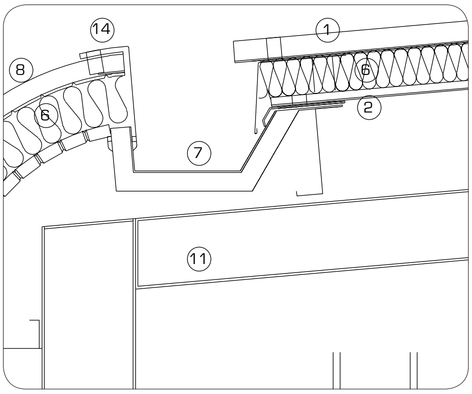
3D detail section view through typical ridge and valley gutter construction

System design

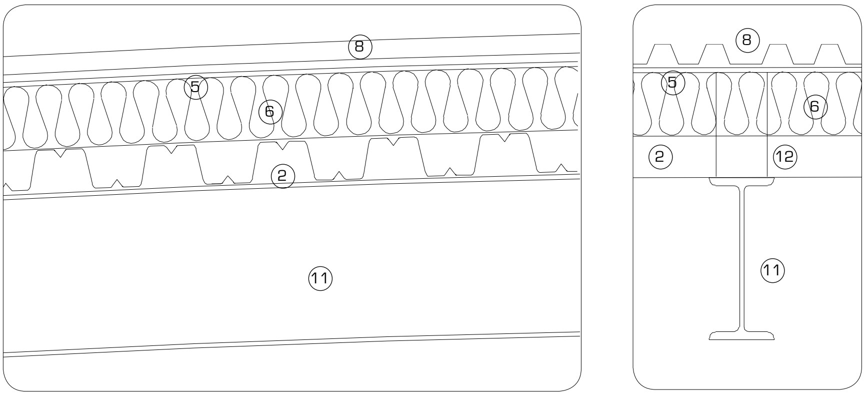
The main advantage of profiled metal sheet over other metal roof types is the ability of the material to span economically up to around 3.5 metres between primary structural supports. This self-supporting ability of the material, combined with its weather resistant, painted coating applied during manufacture, makes it able to be used as both a substrate material for a finish in a different material set onto it, or as a single layer structural and weatherproof material. While standing seam roofing, with its high projecting folds, is suited to long, straight, or gently curving spans, profiled metal sheet can both span between supports and form complex geometries. It is this flexibility of being both structural deck and waterproofing layer that has an advantage where the interior finish is designed to be in a different material, such as dry lining or decorative boarding. In recent years roof pitches have greatly reduced to make the roof as flat as possible, usually for visual reasons. Most profiled sheet is laid to a minimum pitch of around 4°. Standing seam roofs can go down to a 1° pitch, depending on the geometry of the roof.

Profiled metal sheet provides a continuous weatherproof skin with the ability to be curved in one direction, where the supporting structure beneath requires only a few structural members to be curved, and most framing can be straight. The material is lapped on all four sides like metal standing seam roofs. The laps are made long enough to avoid capillary action through the joint. This simple jointing system provides large areas of reliable, weathertight roofing that can be installed quickly. In common with standing seam roofing, profiled metal roofs can be used as a roof covering in either sealed or ventilated construction. Ventilation is used mainly where a timber supporting structure is used, where the timber is ventilated to avoid rot in the material from moist air in the void that would otherwise be trapped within the construction.

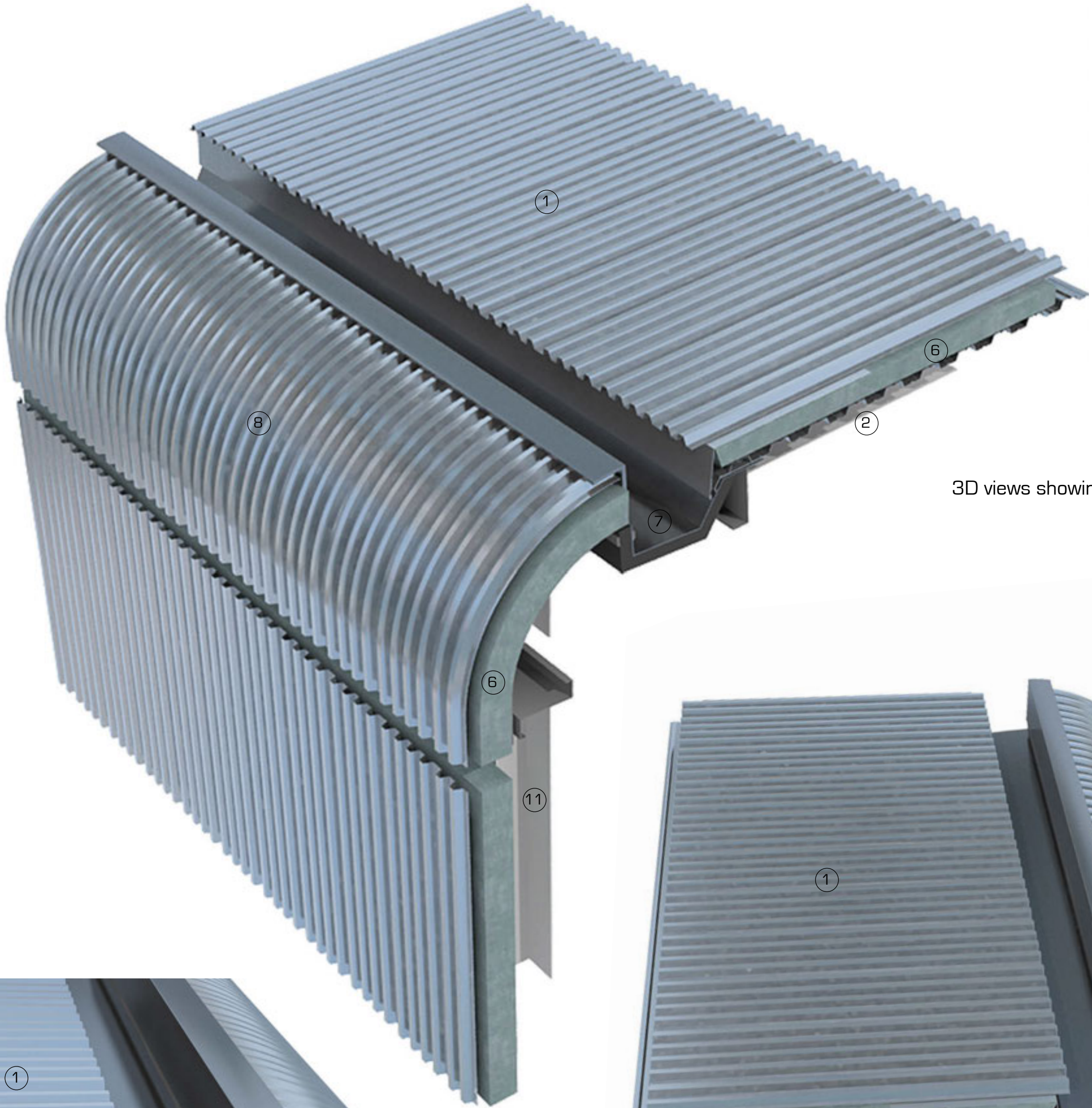
In sealed roofs, the thermal insulation usually fills the voids in between the inner and outer skins, but ventilators are often provided at the ridge and eaves to allow some breathing through the ribs of the profiled sheet. This helps to keep the insulation completely dry. Because the inner lining sheet presents a hard surface under the roof, perforated sheets are used to improve sound absorption. Sound is allowed to be absorbed partly by the insulation quilt. This helps to reduce reverberation, particularly in noisy internal environments. A vapour barrier is set between the thermal insulation and the thin layer of acoustic insulation beneath. Profiled metal sheet roofs have the ability to conceal the supporting structure within the depth of the roof construction. This gives a smooth finished appearance to the inside face of the roof. An outer metal sheet is supported on metal roof purlins, and an inner lining tray, which supports the thermal insulation, is fixed to their underside. Sheets are fixed with self tapping screws which, in addition to fixing the sheets to the supporting structure, are also required to be weathertight. A vapour barrier is provided on the warm (in winter) side of the insulation, between the liner tray and the thermal insulation. Laps between profiled sheets along their top and bottom edges



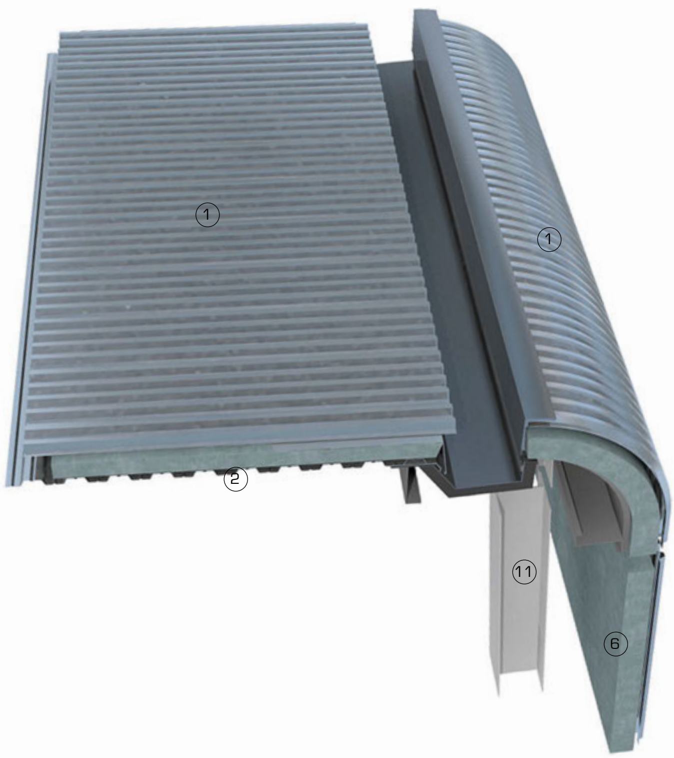
Vertical section 1:10. Concealed gutter detail



Vertical section 1:10. Typical profiled metal sheet roof build-up and supporting structure

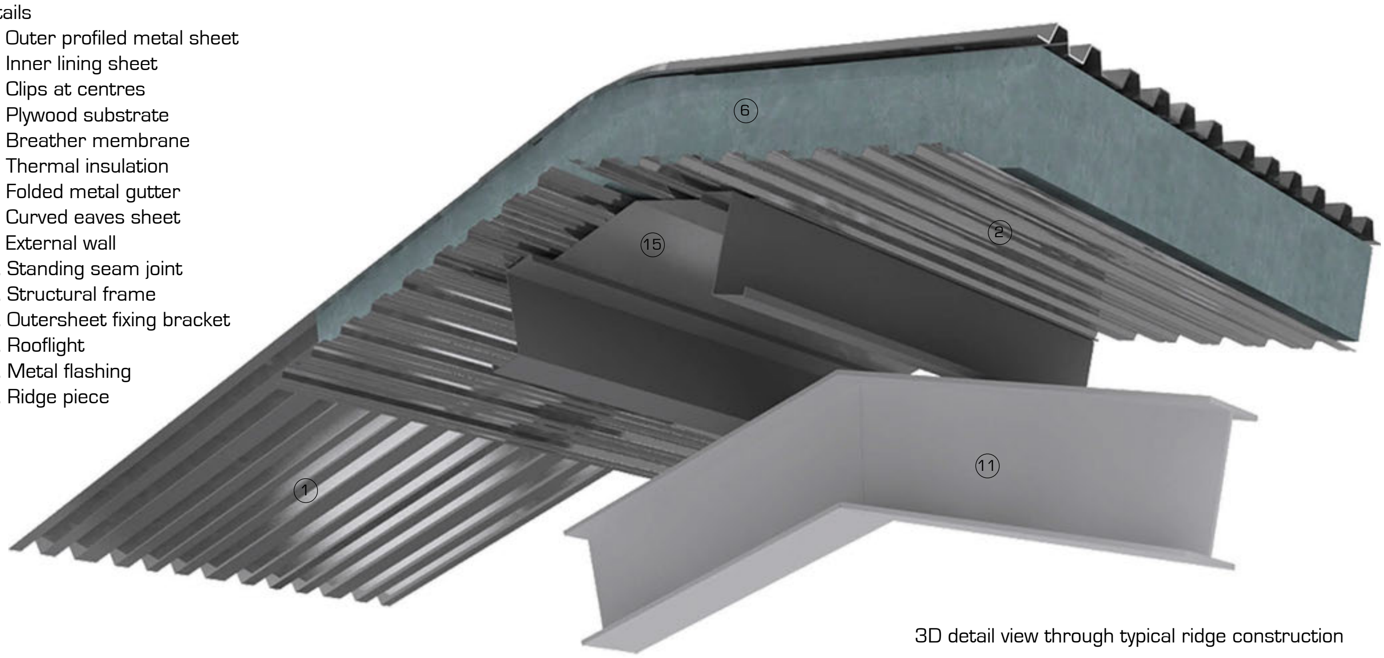


3D views showing curved profiled metal roof construction

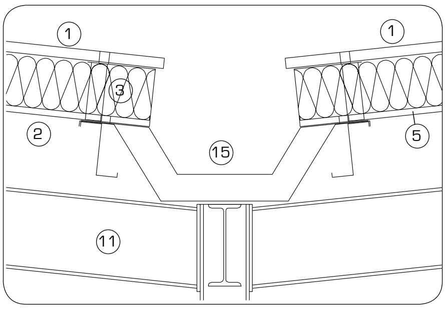


(Right) 3D views showing gutter condition in curved profiled metal roof construction

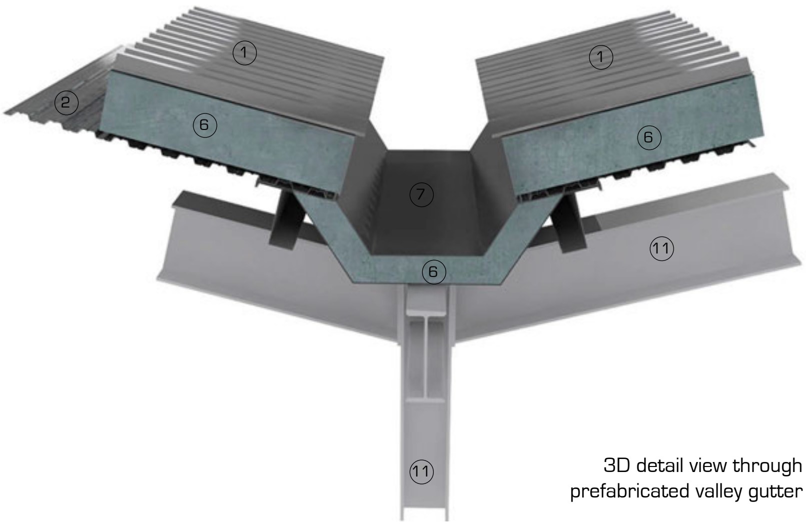
Details
1. Outer profiled metal sheet
2. Inner lining sheet
3. Clips at centres
4. Plywood substrate
5. Breather membrane
6. Thermal insulation
7. Folded metal gutter
8. Curved eaves sheet
9. External wall
10. Standing seam joint
11. Structural frame
12. Outersheet fixing bracket
13. Rooflight
14. Metal flashing
15. Ridge piece



3D detail view through typical ridge construction



Vertical section 1:20. Prefabricated valley gutter



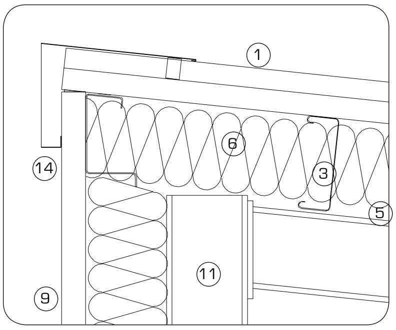
3D detail view through prefabricated valley gutter

are sealed with butyl sealant strip. Two strips are normally used, one at the end of the external lap and the other at the top end of the internal lap. The outer seal provides protection against capillary action of rainwater being drawn up into the lap between sheets, while the other provides a vapour barrier that avoids moisture, generated inside the building, from condensing in the joint. Self-tapping screws that hold the sheets in place clamp the two sealed surfaces together. Sheets are normally lapped 150mm over one another, while laps between sheets on their side edges are made with a single lap of profile, with a single seal of butyl tape set at the centre of the lap.

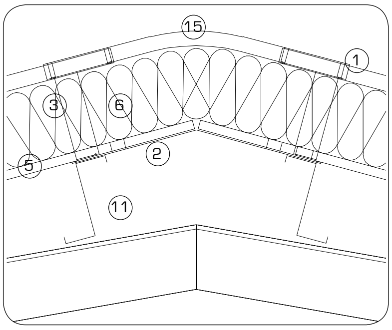
System details
Ridges at the junction of a double pitched roof use a folded metal strip to form a continuous ridge sheet. These sheets can be folded on a straight line or formed to a curved line. The void beneath is filled with thermal insulation in addition to that used beneath the profiled sheet. Closer strips are used to seal the gaps in the profiled sheet where it meets the ridge cover strip set on top of the profiled sheet.

Parapets are formed by creating a gutter at the base of the profiled sheet, then continuing the line of the gutter up to a parapet coping with laps over the top. The gutter is formed from a single folded sheet to avoid the possibility of leaks, and is lapped under the vertical sheet that forms the seal between gutter and coping. Parapets in profiled metal sheet are often used where the external wall is formed in a different material, so that the parapet forms a visual break between them. However, many profiled metal roofs are used in conjunction with walls in the same material using a concealed gutter that allows wall and roof to be continuous.

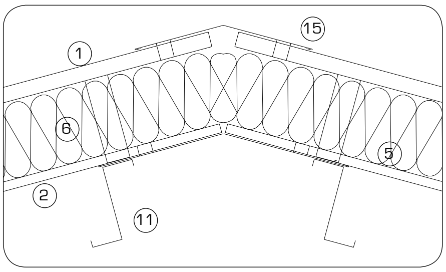
Ridges and valleys are formed using the same methods discussed in the previous section on standing seam roofs. But where standing seams can be cut down to form a flat ridge without a projecting ridge piece, this is not possible in profiled sheet, and instead a folded ridge piece is fixed to the upper surface of the profiled sheet. The gaps between the ridges and troughs of the profiled sheet are filled with a proprietary metal filler piece, usually forming part of the manufacturer's system. Ventilated roofs do not require this filler piece, with the resulting gap between the folded ridge sheet and the profiled sheet being usually sufficient to provide ventilation into the construction.



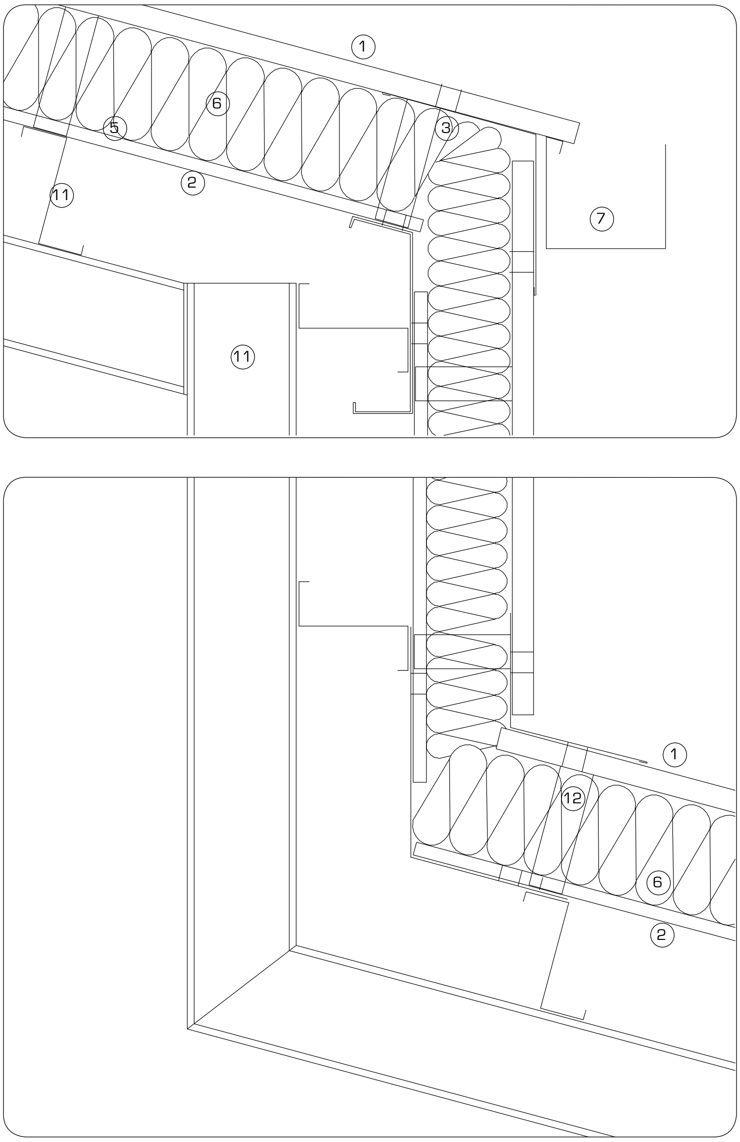
Vertical section 1:20. Monopitch ridge



Vertical section 1:20 Ridge with flashing



Vertical section 1:20. Ridge with flashing



Vertical section 1:20. Eaves with exposed gutter and abutment with vertical roof panel

3D detail view through prefabricated valley gutter

3D detail view through typical ridge construction

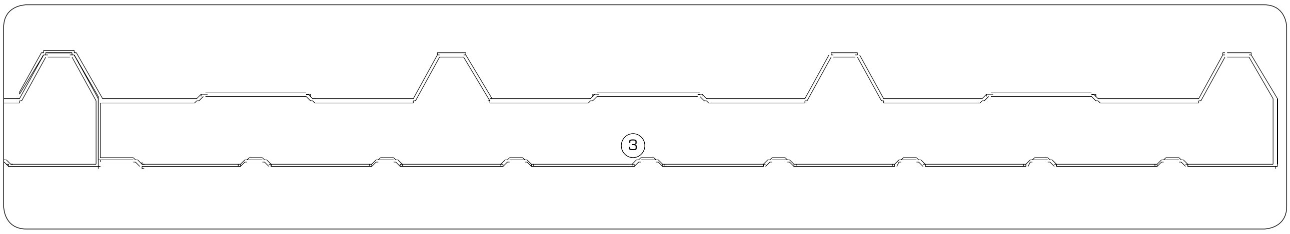
3D views showing vertical section through parapet edge and folded metal gutter between panels

System design

There are two types of composite panel used for roofs: double-sided panels and single sided panels. The first is a development of profiled metal sheet, where outer sheet, thermal insulation and inner sheet are combined into a single panel. These are used in pitched roofs and have an appearance very similar to that of profiled metal roofs. Their main advantage over profiled metal roofs is the speed of erection on site, but they are usually a little more expensive than an equivalent profiled metal sheet roof. Single-sided panels consist of profiled metal sheet bonded to one side only of a layer of foam-type thermal insulation. The insulation is laid face up to receive a separate waterproofing layer, typically a single layer membrane. The membrane is then typically finished in rainscreen panels or smooth pebbles, depending on the geometry and required appearance of the roof. This second panel type can be used on nominally flat roofs.

Single-sided composite panels have a single sheet of profiled metal on the lower loadbearing face of the panel, which is bonded to a foam-based insulation that fills all the voids in the profiled sheet, providing a smooth, flat upper surface. The depth of the panel is determined by both structural requirements and the U-value required, varying the thickness of the thermal insulation. The upper face of the panel is waterproofed with an independent membrane, typically an elastomeric type that requires no upstands or special joints between sheets. Panels are usually set butted up to one another, with the gap between panels filled with foam-based thermal insulation. A separating layer is usually set between the waterproof membrane and the insulated panel to allow movement to occur freely in both the membrane and the composite panel substrate. The membrane is often protected with a lightweight covering of smooth pebbles that can be walked upon for maintenance access without puncturing the surface. Metal rainscreen panels are also used to protect the membrane from the effects of direct sunlight.

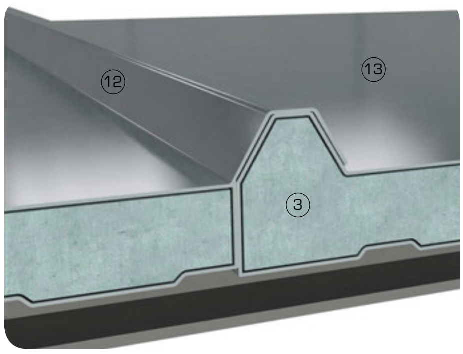
Double-sided composite panels which combine the separate components of profiled metal sheet have two joint types: a double seam with a cap on top in the manner of standing seam roofing, or a single projecting lap of metal profile that forms a lapped connection with the adjacent panel. With the first method, panels have raised edges on their long sides running down the slope. The raised edges are butted together and sealed with butyl tape. A metal capping is fixed over this joint to provide a weathertight seal which sheds water onto the panels either side of the joint, giving this method a distinct appearance of wider joints. The second method has an uninsulated rib of the outer sheet projecting from the panel on one long side which laps over the adjacent panel. This gives a continuous ribbed appearance to the roof that is visually no different on its outside face to profiled metal roof cladding. Both methods have lapped joints on their short (horizontal) edges, where an uninsulated edge projects down to form a lapped joint very similar to that used in profiled metal roofs. These horizontal joints are also sealed with butyl tape to avoid capillary action from rainwater outside, and to prevent the passage of water vapour into the joint from inside the building.



Vertical section 1:10 through composite panel showing panel-to-panel junction

3D detail views showing composite metal panel build-up

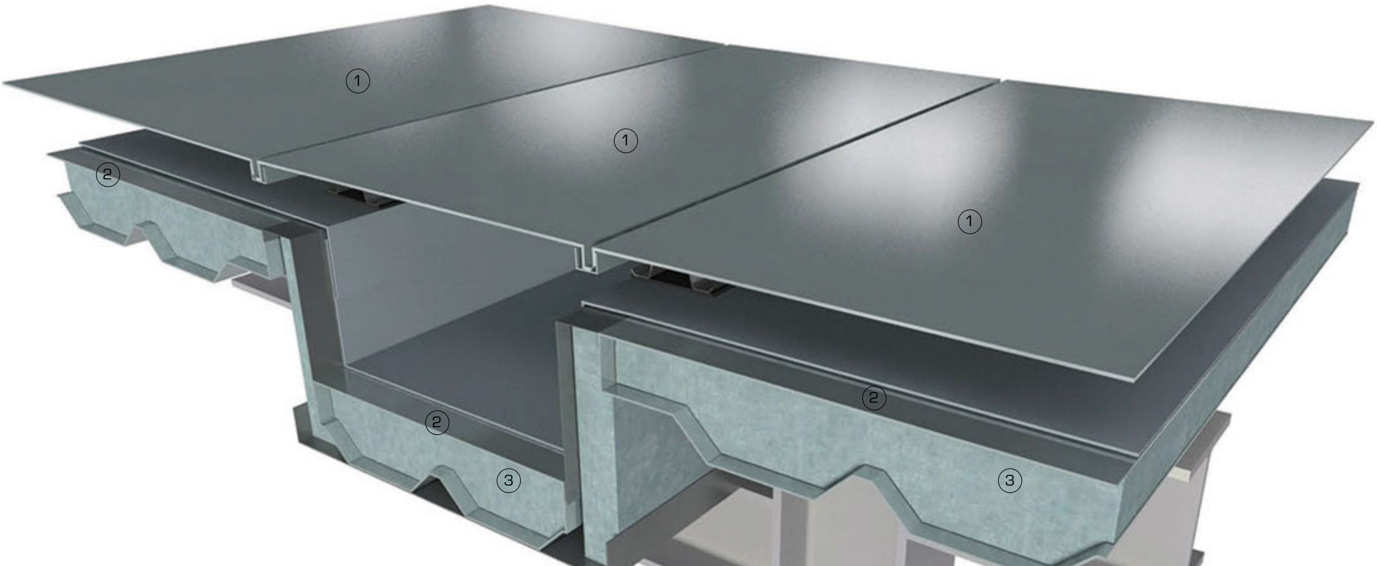
3D view showing verge with parapet upstand

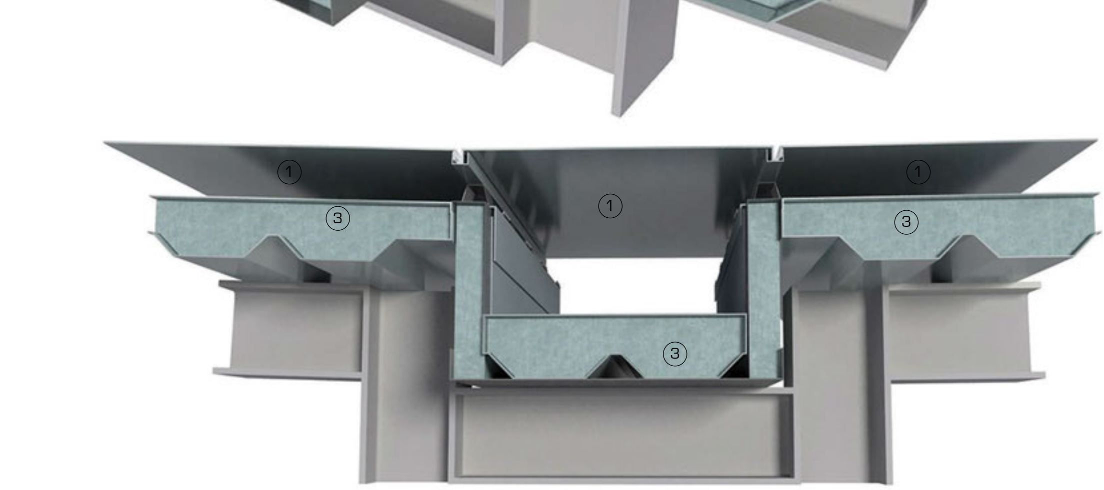


3D detail view showing panel connection

Details
1. Metal rainscreen panel
2. Single layer membrane
3. Composite panel
4. Folded metal coping
5. Purlin or structural beam
6. Secondary purlin
7. Folded metal gutter
8. Folded metal drip
9. Metal fascia panel
10. External wall
11. Outer sheet fixing bracket
12. Panel 1
13. Panel 2

3D view showing vertical section through parapet edge and folded metal gutter between panels





Details
1. Metal rainscreen panel
2. Single layer membrane
3. Composite panel
4. Folded metal coping
5. Purlin or structural beam
6. Secondary purlin
7. Folded metal gutter
8. Folded metal drip
9. Metal fascia panel
10. External wall
11. Outer sheet fixing bracket
12. Panel 1
13. Panel 2

System details

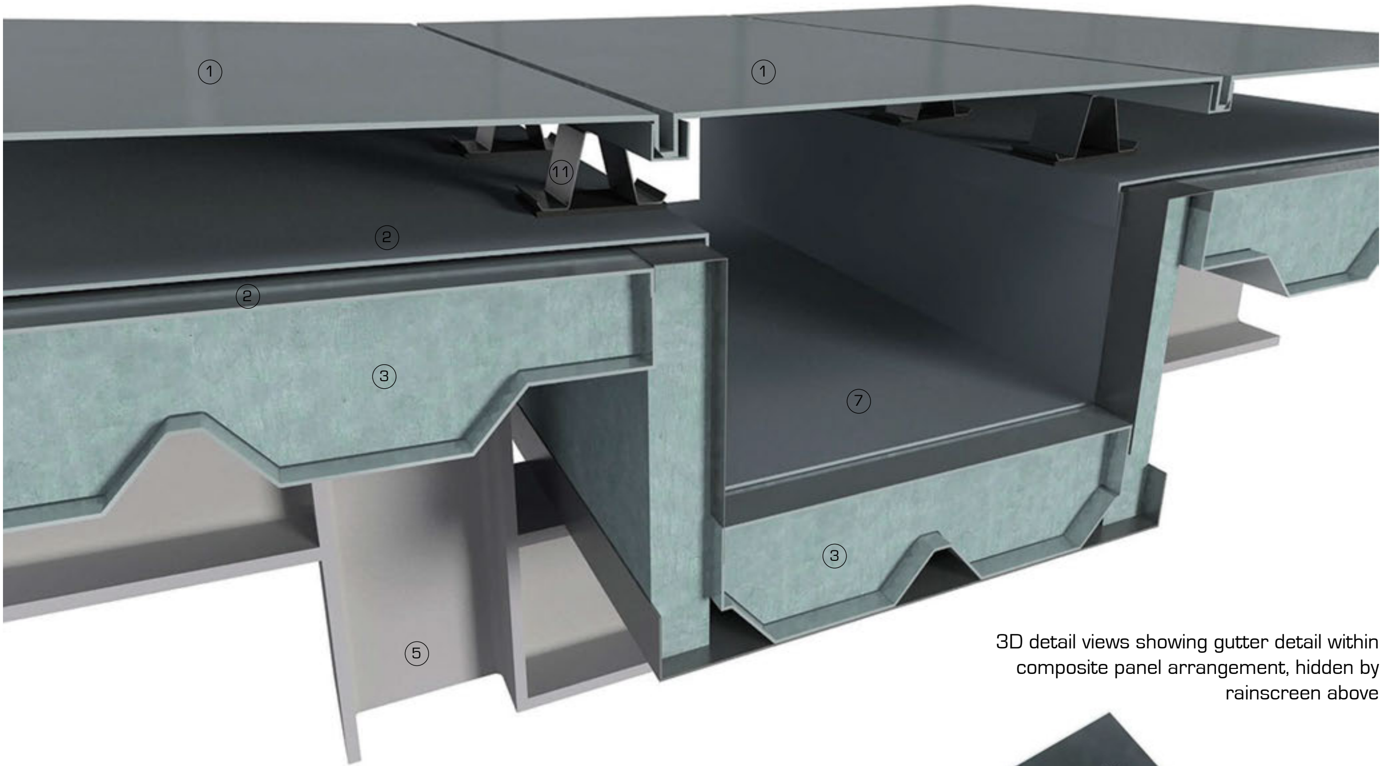
Ridges and folds of single-sided panels are formed in the same way as the panel to panel joints, filled typically with a foam insulation applied by injection on site. The membrane sheets are usually joined at the fold in the roof and a strip of the same material is bonded along the joint to provide a weathertight seal. At parapet gutters of single-sided panels, an upstand is formed in the same insulation material as that used in the composite panels, the upstand being bonded to the composite panel beneath. The outer edge of the upstand is sealed and stiffened with a metal strip fixed to the underside of the composite roof panel or the supporting structure beneath.

Ridges for double-sided composite panels are formed by fixing a metal flashing over the junction between the panels. The flashing is profiled to match that of the panels onto which it sits. The gaps are then closed with a profiled filler piece as used in profiled metal roof construction. The ridge flashing has visible fixings which are difficult to conceal, so that precise positioning is essential to the overall visual appearance of the ridge. The gap between the panels is filled with thermal insulation on site, with either mineral fibre quilt or, more frequently, with the same foam-based insulation used to manufacture the panels. Insulation is injected into the gap to provide a U-value to match that of the adjacent panels.

The inner face of the panels forming the ridge is sealed with a folded metal sheet, typically fixed to adjacent roof purlins and sealed against the inner face of the composite panel to provide a continuous vapour barrier. This inner trim is made either flat or profiled to suit the composite panels used.

Eaves are formed in a similar way to profiled metal panels, by lapping the edge roof panel over a gutter. The gutter is closed against the underside of the composite panel either by folding it outwards and sealing it or by folding the top edge inwards, up the underside of the panel. Unlike eaves gutters, parapet gutters are thermally insulated, forming part of the external envelope. The gutter is usually prefabricated to form part of the overall composite panel system. The gutter shape, in cross section, is formed to provide continuity in the thermal insulation from roof panel through to the adjacent parapet wall.

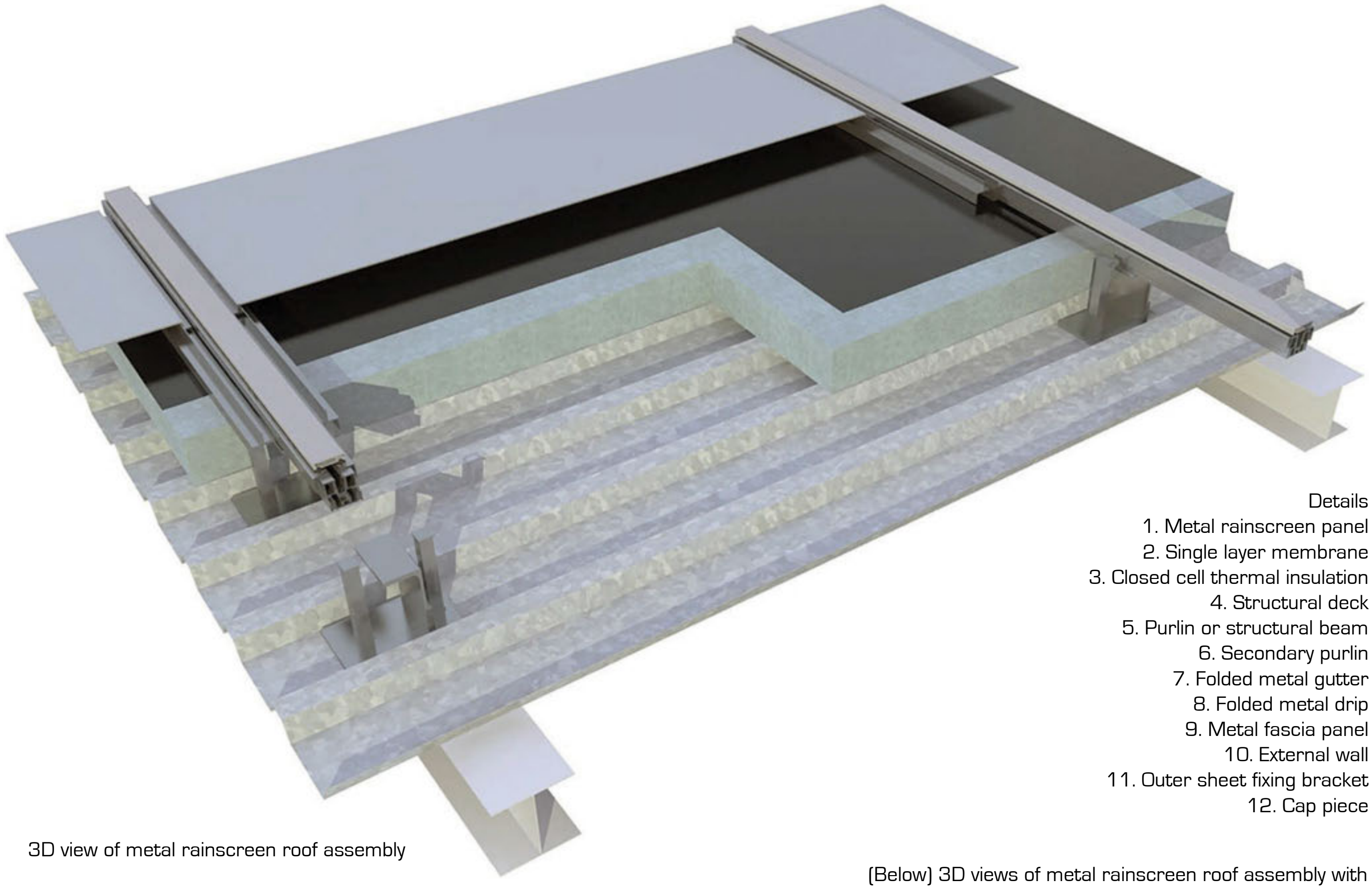
The tops of parapets are closed with a pressed metal coping that is folded down over the face of the external wall and the inside face of the parapet to provide a complete weathertight seal. The top of the coping is usually inclined towards the inside face of the wall, into the gutter, to avoid dust settling on horizontal surfaces from being washed down the face of the external wall during rain.



3D detail views showing gutter detail within composite panel arrangement, hidden by rainscreen above

3D detail view showing panel fixing method

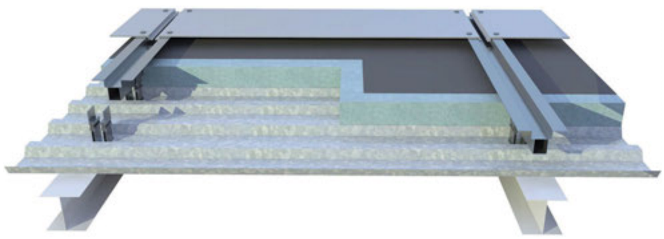
3D detail view showing gutter detail within composite panel arrangement, hidden by rainscreen above

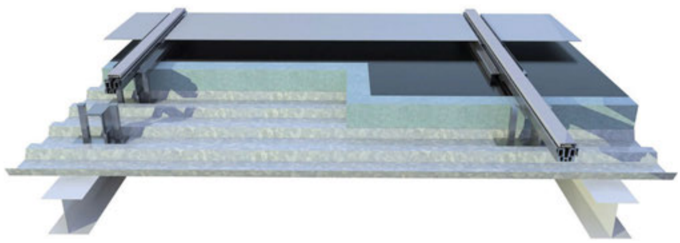


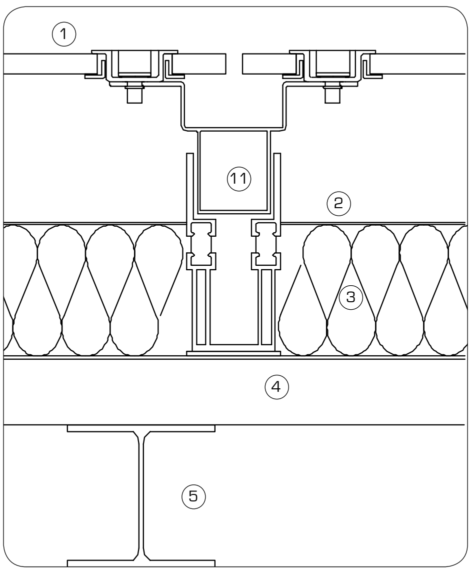
3D view of metal rainscreen roof assembly

Details
1. Metal rainscreen panel
2. Single layer membrane
3. Closed cell thermal insulation
4. Structural deck
5. Purlin or structural beam
6. Secondary purlin
7. Folded metal gutter
8. Folded metal drip
9. Metal fascia panel
10. External wall
11. Outer sheet fixing bracket
12. Cap piece

(Below) 3D views of metal rainscreen roof assembly with varying panels joint approaches



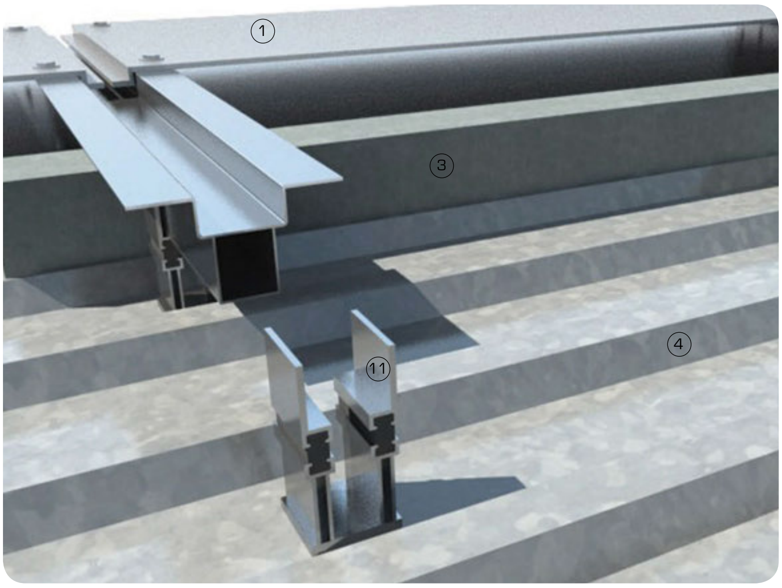




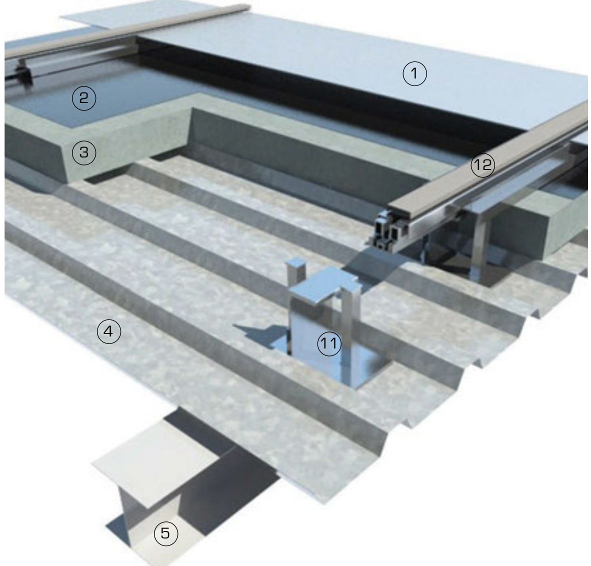
Vertical section 1:10 through roof assembly

System design

The use of metal rainscreen panels is relatively new in roof construction and has developed from using the panels in external walls, albeit in a different configuration. Firstly, most of the rain falling onto a metal rainscreen roof is not usually drained away on the outer layer of panels, unless the roof has a relatively steep pitch or curved section. Rainwater is still expected to drain onto the waterproofing layer beneath as if the panels were not in place. The main function of the rainscreen panels on roofs is to protect the membrane from the effects of the sun (heat and UV radiation), from the worst effects of windblown rain and as protection for maintenance access. Rainscreen panels also provide a lightweight covering that forms part of the visual language of the external walls. Although smooth pebbles are also used to protect waterproofing membranes on non-visible flat roofs, they are obviously not suited to sloping or curved roofs. The use of metal rainscreen panels is well suited to these more complex roof geometries which form a visible part of the design. These rainscreen panels allow traditional roof elements which are usually visually dominant such as gutters, parapets and ridges, to be accommodated within a smooth, continuous outer skin, allowing roofs to take on the visual characteristics of external walls, contributing to the overall architectural effect.

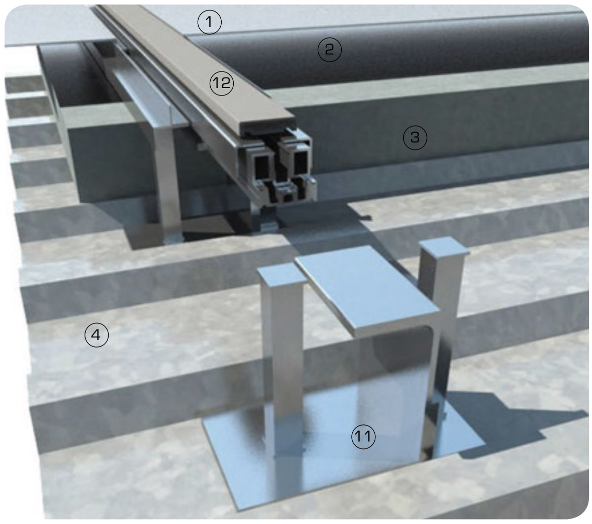


3D view of metal rainscreen roof support system



3D view of metal rainscreen roof assembly with optional capping to seam

3D view of metal rainscreen roof fixing channel



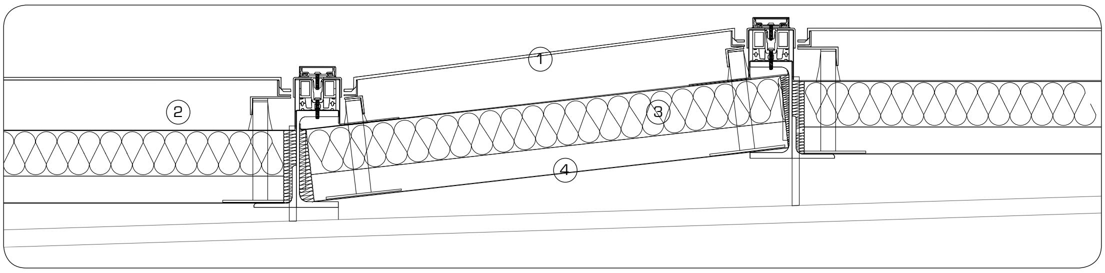
3D view of metal rainscreen roof assembly with optional capping to seam

Although metal sheet is used for rainscreens, metal and plastic composites are becoming increasingly popular. In such materials a thin layer of plastic is faced with two thin sheets of aluminium which are bonded to the plastic sheet core to provide longer size panels than those of sheet metal, with the benefit of providing greater flatness. They are less likely to experience localised impacts from foot traffic during maintenance work, with the 'oil canning' effect of depressed or dented panels resulting from regular maintenance access usually avoided by using these composite sheet materials. However, the size of metal rainscreen panels is restricted more by the panel width that can be walked upon for maintenance access than by the sheet size available. The maximum size of metal sheet is usually in a width of 1200mm or 1500mm metal coil. Composite sheets are typically 1000mm to 1200mm wide, in lengths from 2400mm to 3000mm, depending upon the manufacturer. In practice, panels may only be around 600mm wide if they do not have additional supporting framing beneath to stiffen them. Framed panels can reach the maximum sizes already mentioned, but care must be taken to avoid the pattern staining or denting that can reveal the frame behind during the life cycle of the roof.

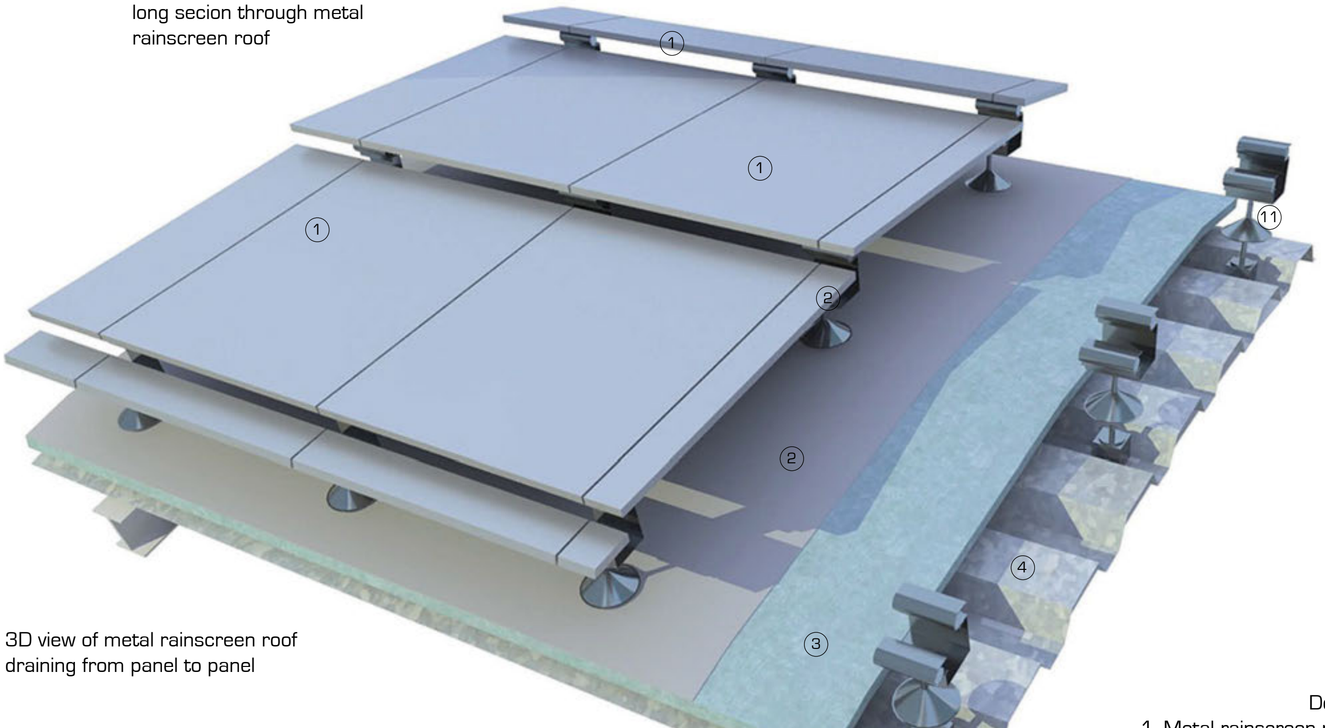
Rainscreen roof panels are typically arranged either as panels laid in a flat grid or as lapped panels, where the bottom edge is lapped over the top of the panel beneath. Side joints remain open jointed and are set in the same plane in this configuration. Panels in a flat grid are set onto metal Z-sections, which are either bonded to the top surface of the waterproof membrane to avoid any risk of water penetration through mechanical fixings, or are set above the membrane on support pads. These pads are usually covered with a waterproofing membrane to reduce the number of fixing penetrations through this layer. The rainscreen panels are then screw-fixed to the Z-section with brackets that avoid the screw fixings being seen at a distance where this is a visual requirement. Concealed fixings are more difficult to accommodate, though such systems are likely to appear over the next ten years as demand for this roof system increases.

System details

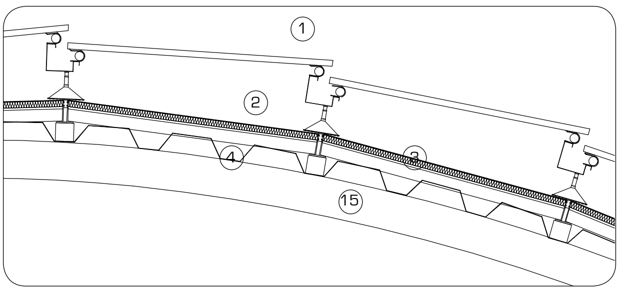
An advantage of rainscreen panels for parapets is that the gutter and upstand can be made without either element being visible, allowing parapets to function as concealed gutters while providing a visual continuity between wall and roof. Consequently, eaves, monopitch ridges and verges can have a similar outward appearance of an uninterrupted panel layout extending from



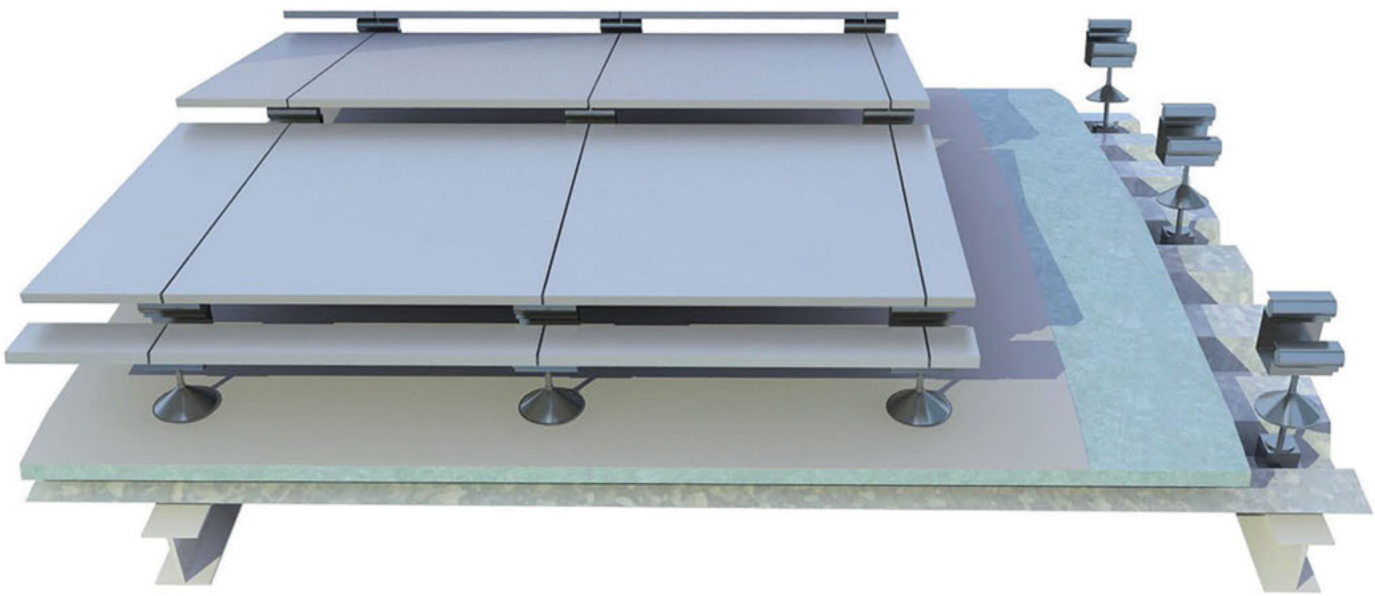
Vertical section 1:25. Typical long secion through metal rainscreen roof

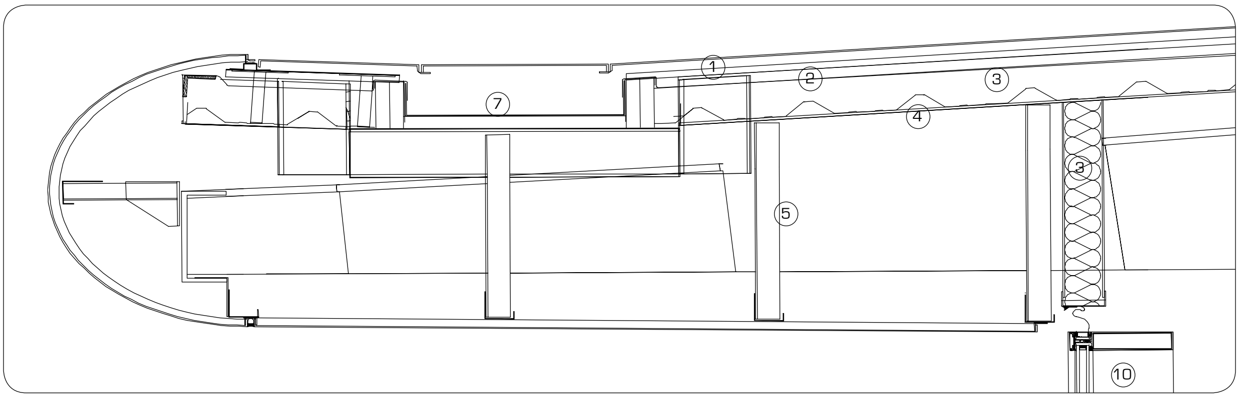


3D view of metal rainscreen roof draining from panel to panel

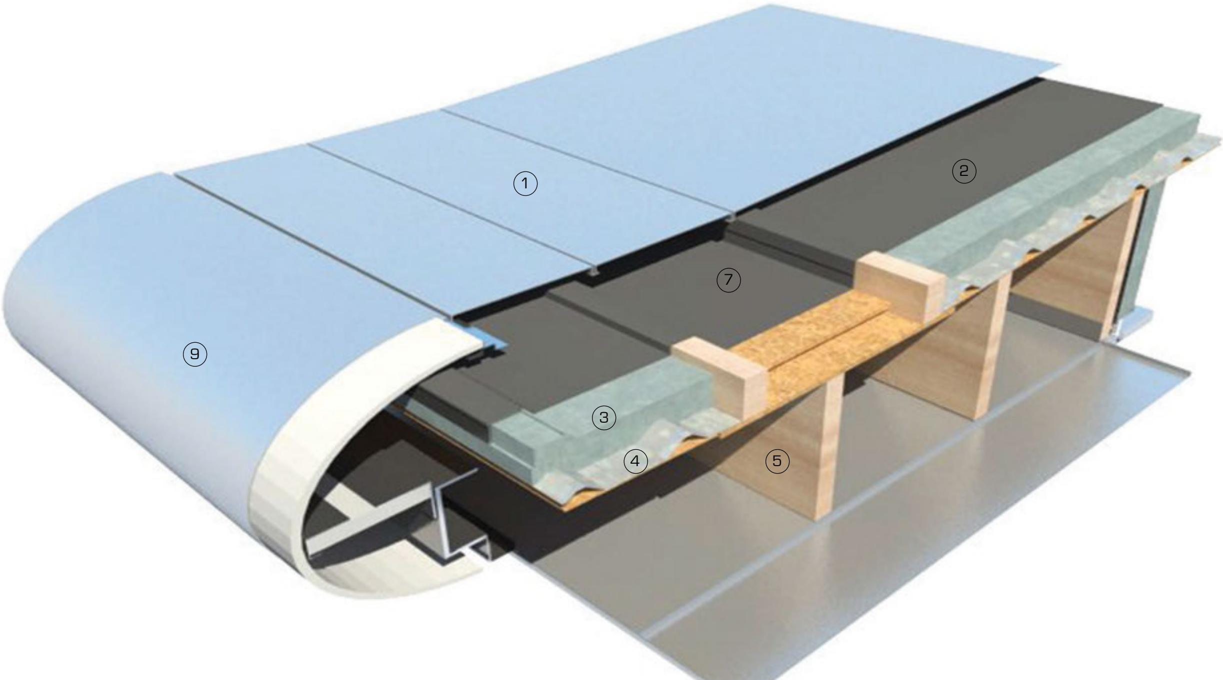


Details
1. Metal rainscreen panel
2. Single layer membrane
3. Closed cell thermal insulation
4. Structural deck
5. Purlin or structural beam
6. Secondary purlin
7. Folded metal gutter
8. Folded metal drip
9. Metal fascia panel
10. External wall
11. Outer sheet fixing bracket





Vertical section 1:10. Concealed parapet gutter with cantilevered edge



3D view of concealed parapet gutter with cantilevered edge

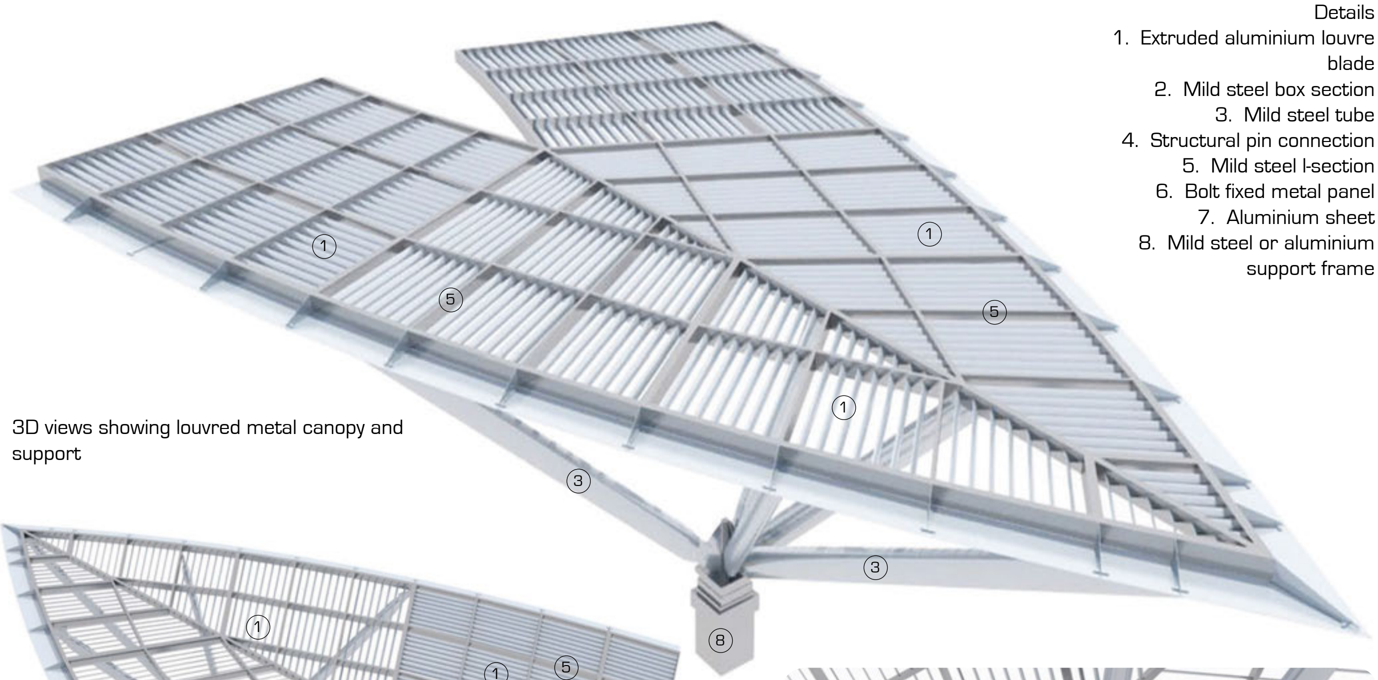
the roof down to the external wall. Parapets are formed only by a gutter that also provides the necessary upstand height for the parapet itself. A coping is then formed by using the same rainscreen panels as elsewhere on the roof in order to provide a continuity of appearance. The waterproof membrane beneath is then sealed against the wall construction or against the side of the sealed roof deck, which is closed off with a folded metal strip, in the case of profiled metal sheet or composite metal panels being used.

The depth of the roof construction is then finished with another rainscreen panel, set vertically, which is fixed in front of the parapet. Unlike parapets in profiled metal or composite panels, the vertical fascia panel can extend up to the top of the wall in order to conceal the coping flashing. In other types of metal roofing, the coping extends over the top of the wall, resulting in a thin visual edge to the top of the wall. This coping line can be concealed from view in rainscreen roof panel construction. The external wall beneath is typically sealed up to the underside of the roof deck.

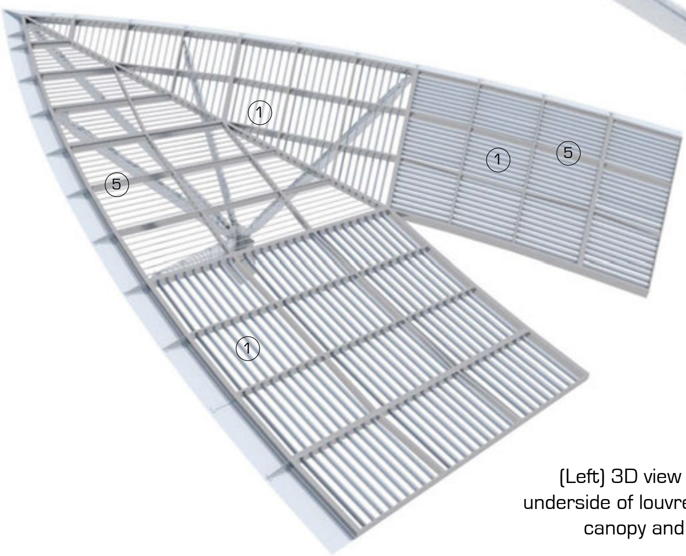
The parapet gutter can be covered with a perforated or slotted metal cover in the same material and finish as the adjacent rainscreen panels. Since rainwater runs off each panel at its edges onto the membrane below, there is no need to leave the gutter uncovered, as is the case with other metal roof systems. Water running down the membrane is drained directly into the gutter, and water underneath the gutter cover drains through slots or perforations.

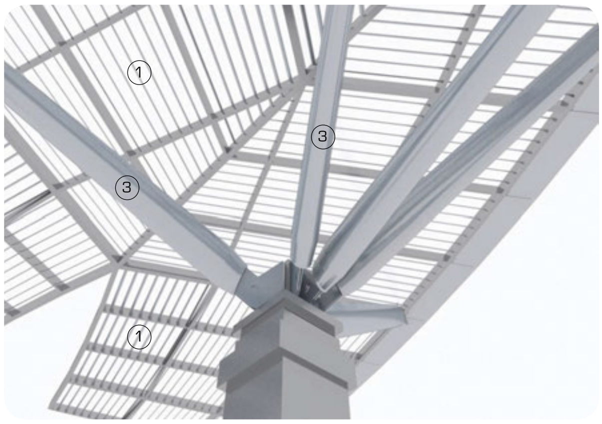
An advantage of rainscreen panels is their ability to form complex geometries from flat panel components. Since the panels are not required to be waterproofed, they do not require any joints between panels that would become difficult and expensive for roofs with complex geometries. Flat panels can be fixed down at their corners on a curved roof to create a set of gently curved panels that are turned in either one or two directions. Panels are increasingly being twisted in two directions in order to create genuinely curved roof finishes. Alternatively, panels can be set flat but with each panel at different angles to create a facetted roof section.

Details
1. Extruded aluminium louvre blade
2. Mild steel box section
3. Mild steel tube
4. Structural pin connection
5. Mild steel I-section
6. Bolt fixed metal panel
7. Aluminium sheet
8. Mild steel or aluminium support frame



3D views showing louvred metal canopy and support





(Left) 3D view showing underside of louvred metal canopy and support

System design

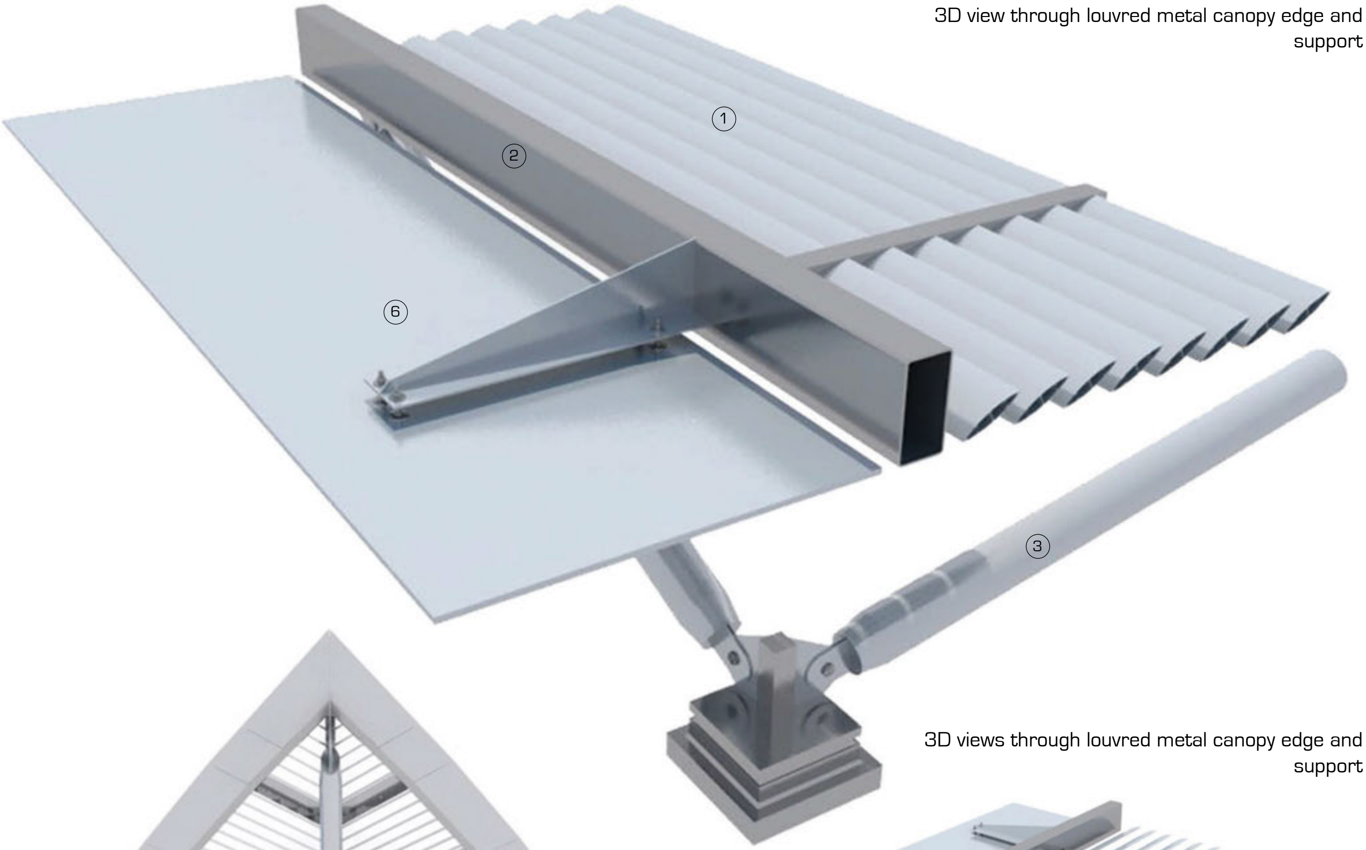
Arrangements of metal louvres are used as canopies to provide solar shading while still allowing daylight to pass through the canopy. Louvre blades are set typically at 45° to the vertical in order to block the passage of direct sunlight but allow the light to be reflected off its surfaces down to the space beneath the canopy. Louvre sections are created from folded strips of aluminium or mild steel sheet, but these have limited stiffness and stability, requiring restraint along their length to hold their straightness in length. Greater stiffness is provided by extruded aluminium sections, where the elliptical section is most commonly used, mainly for its ability to reflect daylight in a way that reveals its three-dimensional form, enhancing its appearance. Sections are either a half ellipse or a full ellipse. Flat louvre arrangements provide much less visual vibrancy when viewed from below. Extruded aluminium sections require end caps, usually for visual reasons, and these are either fixed with countersunk screws into the wall of the section, or are welded and ground smooth. Where end caps are screwed to the ends, the aluminium profile has screw ports that form part of the extrusion, into which the screws are fixed. Aluminium extrusions can be made in lengths up to around 6000mm, and are supported at centres to suit their structural depth. An elliptical section will span typically 1500mm for a 75mm to 100mm deep section while a 250mm deep section will span 2500mm, depending upon design wind speed and relative loads. When fixed at their ends, a fixed louvre assembly can be made without visible fixings.

System details

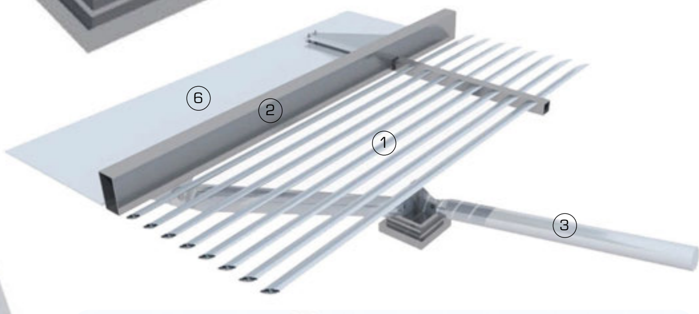
The supporting structure to the example shown comprises a mild steel frame fabricated from box sections, supported by tube sections that spring from points below the roof. The box sections are shown bolted together to form a flat frame structure, into which are set louvre panels, prefabricated and finished in a factory, then fixed to the supporting mild steel frame on site. The steel tubes are fixed to the flat frame with pin connections. Two flat plates are welded to the ends of the tubes, and a single plate forming a cleat is fixed to the underside of the flat frame and the base support below the roof. The fork ends of the tubular supports and the support cleats to which it connects are fixed together with face-mounted or countersunk bolts to form a visually crisp connection. The tubes have tapered ends shown which is typical of this type of steel construction. The aluminium louvre panels are fixed to the supporting flat frame with brackets that are welded to the sides of the bottom flange of the steel I-section. The aluminium louvre panel is supported on these brackets, with a nylon spacer between them to allow for thermal movement. The louvre panel is fixed to the cleat bracket with a countersunk bolt.

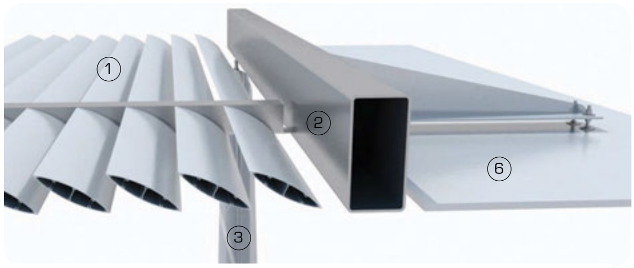
The supporting structure to the moving louvre assembly shown is made from either mild steel or aluminium sections. Aluminium sections are usually preferred for their durability but mild steel is often used for its greater rigidity. Mild steel is galvanised, painted, or both, while aluminium, with its greater durability, can be natural, anodised or cromated (similar to

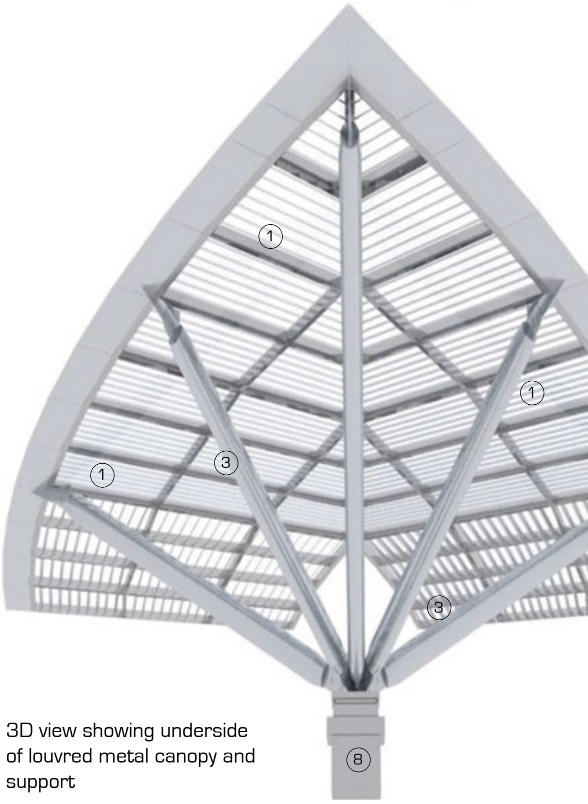
3D view through louvred metal canopy edge and support



3D views through louvred metal canopy edge and support







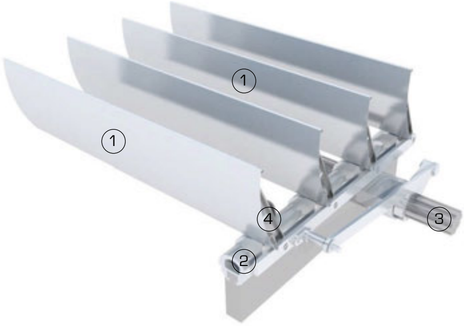
3D view showing underside of louvred metal canopy and support

3D view showing underside of louvred metal canopy and support

3D views showing electrically operated louvre panel in open position

3D views showing electrically operated louvre panel in open position

3D view showing electrically operated louvre panel in open position



3D view showing electrically operated louvre panel in closed position

3D views showing electrically operated louvre panel in closed position

3D view showing electrically operated louvre panel in open position

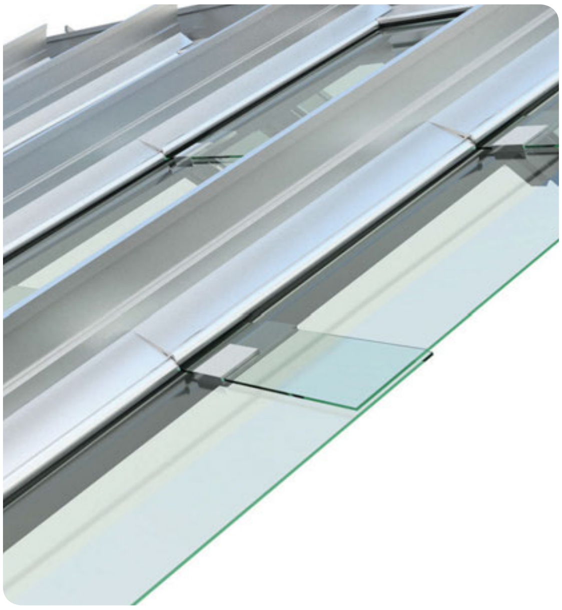
Details
1. Extruded aluminium louvre blade
2. Standard rackarm
3. Drive shaft
4. Slat clip

3D view showing electrically operated louvre panel in open position

anodising) depending on the individual application. Metal panels of large size, made from a 1200mm x 2400mm sheet, can result in a gentle oil-canning effect around their edges. This gives panels their characteristic soft edge, but they look smooth and consistent, and this is usually accepted visually as part of their appearance. If much thicker sheet is used, there is a disadvantage in increased cost as well as a greater difficulty in working the sheet to form smooth shaped pressed panels. Aluminium panels are typically either PVDF coated or polyester powder coated, while steel sheet is usually polyester powder coated only. The use of anodised aluminium as a finish on sheet has increased in recent years as the result of greater reliability of the finish, which until recently has suffered from uneven colour consistency. The silicone used to seal the joints can be applied in a variety of monotone tints, ranging from white, to greys, to black. Some silver-grey colours match well with silver coloured panels to give an overall appearance of a single colour for the complete canopy, particularly when recessed joints are used between panels. Flush joints in silicone tend to give the canopy surface an homogenous appearance, giving it more the appearance of concrete than of metal. This can detract from the crisply fitted assembly of panels which is characteristic of metal and also one of the advantages of the material.

Louvres are typically a maximum of around 6000mm long for those 75mm to 100mm deep, requiring support at 1000mm to 1500mm. Sliding arms typically support up to a 6000mm length of louvre blades, giving an overall square shape (in plan) to each set of controlled louvres of 6000mm x 6000mm size which are fixed into the supporting I-section frame. A 100mm deep I-section will span typically 1000mm - 1500mm between supports depending on the design of the glazed roof below. The distance between the moveable louvre panels and the glazed roof below is made sufficient to allow for access for cleaning the glass below and the louvre assembly itself.

Electrically operated louvre canopies are also used for horizontal and inclined glazed roofs, excluding up to 90% of solar heat gain when set at a 45° angle. Louvre blades are 75mm-100mm in typical proprietary systems but blades up to 300mm wide can be made as a single extrusion. Nylon sleeves and washers are used at the connection of moving parts, rather than metal, to avoid the need for regular lubrication. Louvres can be solid or perforated to different percentages of solid to void, from around 10% void to a maximum of 50%, though the latter is difficult to fabricate. Louvres are fixed by steel pins into a sliding aluminium section at each end of the profile. The louvres are also fixed at their centre in section. As the sliding aluminium rod moves, the aluminium louvres move together, opening and closing together. The sliding rods are connected at each end of the louvres and are fixed to a supporting frame of aluminium I-sections. The single tube is powered by an electric motor, and as it turns, the sliding arms move through the arrangement of gears.



3D detail view showing glazing support

Details
1. Extruded aluminium glazing bar
2. Single glazed sheet
3. Rubber seal
4. Aluminium glazing clip
5. Extruded aluminium section
6. Aluminium clip on capping
7. Aluminium footing
8. Concrete base
9. Polycarbonate sheet
10. Double glazed unit

3D view of typical eaves connection

Systems design

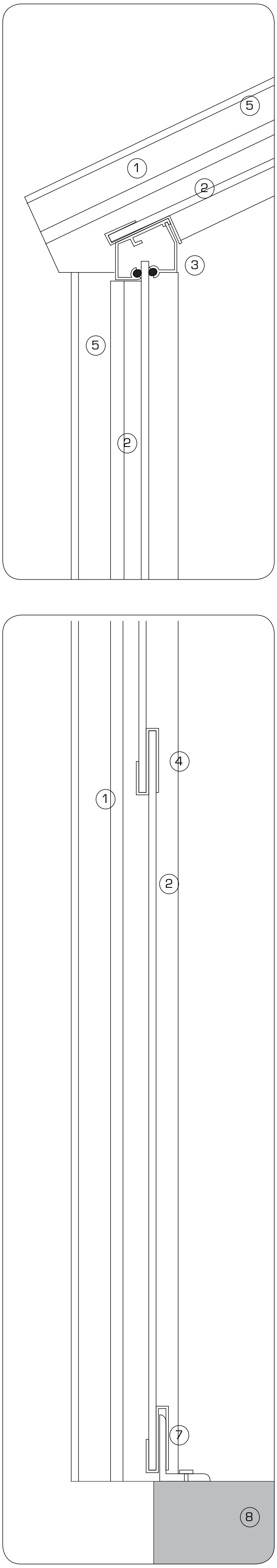
Curtain walling principles used in external walls have been adopted, over the last 20 years, as a reliable method of constructing glazed roofs to replace earlier systems developed from greenhouse glazing. This glazing system is still used in greenhouses for agricultural activities, but has poor thermal insulation, since their purpose is to absorb the heat from the sun rather than excluding it. The use of single glazing, with no thermal breaks and high air infiltration rates (by curtain walling standards), make it ideal for agricultural use, but very poor for use in general building construction. However, the concept of greenhouse glazing has been developed into the highly insulated, air sealed and watertight glass roof systems used in contemporary buildings.

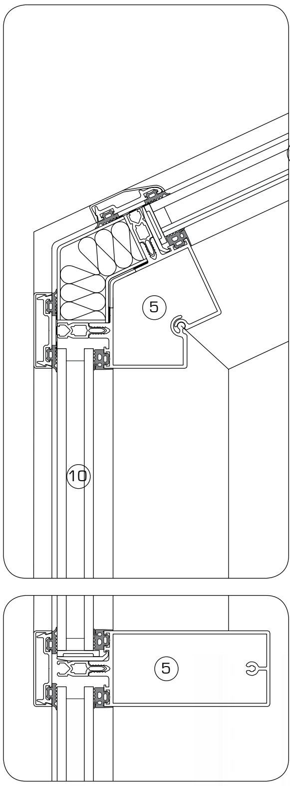
An essential component of greenhouse glazing that has been retained in modern glazed roofs is the glazing bar, which corresponds to a mullion in glazed walls. The greenhouse glazing bar has a condensation channel beneath the glass to drain away water that passes through the outer seal during rain. The condensation channel also serves as a drain for moisture inside the building that has condensed within the framing. Condensation channels are either open at the edges or are enclosed. Modern greenhouse glazing is made from extruded aluminium sections with no thermal break, since high thermal insulation is not required, but includes the condensation channels to avoid water from dripping below. The horizontal joint between lapped glass sheets is sealed with either a sealant, typically silicone, or with continuous aluminium clips. Some greenhouse systems still have lapped glass with no seal at between the glass sheets, making it very economic but not very airtight, which suits certain agricultural applications.

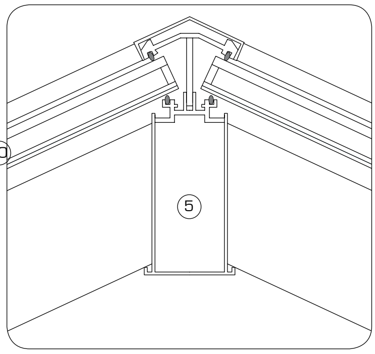
Ventilation in greenhouse glazing is provided at the eaves and at the ridge, while opening lights are used for more closely controlled ventilation. Single glazed sheets are held in place on their sides by supporting them on the glazing bars and securing them in place with continuous aluminium clips that snap onto the glazing bar. The aluminium sections are separated from the glass by extruded rubber-based seals which are held in place on the aluminium glazing bars and which press against the glass to provide both a cushion for the glass as well as a water and air seal. The strength and stiffness of the glazing bar is provided by the central flat bar that extends beyond the glazing line either inside or outside the glazing. Unlike curtain walling based systems, where the structural mullion extends on the inside face of the glass with a pressure plate on the outside, greenhouse glazing has only clips on either side of the control bar, allowing it greater freedom to extend both inside and outside the face of the glass. The rubber seals are deep enough and soft enough to allow the bottom of the glass sheet to lap over the top of the sheet below on the horizontal joints.

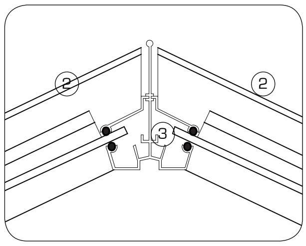
System details

Systems for contemporary glass roofs use the principles of traditional greenhouse glazing, but incorporate the techniques



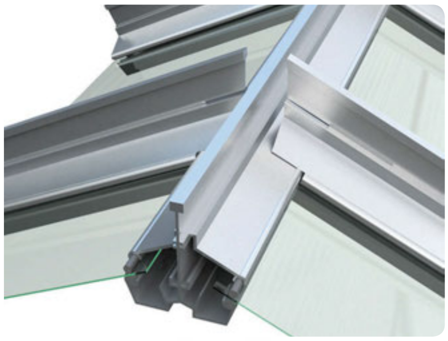


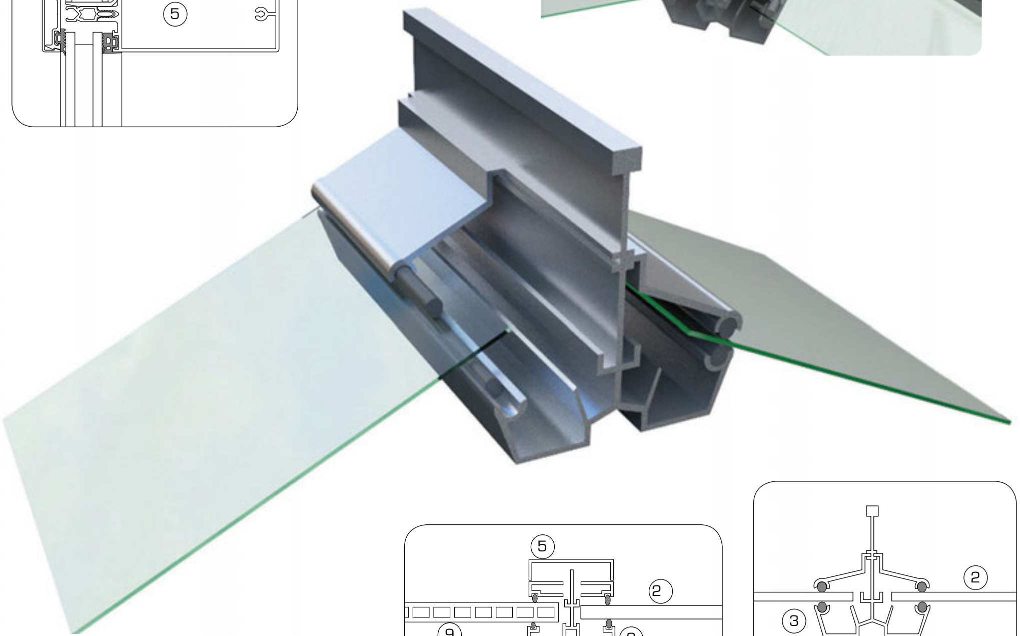




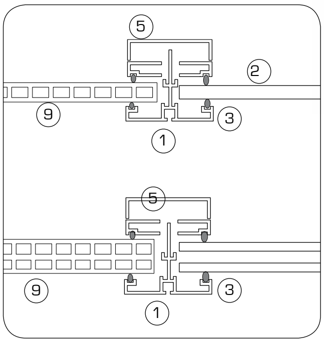
Vertical section 1:5. Ridge in greenhouse glazing

(Right) 3D detail of ridge

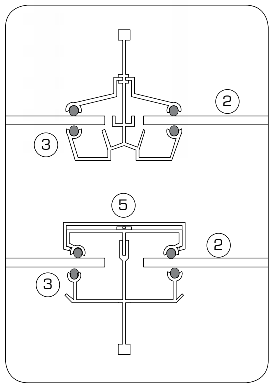




3D view of ridge in greenhouse roof

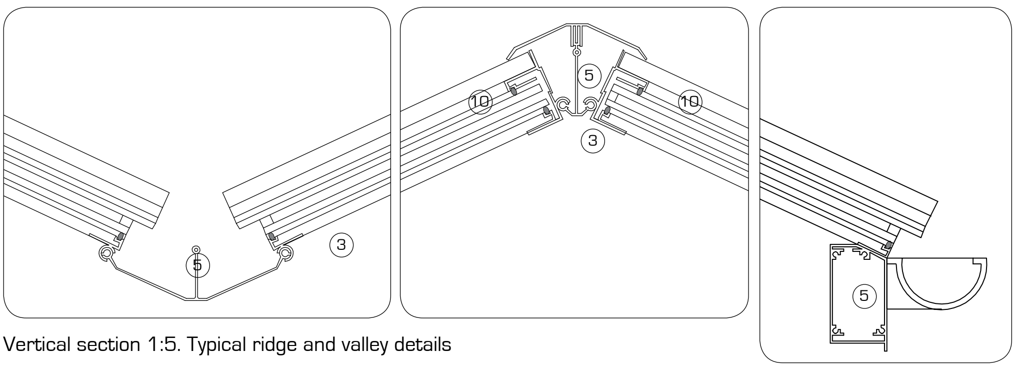


Vertical section 1:5. Clamping details for glass to glass connection

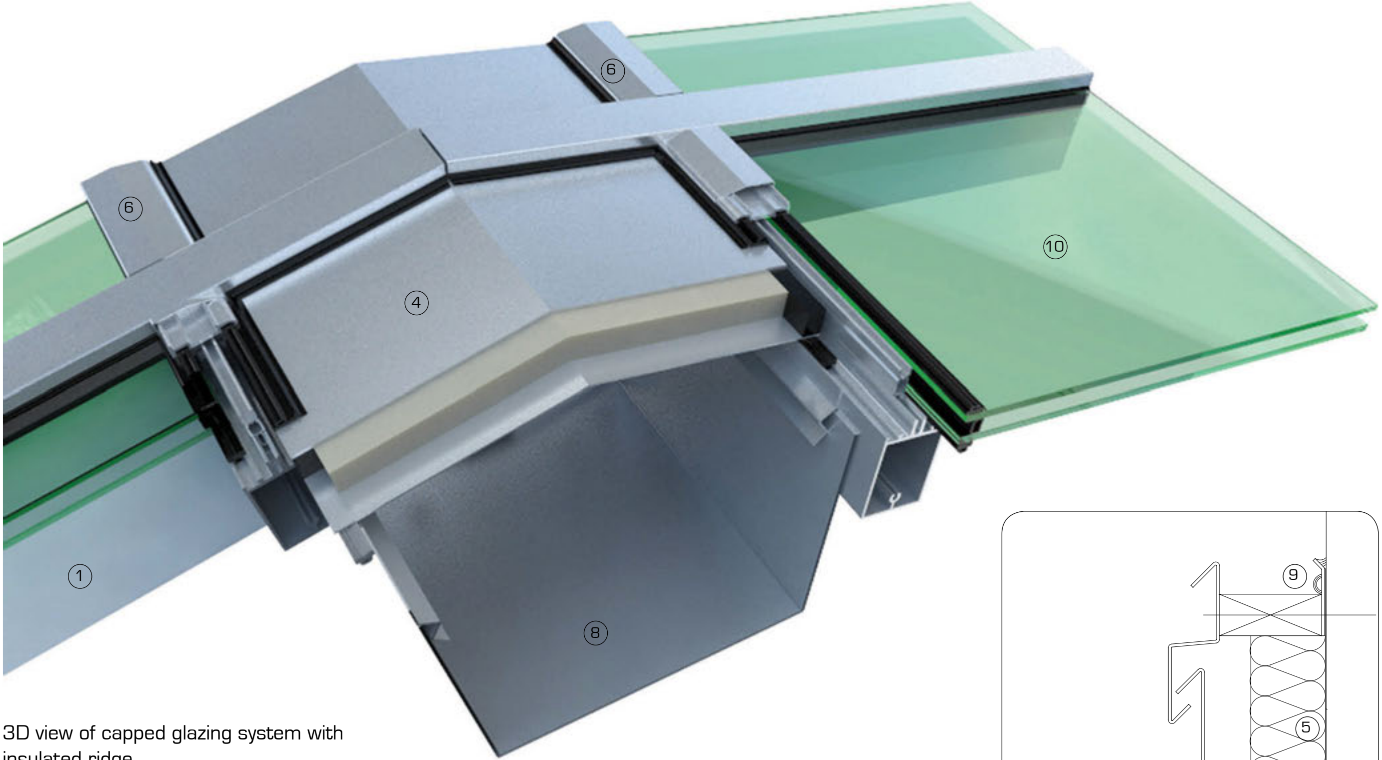


Vertical section 1:5. Clamping details for glass to polycarbonate connection

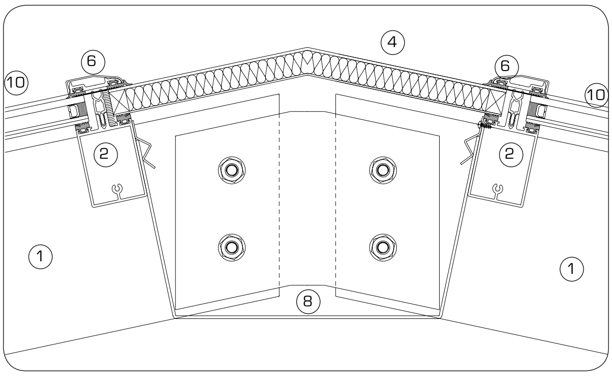
Vertical sections 1:5. Greenhouse glazing system showing typical details



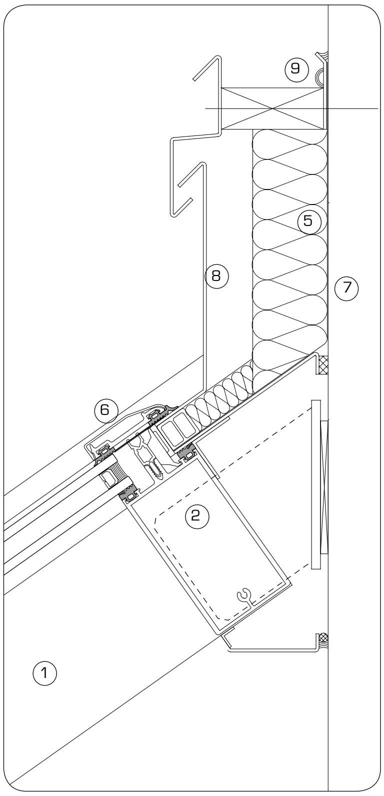
Vertical section 1:5. Typical ridge and valley details

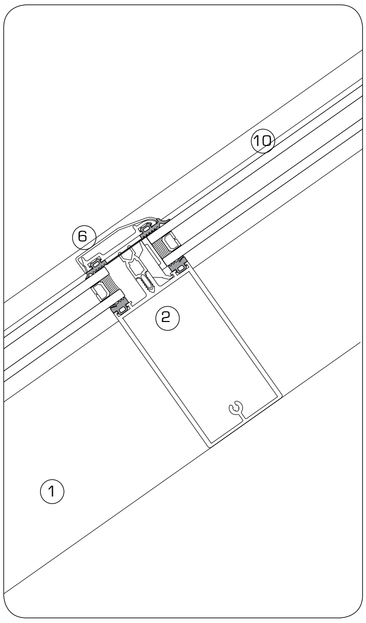


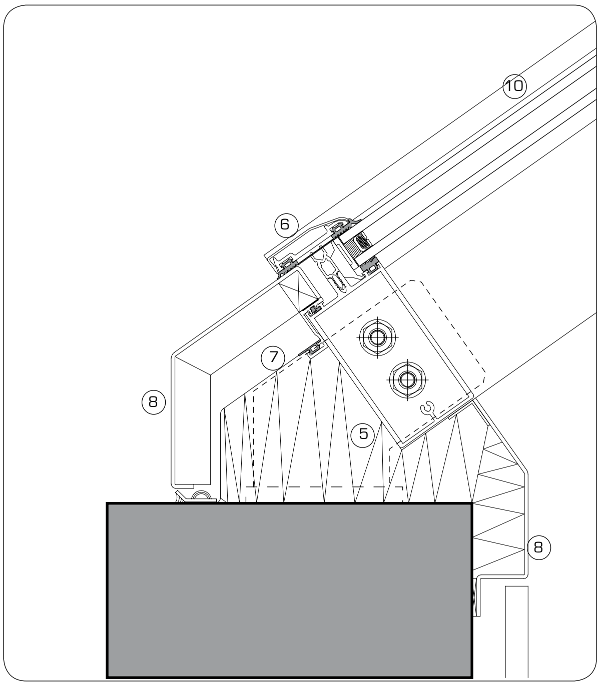
3D view of capped glazing system with insulated ridge



Vertical section 1:10. Ridge detail

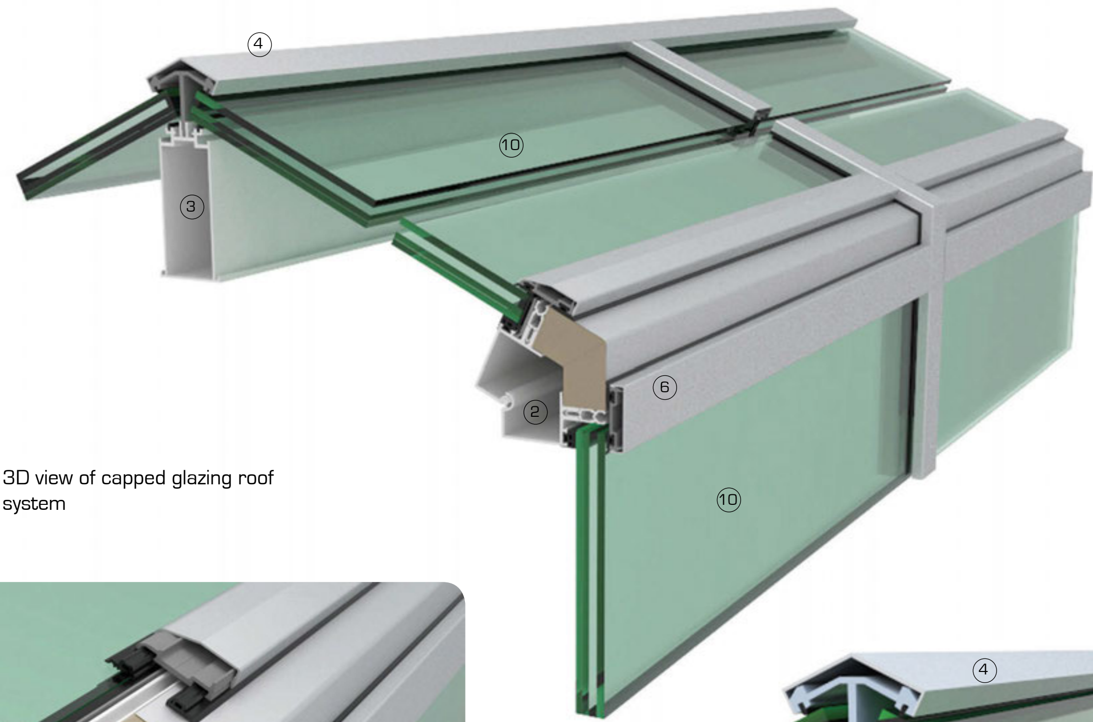




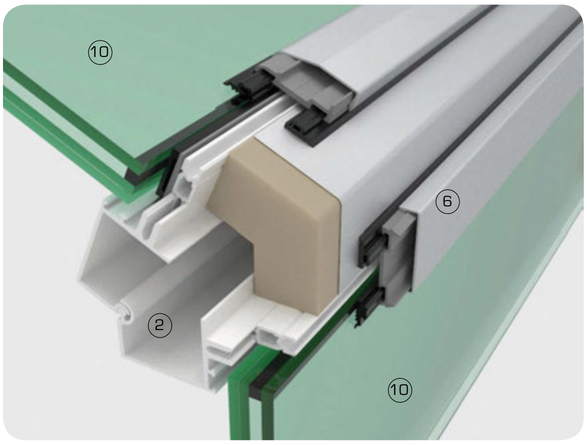


Vertical section 1:10. Capped glass roof with abutments

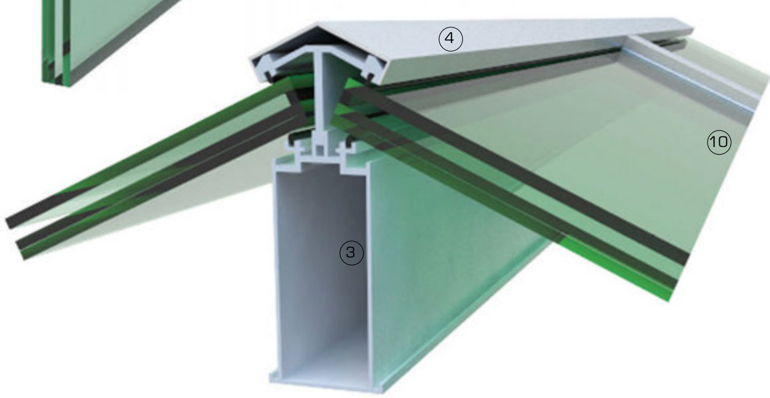
Details
1. Extruded aluminium glazing bar
2. Extruded aluminium transom
3. Ridge bar
4. Ridge capping
5. Thermal insulation
6. Pressure plate and capping
7. Rubber seal
8. Aluminium flashing
9. Aluminium clip on capping
10. Double glazed unit



3D view of capped glazing roof system



3D cutaway of glass to glass corner detail in cpped glazing

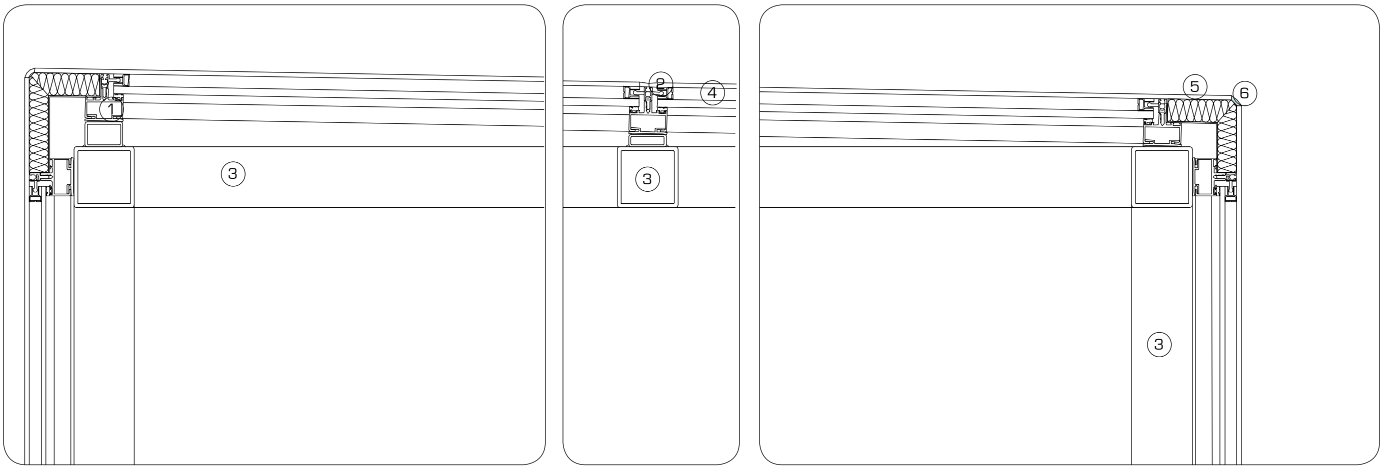


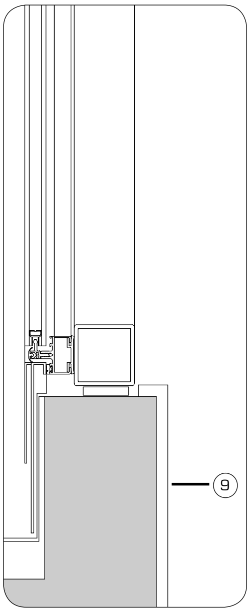
3D detail of capped ridge

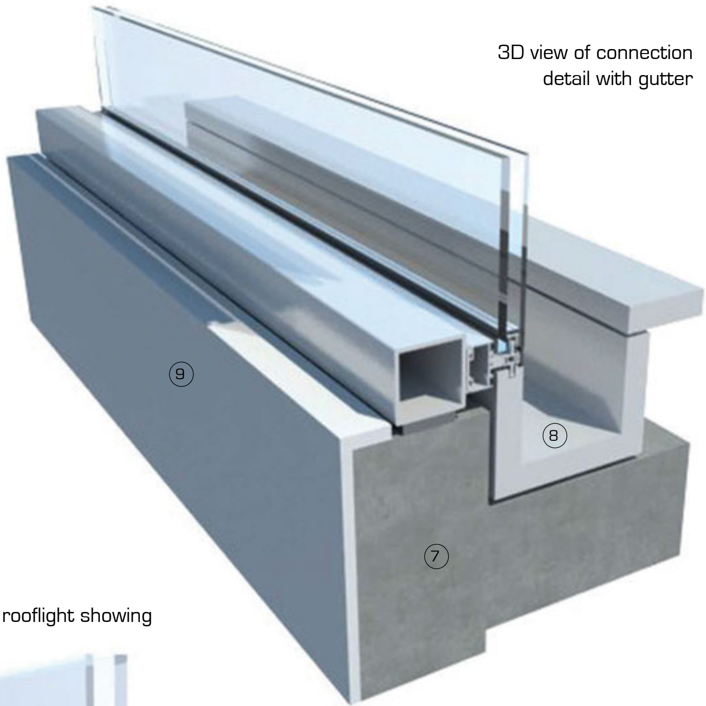
of glazed curtain walling. Drained and ventilated systems are used, with thermal breaks and double glazed units. Pressure plates rather than clips are used to hold large glass units in place in capped systems, and toggle-type plates are used to provide flush joints in silicone based systems. This latter type is discussed in the next section on silicone sealed rooflights, while this section focuses on pressure plate systems, so-called 'capped' glazing. A typical system comprises glazing bars which are assembled on site in a grid of members that resemble the mullions and transoms of stick glazed curtain walling. The base of the curtain wall, at the bottom of the extruded profile, may have an additional condensation channel, as shown. This provision can also be made by setting the condensation channels immediately beneath the glass. The glass is set onto rubber-based air seals fixed to the glazing bar and is secured with a continuous pressure plate of extruded aluminium. A strip of extruded EPDM is set between the pressure plate and the glass to provide a weathertight seal. As with glazed curtain walling, the glazing bars are drained and ventilated, or pressure equalised, internally. Water that is able to find its way through the outer seal drips into an internal channel where it is drained away safely to the bottom of the roof, typically at the eaves. In smaller roofs without eaves, where the roof angle changes from pitched to vertical wall, rainwater is allowed to run on down the wall to the base of the roof. At the 'fold' point of the roof the internal drain in the glazing bar is continuous with the vertical wall, and the system is drained at the base of the wall, which could be a reinforced concrete slab at roof level.

While glazing bars running down the roof project above the surface of the glass, those running along the roof which hold the top and bottom edges of the glass in place, require a method of allowing the water to run over the junction. Some systems use a step at this point, without a pressure plate on top that would otherwise impede the passage of water down the roof. Other systems use a pressure plate and cover capping with chamfered edges that allow rainwater to pass over it easily. A small amount of water is left trapped on the top edge of this horizontally-set glazing bar, but this is soon blown away by the wind or else evaporates. Any water that penetrates the outer seal is drained away through the internal drain in the glazing bar.

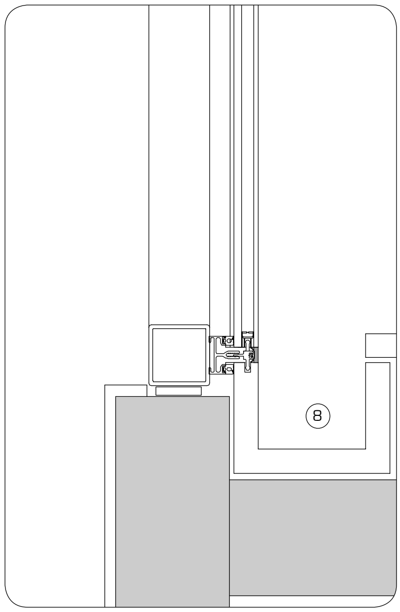
Ridges, like glazing bars, follow the main principles of greenhouse glazing. The box section, or chosen profile of the typical glazing bar is usually made deeper to take the higher structural loads of the ridge. Gutters, at both valleys and eaves, are very different to greenhouse glazing. Instead of lapping the glass into the gutter, the gutter profile (or downstand flashing) is clamped into one side of the horizontally-set glazing bar at the base of the pitched roof.







3D view of connection detail with gutter

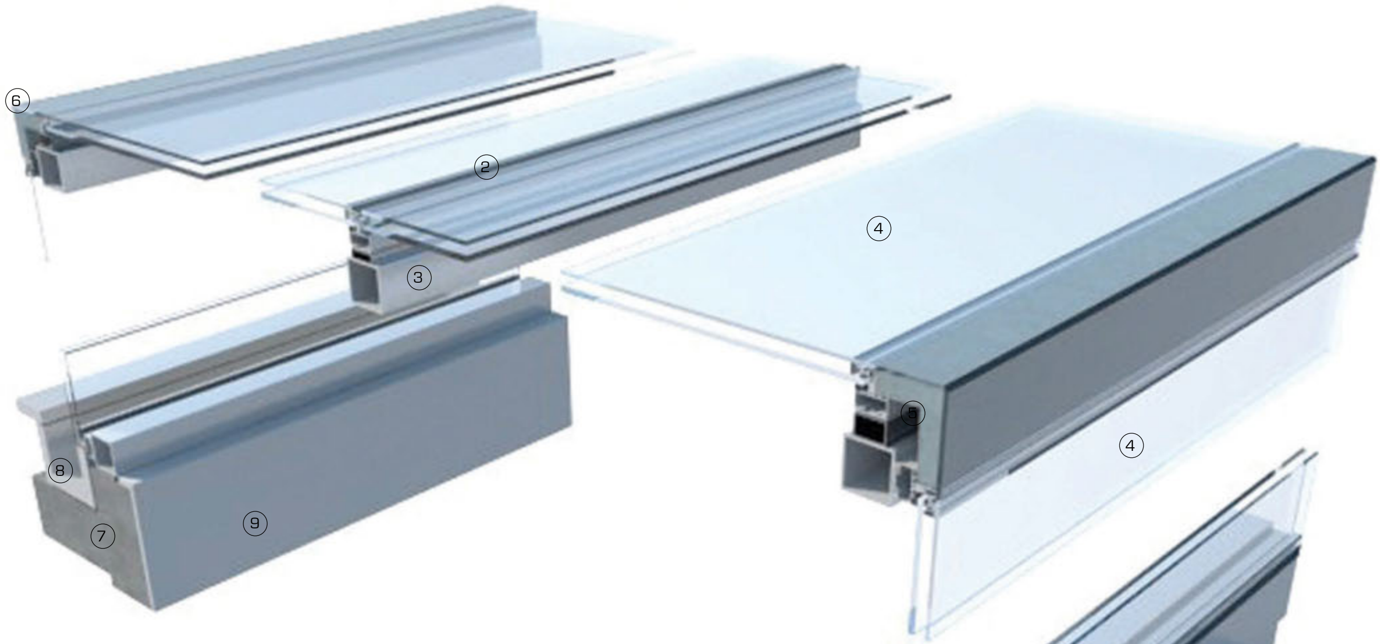


Vertical section 1:10 through rooflight showing typical details

3D view of connection to concrete base

System design

While capped systems, described in the previous section, suit pitched roofs, they cannot reliably be used on nominally flat roofs, where the roof pitch is usually 3° to 5°. This is mainly because the rainwater running down the roof cannot pass the horizontal glazing bars which project above the surface of the glass. The smooth, continuous finish required for flat glazed roofs is achieved with a silicone seal between glass panels that is set flush with the surface of the glass. The glass is clamped in place with short lengths of pressure plate that are recessed below the outer seal. The recessed plates are secured to an aluminium channel which forms an integral part of the double glazed unit and which is continuous around its perimeter. The extruded aluminium channel is recessed into the gap at the edge of the unit usually used to bond the unit together and to seal the edges behind the spacer. The adjacent spacer in the double glazed unit both keeps the glass at a fixed distance apart as well as having desiccant within it to absorb any residual moisture within the sealed cavity between the glass sheets. The recessed aluminium channel is bonded to each glass sheet and also provides the edge seal to the completed unit, as in a regular double glazed unit. The short lengths of pressure plate are then set into the gap formed by the recessed channels of abutting glazed units, and are clamped to the glazing bar



3D view of typical rooflight assembly with uncapped horizontal joints

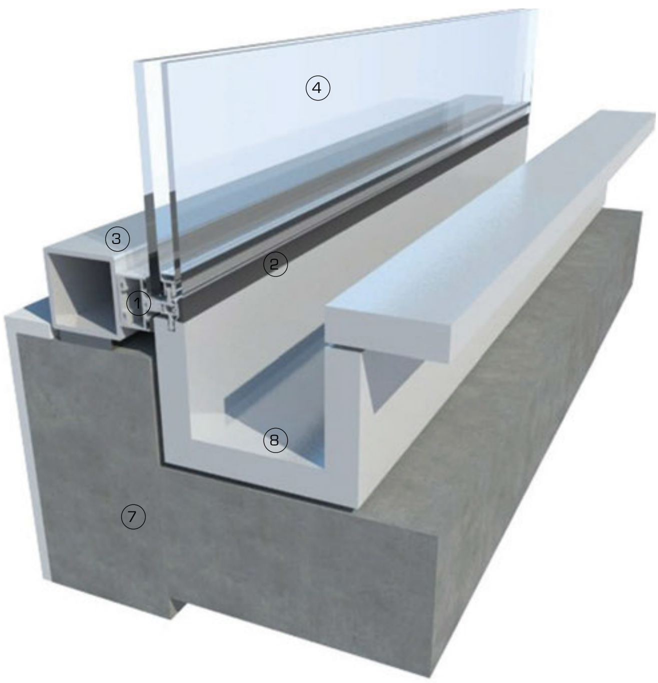
Details
1. Extruded aluminium glazing profile
2. Pressure plate and capping
3. Mild steel support frame
4. Double glazed unit with recessed edge
5. Thermal insulation
6. Silicone seal
7. Concrete base
8. Gutter
9. Internal finish

with self tapping screws, typically at 300mm centres. The gap between the glazed unit is sealed with silicone, typically 15mm to 20mm wide, and with a backing strip or 'backing rod' behind it to form a back edge to the silicone seal.

The glazing bar has its structural box or fin removed in order to fix it directly to a steel support frame. Alternatively, an all-aluminium glazing bar can be used. As with capped systems, small amounts of rainwater that pass through the outer silicone seal are drained away in the condensation channels set below the glass, within the glazing bar. In practice, silicone seals are very reliable but are dependent upon correct workmanship on site, so the condensation channel is often not used in practice but serves as a secondary chamber to support the inner air seals. Silicone-sealed glazing bars can be used in all directions across a roof, unlike capped systems, since the glazing bars present no barrier to the passage of water.

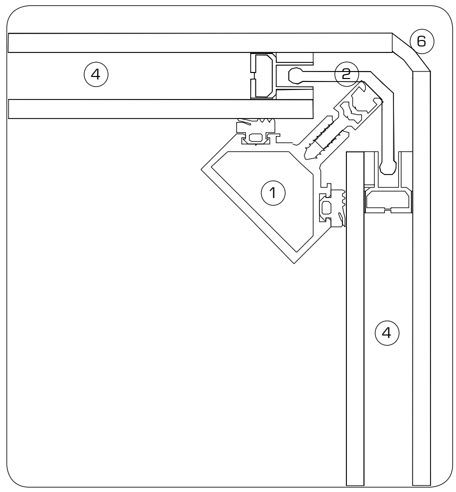
System details

Since the advantage of silicone-sealed systems is of continuous glazed surfaces uninterrupted by visible glazing bars, ridges and valleys are treated only as folds in the surface of the glazing, for rainwater runs across the complete sealed surface of the glass rather than being directed into gutters set across its surface.



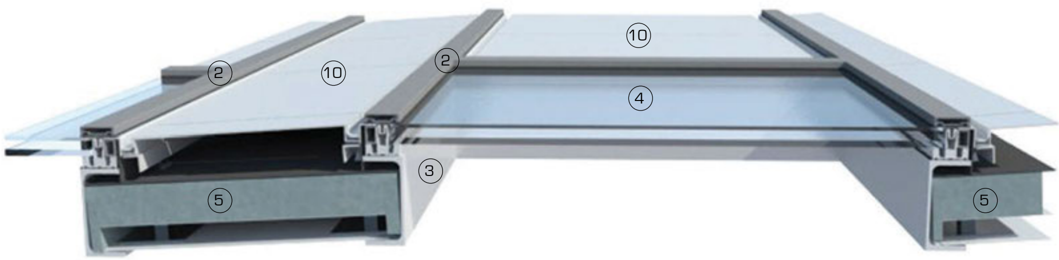
3D view of gutter detail

3D view of corner detail showing folded pressure plate to achieve desired angle



Vertical section 1:5. Corner detail

Details
1. Extruded aluminium glazing profile
2. Pressure plate and capping
3. Mild steel support frame
4. Double glazed unit with recessed edge
5. Thermal insulation
6. Silicone seal
7. Concrete base
8. Gutter
9. Internal finish
10. Opaque roof cladding panel



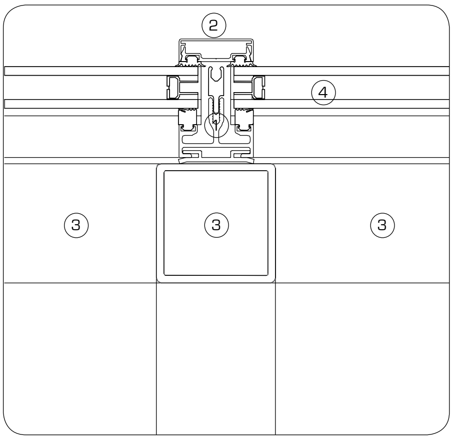
(Right) 3D view showing silicone-sealed rooflight set within opaque-panelled roof configuration

The short lengths of pressure plate can be folded in the factory to the required angle, while the glazing bar forming the ridge is the same as that used elsewhere on the roof, with some modifications to the angle of the clips that hold the inner EPDM seal in place. The edges of roofs are also treated as folds, with rainwater usually allowed to run off the edge into a gutter, either just below the roof, or down to the base of the glazed wall below the glazed roof. An advantage of this system is the ability of the roof to be continuous with a glazed wall in the same system with a simple 'fold', without reducing its weather tightness. Typically the wall is not very high, forming part of a larger glazed roof. Dust that is carried down off the roof during rain is washed down the vertical glazing, rather than being carried away in a gutter, but in practice glazed rooflights require regular cleaning to maintain their crisp appearance.

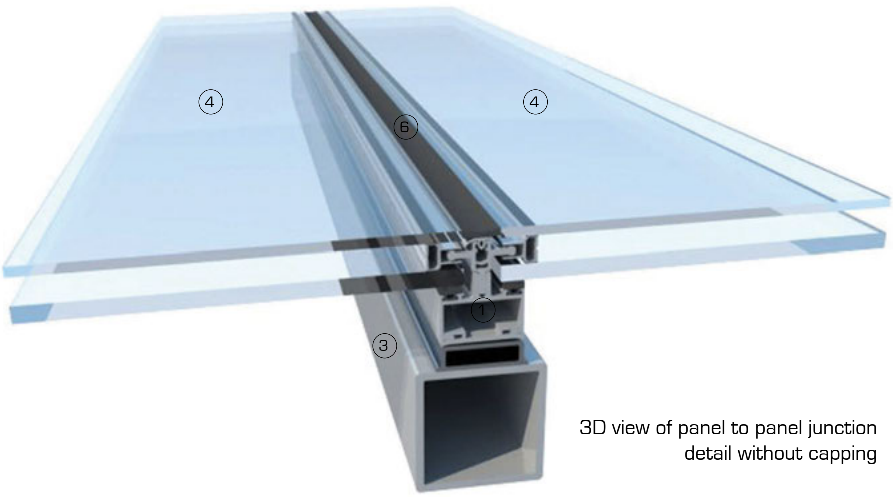
Folded corners are formed with either a single specially formed glazing bar, or with two glazing bars meeting. The recessed lengths of pressure plate are folded to form the required angle, and the silicone is chamfered to form a flat surface between the two meeting glass panels. Silicone is rarely used to make a sharp angle between the two double glazed units, as it is very difficult to achieve a straight line without the assistance of an additional metal angle bedded into the silicone. The alternative method of forming a roof edge requires the edge of the double glazed unit to be coated or 'opacified' to avoid the frame behind being visible through the glass. This is often achieved by stepping the glazed unit, with the outer glass extending to meet the corner, while the inner glass stops at the glazing bar to allow the recessed aluminium angle to be bonded in its usual position adjacent to the glazing bar. The glass unit is secured in the same way, with a recessed length of pressure plate, while the outer glass is cantilevered to meet the adjacent glazed unit at the corner.

An advantage of silicone sealed glazing is its ability to be mixed with capped glazing. Since both systems are drained and ventilated (pressure equalised), the same glazing bar can be used in a mixed roof system of flush silicone joints and capped profiles. Although this mix is often done for visual reasons, it does allow for easily formed junctions with adjacent areas of roof in different materials, and for a mix of actual panels and glazed panels in a single roof using a reliable drained and ventilated system. The most common application of this method is where capped profiles are used for the vertically-set glazing bars running down the slope of a roof, while silicone-sealed glazing is used on horizontal joints to allow rainwater to pass down it unimpeded by any projecting glazing bars. Junctions in silicone sealed glazing, such as edges of roofs and ridges, are formed in the same way, while the capped system follows the folds with continuous pressure plates that are mitred and sealed at the folds. Butyl tape is used as an extra seal at folds, set between the pressure plate and the outer EPDM gaskets. Cover caps are also mitred to give a crisp appearance.

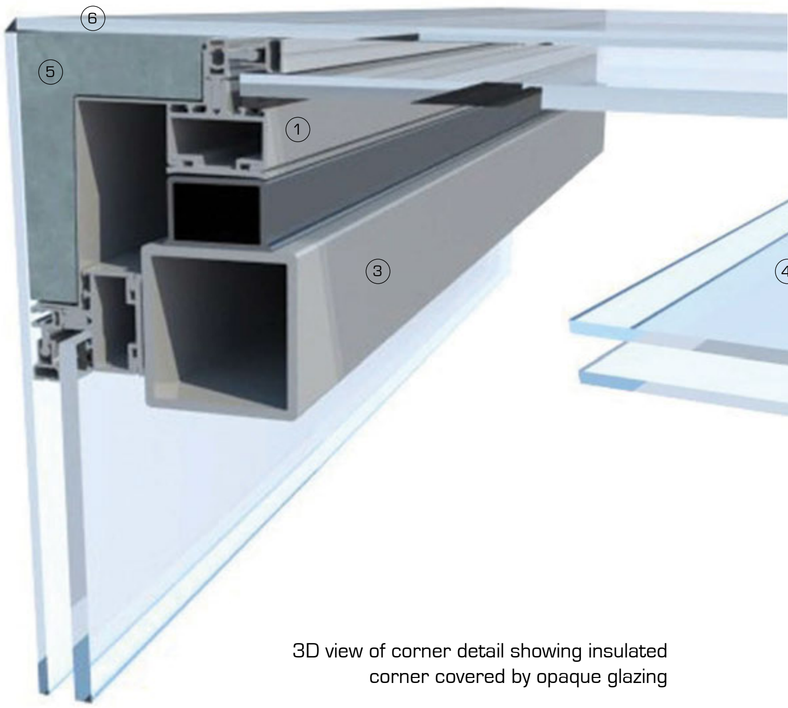
3D view showing silicone-sealed rooflight set within opaque-panelled roof configuration



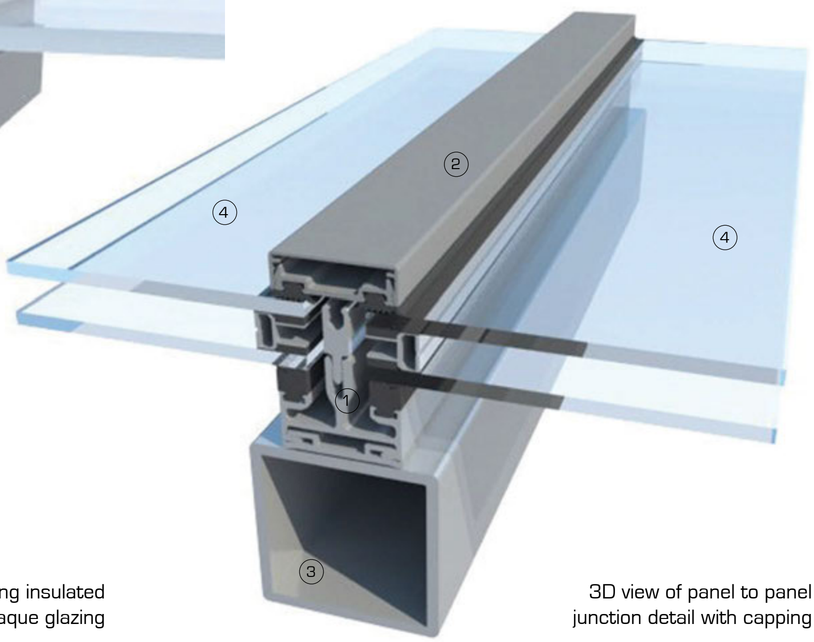
Vertical section 1:5. Panel to panel junction with capping



3D view of panel to panel junction detail without capping



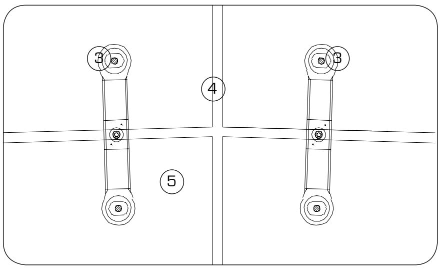
3D view of corner detail showing insulated corner covered by opaque glazing

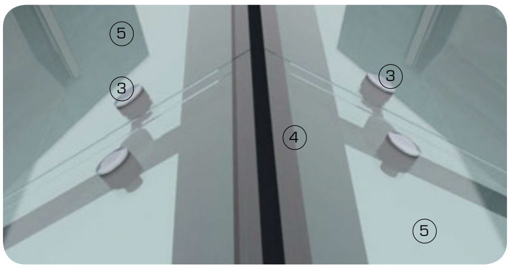


3D view of panel to panel junction detail with capping

3D view showing bolt fixed glazing with internal fold

3D view showing bolt fixed glazing with external fold





(Far Left) Horizontal section 1:25. Typical clamp assembly

(Left) 3-D view showing typical clamp assembly

System design

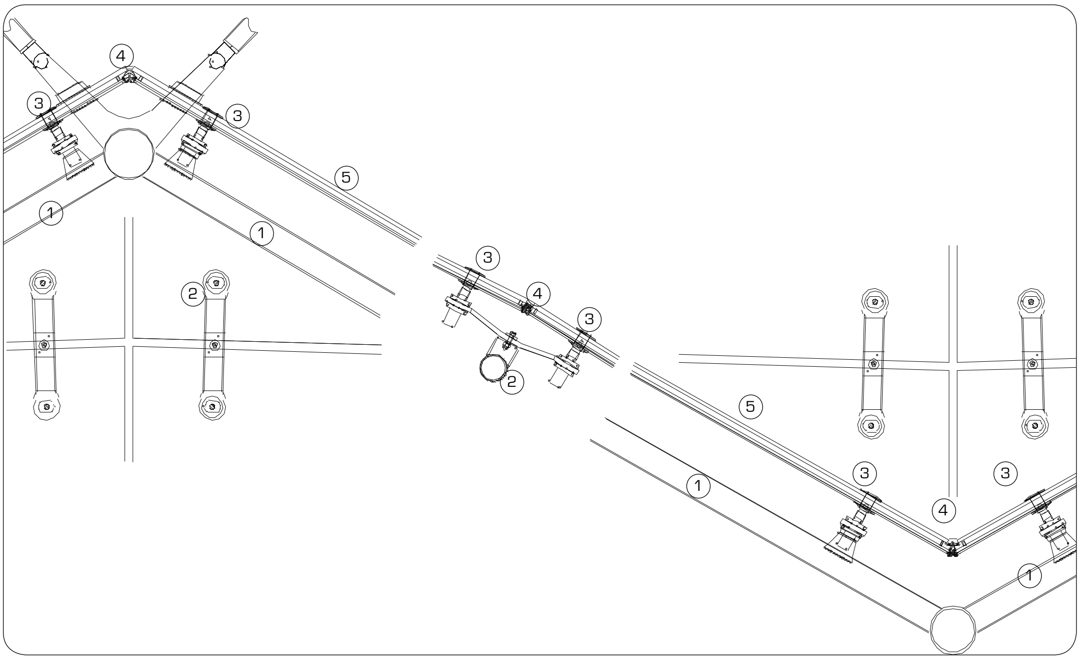
This method of glazing for roofs has been adapted from the technique used for glazed walls, where glass is fixed at points with specially designed bolts rather than with a frame supporting the perimeter of the glass. Bolt-fixed glazing for facade construction developed from earlier patch plate glazing, where single glazed sheets of glass are bolted together with mild steel brackets. Glass fins are used to stiffen the glazed walls to replace the aluminium mullions. The L-shaped patch fittings bolt the fins and glass together, as well as bolting the glass to the supporting structure at the top and bottom of the wall.

Where glazed walls are usually structurally supported by either top hung or bottom supported methods, the support of glazed roofs is by trusses, steel sections or purlins that span across the roof opening. For nominally flat roofs, the most common arrangement is a supporting beam set under each glass joint, so that bolts are supported on each side of the beam by a short bracket. Only half the number of beams are required to support the same three panels of glass. This is achieved by setting the beam in the middle of alternate glass panels. Brackets are cantilevered from the beam to support the edge of the panel above as well as one side of the panel next to it. This method provides greater visual transparency but requires larger brackets, which in practice detract little from the increased effect of transparency.

The single tube section shown in the diagrams would suit only a short span, as in a rooflight, but large span roofs require deeper beams, usually formed as open trusses in order to maintain the sense of transparency at oblique viewing angles. Triangulated trusses provide both structure and support for the glass, but tend to be visually heavy. Cable trusses are often preferred, but they require a ring beam around the edge of the glazed roof to form a tensile supporting structure like a tennis racquet. The cable trusses, always in tension, require an equivalent surrounding structure in compression to transfer the loads to the main building structure.

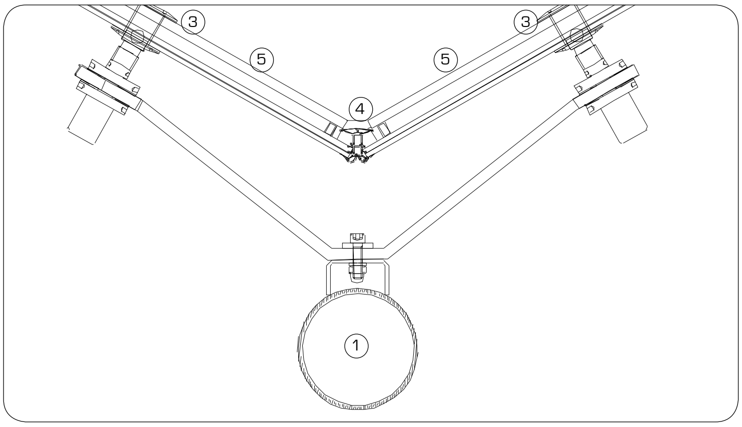
System details

The essential component in this glazing method, the bolt fixing, is made typically in stainless steel and consists of several components that form the complete assembly. The part that passes through the glass has either a disc on each side of the glass to clamp the glass or double glazed unit together, or alternatively is angled to form a countersunk device within the depth of the double glazed unit. The countersunk fitting is set flush with the outer face of the glass, and the face fixed disc type is set forward of the face of the glass. A polished stainless steel finish is mostly used on the outside in order to make it easy to clean and maintain. In the face fixed type, which is currently the most commonly used fixing, the inner disc screws over the threaded shank that forms part of the outer disc until it is tight up to the inner face of the glass. The threaded shank

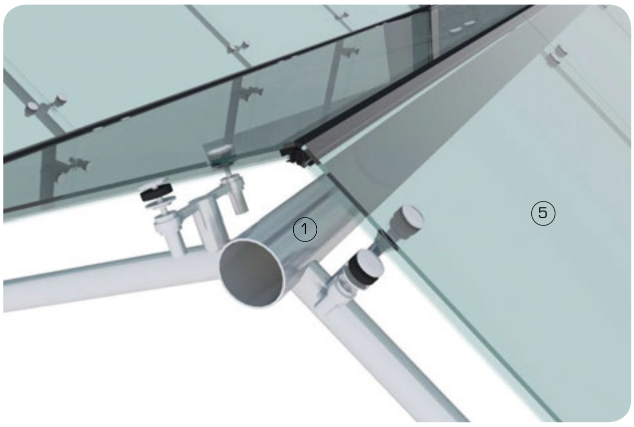


Vertical section & elevations 1:25. Bolt fixed roof with folded profile

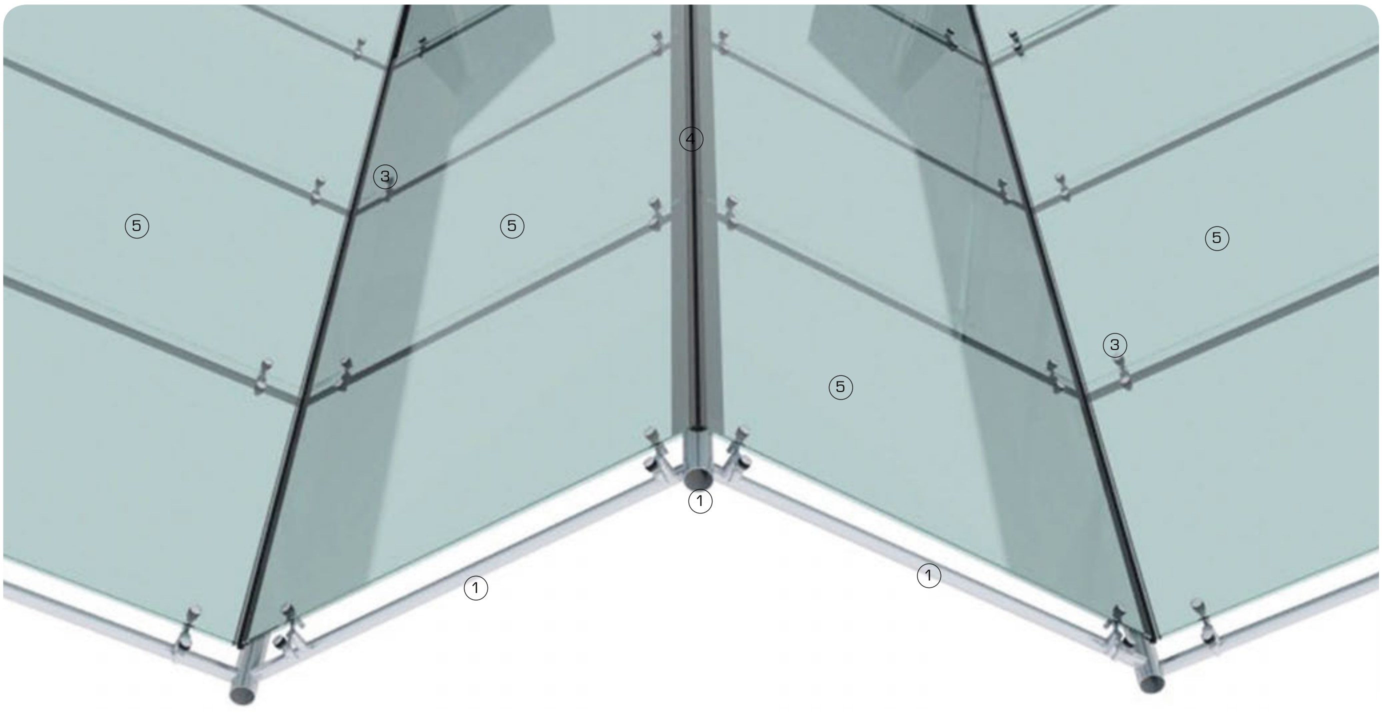
Details
1. Structural steel support
2. Connector plate
3. Bolt fixing
4. Silicone seal between glass panels
5. Single glazed or double glazed unit
6. Support bracket
7. Silicone seal
8. Adjacent external wall
9. Insulation
10. Extruded metal cylindrical section
11. Roof construction
12. Concrete base



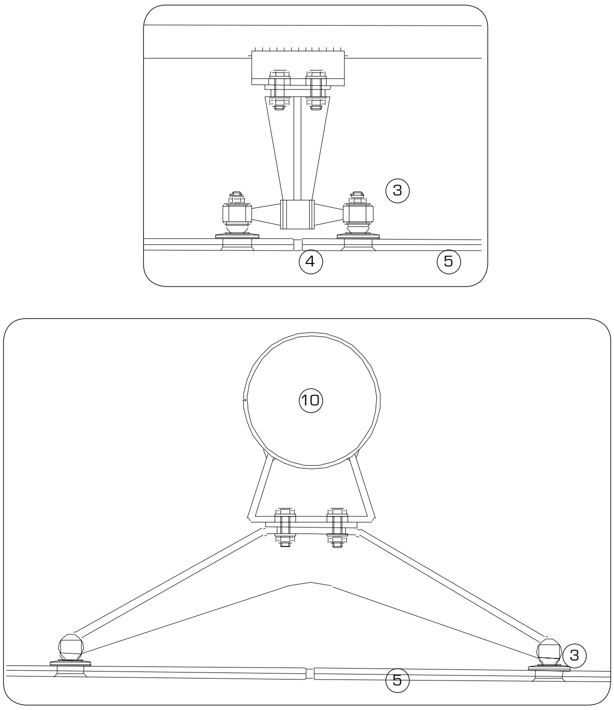
Vertical section 1:10. Internal fold



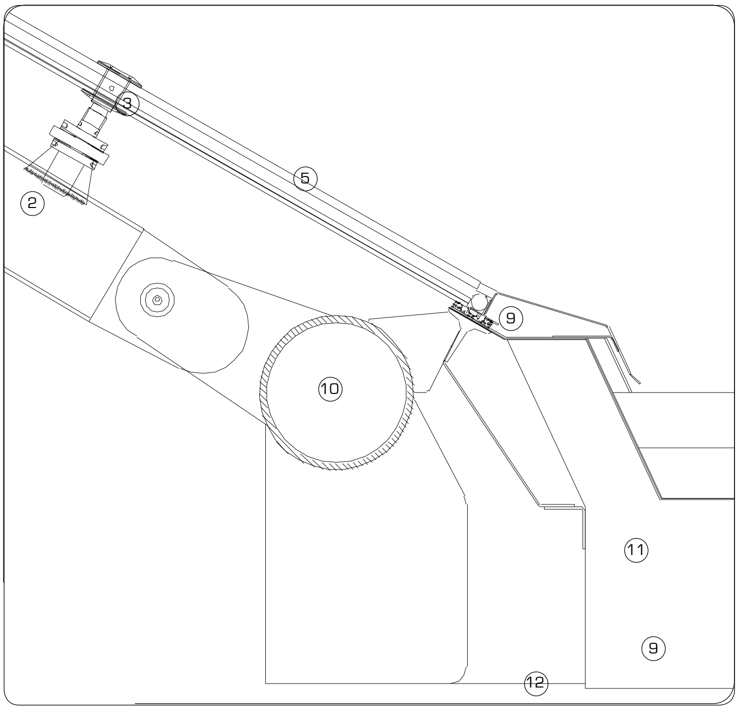
3D view showing external fold



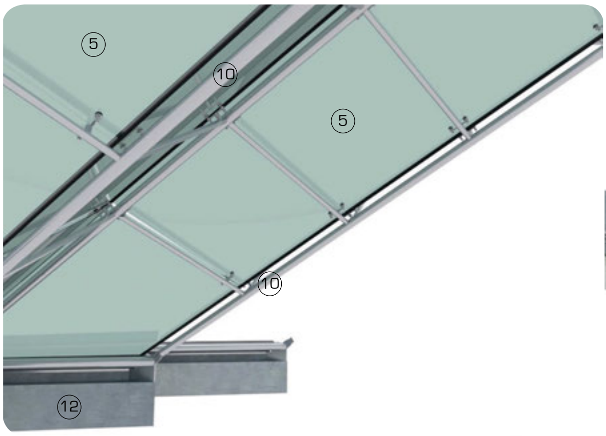
3D view showing bolt fixed roof with folded profile

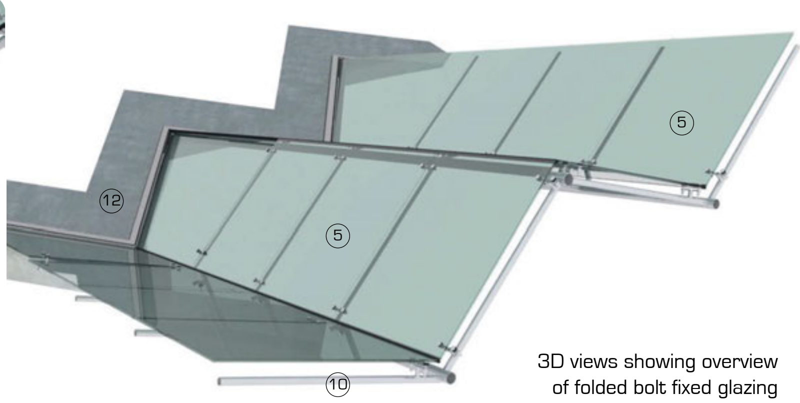


Vertical sections 1:10. Bracket support



Vertical section 1:10. Connection to roof deck





3D views showing overview of folded bolt fixed glazing

projecting into the building is able to rotate about a ball bearing where it meets the inner face of the double glazed unit. This allows the double glazed unit to rotate up to around 12° under wind load and associated structural deflections. This swivel joint is essential in avoiding the over stressing of the glass under full wind load that would otherwise result in breakage of the glass unit. The threaded shank is then used to clamp the complete bolt fixing to a support bracket with either threaded discs or nuts. The visible thread in the shank can be either left exposed, or be covered with threaded sleeves and stop ends. This bolt type is used regardless of the orientation of the roof, whether flat or pitched.

In common with other glass roof types, the inner glass of a double glazed unit is usually made from laminated glass. In the event of a double glazed unit being broken, the inner laminated sheet remains intact, while the broken pieces of the heat strengthened or fully toughened outer sheet come to rest on top of the damaged, but intact, inner sheet. The double glazed units are first fixed and adjusted to form even joint widths between all the units. Joints of 20-28mm are used, though around 20mm is the most common joint width (in elevation) that allows for both structural movement and the slight variations in the size of the glass panels. Unlike capped roof glazing systems, the entire double glazed unit is visible from both outside and inside, the edges are not set behind pressure plates that conceal any variations in glass panel size. Joint widths up to around 28mm, which is deemed close to the maximum practical joint width for the adhesion of silicone sealant in a regular double glazed unit, is used where brackets penetrate the outer seal from inside the roof to outside. If required, these brackets are used to support external sun shading and maintenance equipment. These brackets are usually in the form of flat plates that are welded to the internal supporting structure, and project through the joint. Although an additional lip around the projecting plate may provide additional protection to water penetration between the silicone and the bracket, in practice it has been found that this detail performs well if the seal is applied to a good level of workmanship.

Seals between double glazed units are made as an outer silicone seal with an inner backing rod of extruded EPDM. The gasket has projecting flaps on each side to form a ‘fir tree’ section which prevents any water that penetrates the external seal from reaching the inner face of the seal. This EPDM gasket also serves as an inner air seal, and provides a crisp appearance of sharp lines in the interior face of the glazed roof.

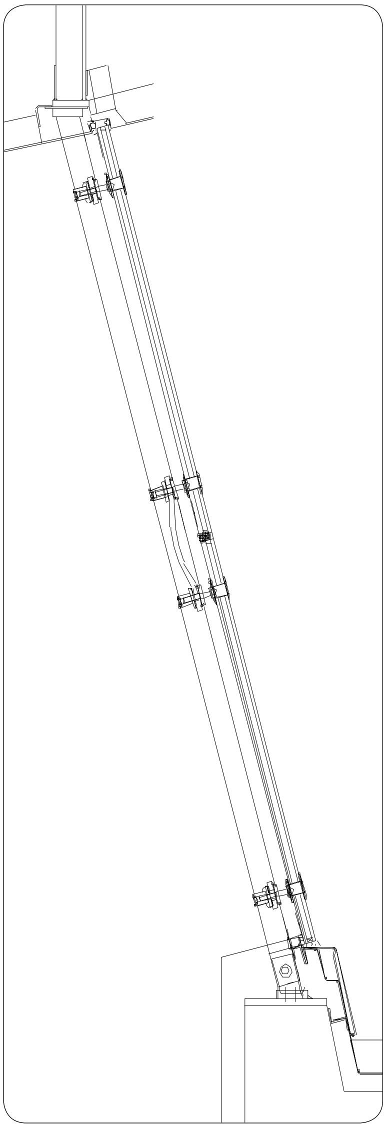
3D view showing bolt fixed glazing with external fold

3D view showing bolt fixed glazing with external fold

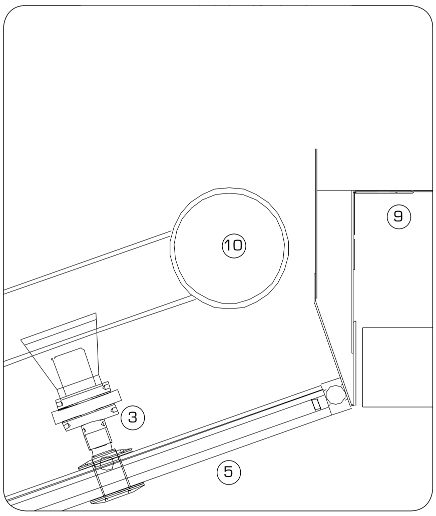
3D view showing bolt fixed glazing with internal fold

Details

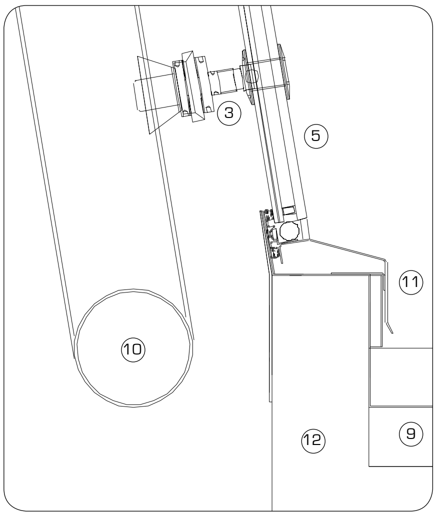
1. Structural steel support
2. Connector plate
3. Bolt fixing
4. Silicone seal between glass panels
5. Single glazed or double glazed unit
6. Support bracket
7. Silicone seal
8. Adjacent external wall
9. Insulation
10. Extruded metal cylindrical section
11. Roof construction
12. Concrete base



Vertical section 1:10. Junction with adjacent wall

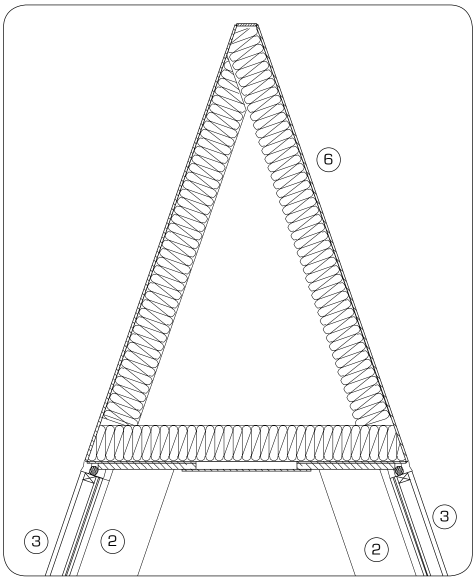


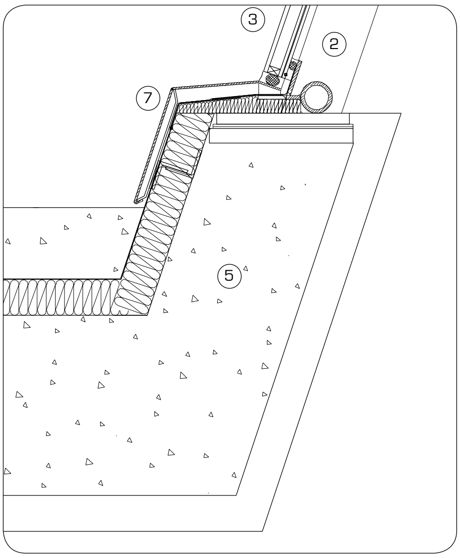
Vertical section 1:10. Upstand at base



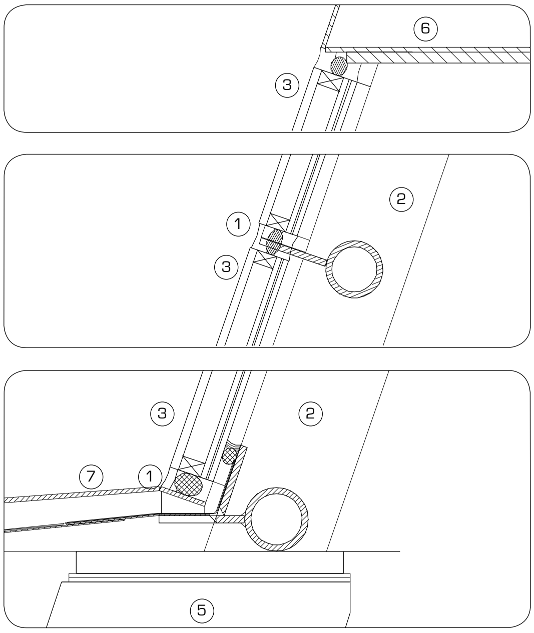
Vertical section 1:10. Base upstand junction

Details
1. Silicone bond
2. Mild steel support frame
3. Single glazed laminated glass panel
4. Silicone seal
5. Concrete base
6. Insulated metal panel
7. Folded metal flashing
8. Reinforced concrete support frame
9. Folded aluminium protective cover
10. Steel aluminium support shoe
11. Structural glass beam

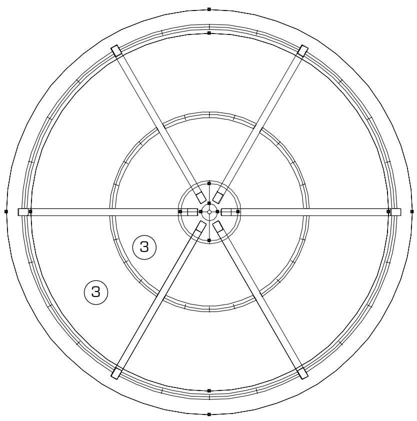




Vertical section 1:10. Base upstand, Junction with adjacent material

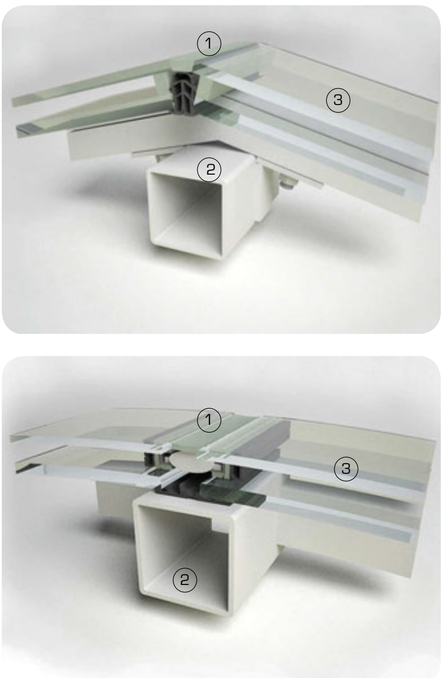


Vertical section 1:5 through rooflight showing typical details



Horizontal section 1:20 of typical rooflight layout

3D view of typical roof light assembly

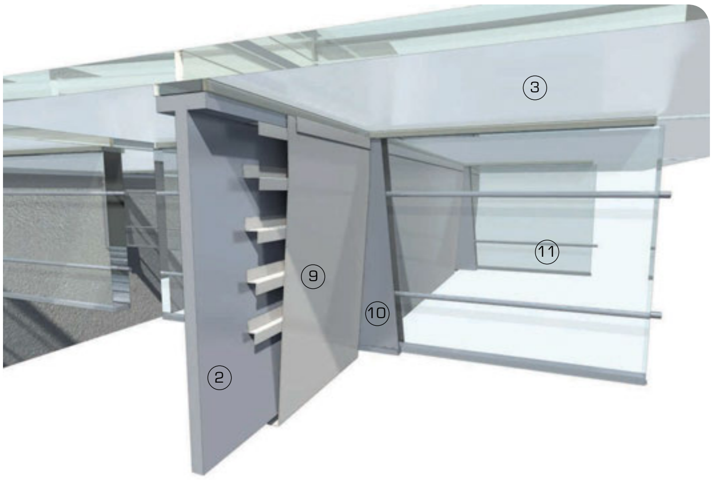


3D Details showing glass to glass junctions

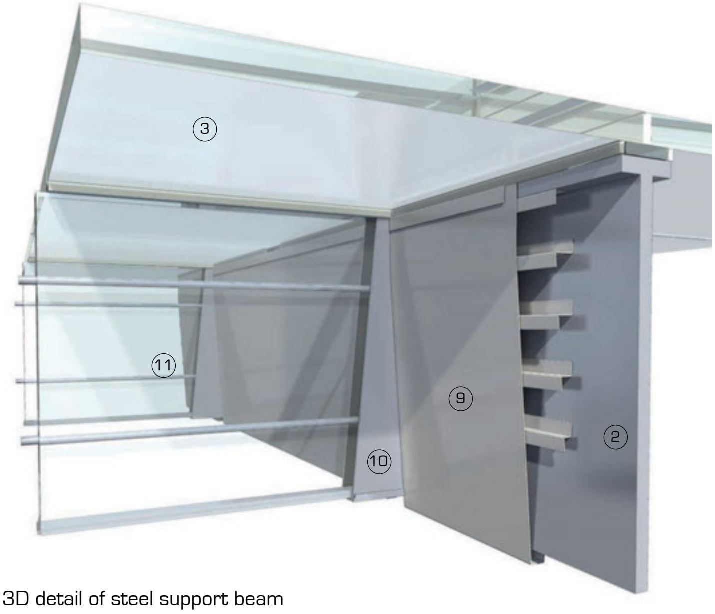
System design

The method of silicone bonding glass to aluminium framing is well developed for use in glazed curtain walling to provide visually smooth glass facades with no visible cappings. The use of silicone sealed rooflights can be taken a step further to become a full bond without the need for the mechanical restraint of pressure plates. In silicone bonded rooflights, the glass is glued to a supporting frame. The glue is also the external seal. This technique is useful for small rooflights, where cappings would be very difficult to fabricate, and in rooflights which are walked upon, where the rooflight is an external glass floor.

The generic conical rooflight shown has curved double glazed units bonded to an aluminium frame. Silicone bonding avoids cover caps that would have to be curved both vertically and horizontally, which would be extremely difficult to fabricate. The rectangular rooflight shown is bonded together without a supporting structure; the glass provides its own support. The flat monopitch rooflight is bonded to a frame to provide a small rooflight from one double glazed rooflight, with laminated glass sheets used to form a surface which can be walked upon. Similar to a glass floor used inside a building, it must also take heavier traffic loadings and be weathertight.



3D view of underside of glass beam and steel support beam

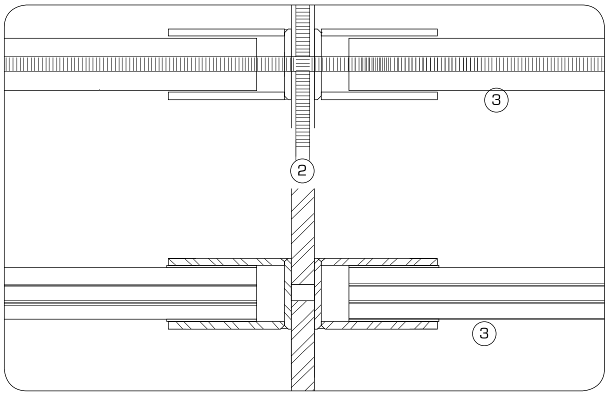


3D detail of steel support beam

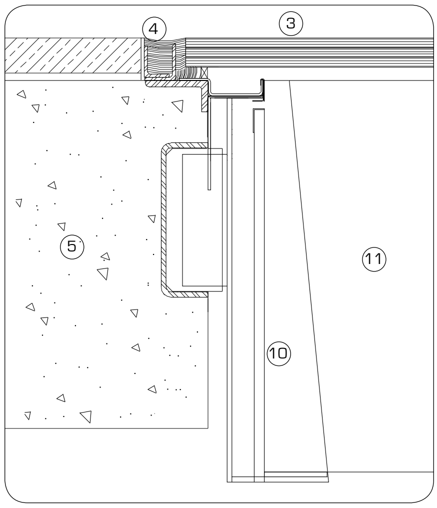
The generic conical rooflight shown has a lightweight steel frame used to support double glazed units that form a rooflight. The structural frame comprises box sections set vertically, held in place by thin tube sections running horizontally to form a circle. The glass panels are supported on steel flat sections which are welded to the horizontally set tube section. The glass is levelled on blocks set onto the horizontal flat section, and the silicone is applied to the joint. At the base, the horizontal metal section projects out to form a flashing over the upstand in which the rooflight is set. An additional inner metal upstand can be provided with another silicone seal if there is risk of future flooding from blocked rainwater outlets, for example. The waterproof membrane for the roof slab is continued up the upstand and is bonded to the base of the horizontal section that supports the glass. This provides a complete seal from the glass to the roof membrane, with the metal flashing providing both a protection to this seal and a means of concealing the closed cell thermal insulation set on top of the waterproof membrane.

The generic rectangular rooflight shown is constructed without a supporting frame. Mechanical restraint is provided at the corners in the form of pressure plate clips. The double glazed units at the corners are fabricated with a recessed groove on the two sides of the panel forming the corner in order to

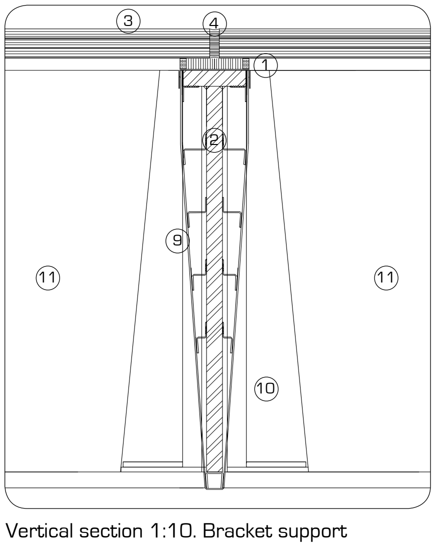
3D view of glass beam with central steel support beam



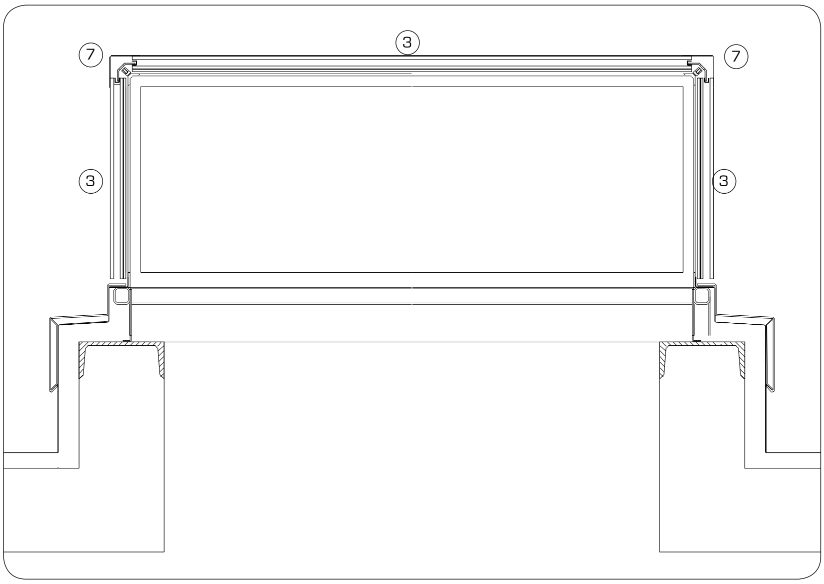
Vertical section 1:10. Support systems for rooflight



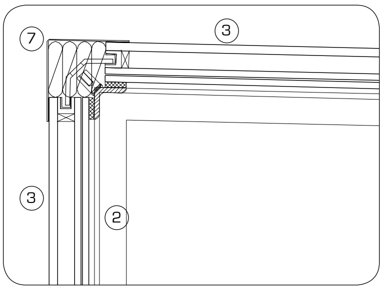
Vertical section 1:10. Junction with adjacent wall



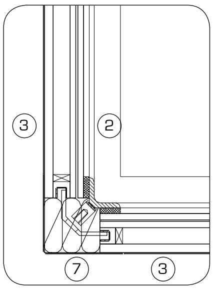
Vertical section 1:10. Bracket support



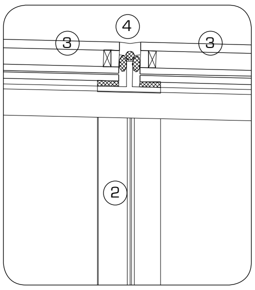
Vertical section 1:10 through bonded glass roof light showing typical details



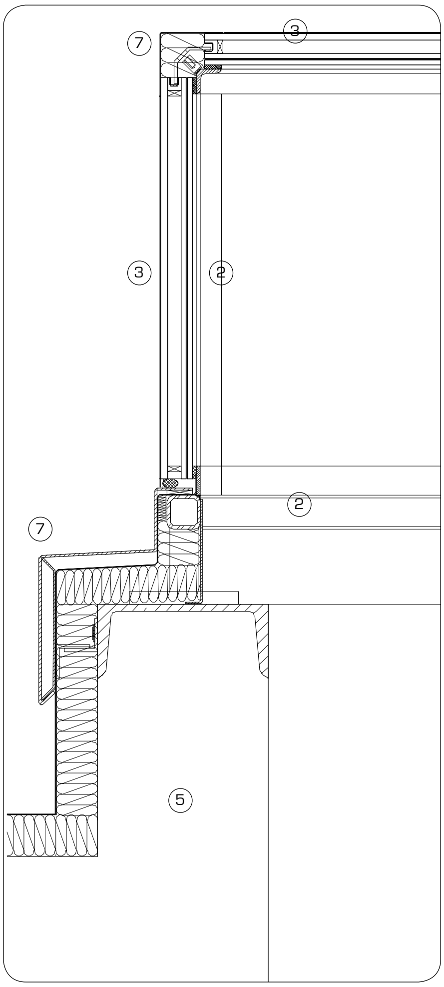
Vertical section 1:5. Typical corner detail



Horizontal section 1:5. Typical corner detail



Vertical section 1:5. Bonded glass to glass connection



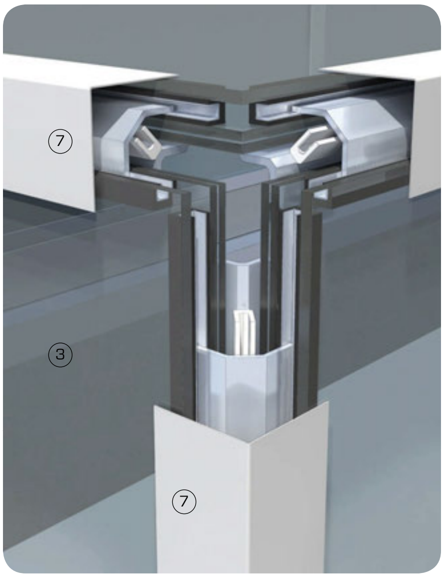
Vertical section 1:5. Typical connection to roof

receive the clip. An alternative method is to fix the metal clip to the outside of the glass at the corner. This avoids the need for specially made corner pieces but it does form a visible fixing. The modest size of this rooflight allows the horizontally-set glass to span from side to side with no additional support. The corners of the rooflight are stiffened by short lengths of pressure plate which hold the glass in place. The glass has a specially shaped groove in the depth of the double glazed unit, to which the pressure plates are fixed. Corner joints have an outer corner piece of folded aluminium which is silicone bonded either to the face of the adjacent glass units, or is folded at 90° to bond it to the side of the unit. Glass-to-glass joints between horizontally-set units have a silicone seal with an aluminium angle set on the inside face to provide a second seal.

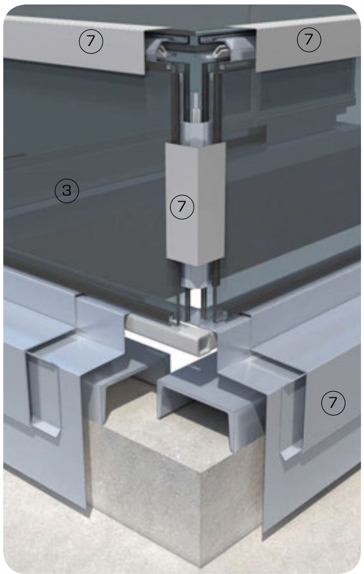
System details
Rooflights formed as nominally flat, accessible roof decks have been in use over the past 10 years. Previously used only inside buildings for walkways and stairs, they are now being used as fully waterproofed external decks, manufactured as proprietary systems. Single glazing is used, since double glazed units are difficult to use as a result of solar gain around the edge of the unit, where the glass is exposed to the outside but is supported on its underside, allowing heat to enter but not to escape. Where black coloured edge 'fritting' is used, the situation is made difficult. However, double glazed roof decking is in development and will no doubt become much more common over the next 10 years.

The glass used is laminated, in common with other rooflights, both to avoid the possibility of any falling objects from penetrating the glass on impact, as well as preventing damaged glass from falling immediately into the space below. The glass is set into a series of extruded aluminium angles to which it is bonded on its underside. A gap between the frame and the top of the glass is sealed with silicone of a different type. An additional condensation channel is set below the glass to catch any water that penetrates the silicone seal, or any water that passes through a damaged joint.

The details here show alternatives for both steel beam and glass beam supports to the glass panels. A typical rooflight is shown with glass panels 2400mm x 1200mm in size. The supporting structure has a glass beam set in the centre, spanning the full length of 6000mm. Its depth is approximately 600mm, but the beam depth will vary depending upon the individual design. Here, steel plate is used to provide a beam instead of laminated glass; a steel flat is welded to the top of the beam to form a T-section that gives enough bearing for the glass deck. The ends of the glass beams are supported by a metal shoe support, made from either mild steel or aluminium. Stainless steel is used where corrosion is an essential consideration of the design. The metal shoe is bolted back to the supporting structure or reinforced concrete floor slab. The gap between the edge of the glass deck and the adjacent roof finish material is made with a silicone seal.



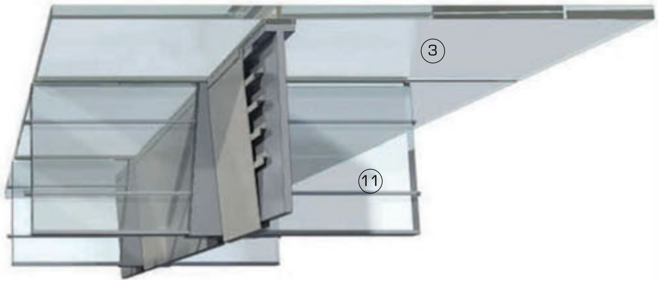
3D cutaway of typical corner detail



3D cutaway of typical rooflight assembly

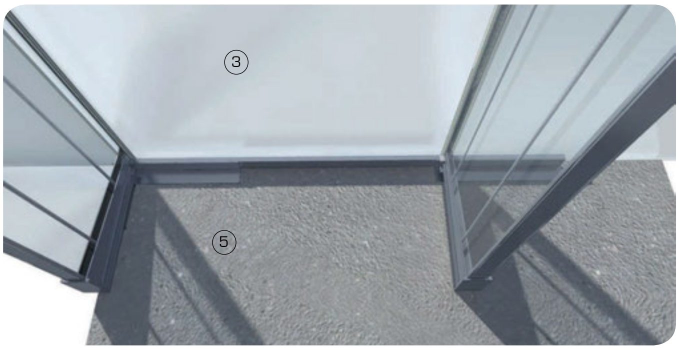
3D cutaway of typical junction with roof

3D detail of connection between glass beam and concrete wall

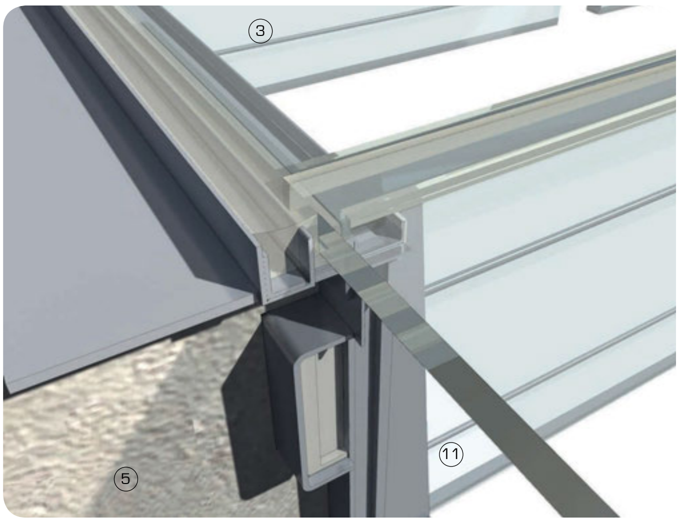


3D detail of junction between glass and steel support beams

3D detail of connection between glass beam and concrete wall



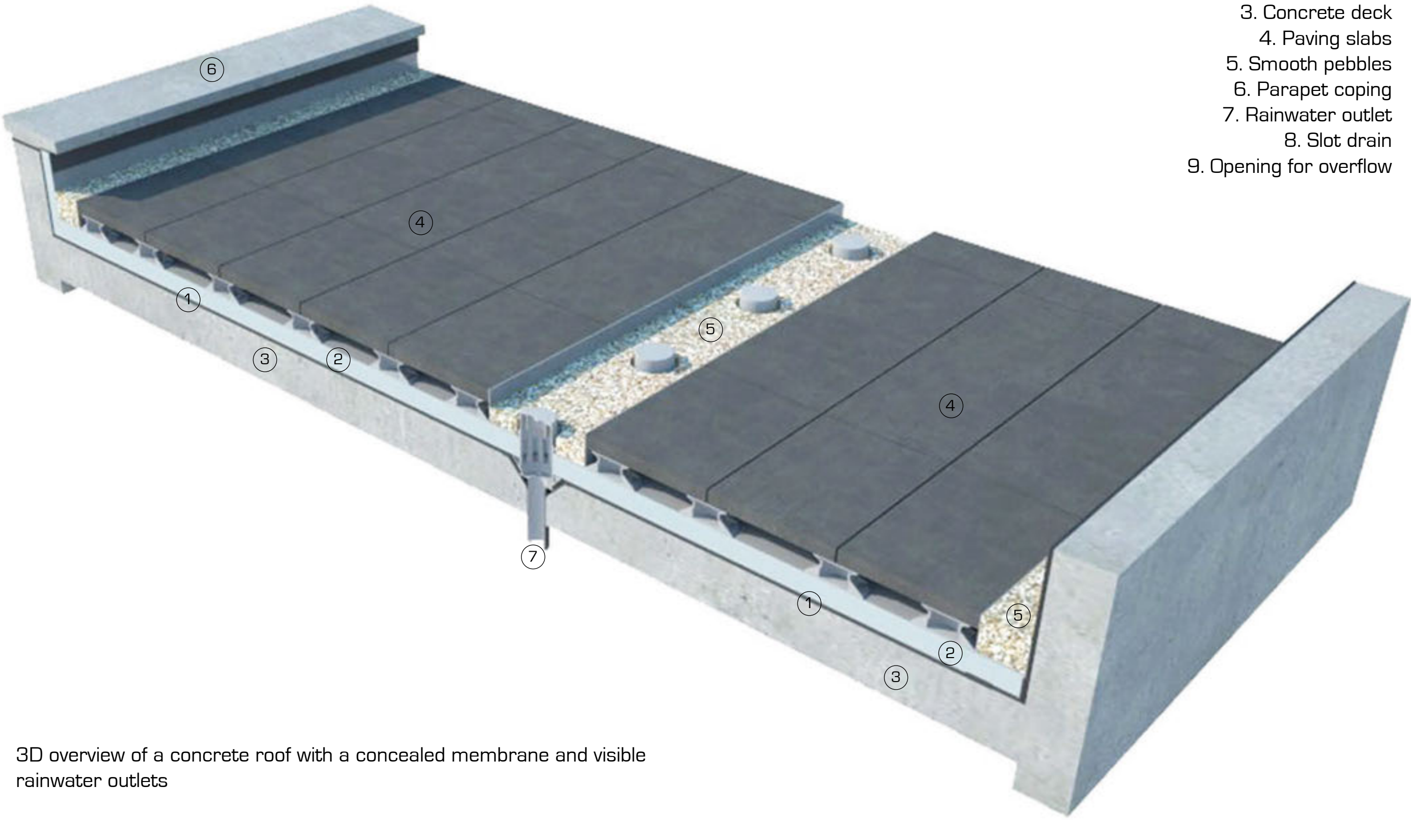
3D view looking up at interior finish at edge of glass beam and concrete base



3D view of junction at edge of glass beam and steel support

Details

1. Silicone bond
2. Mild steel support frame
3. Single glazed laminated glass panel
4. Silicone seal
5. Concrete base
6. Insulated metal panel
7. Folded metal flashing
8. Reinforced concrete support frame
9. Folded aluminium protective cover
10. Steel aluminium support shoe
11. Structural glass beam



3D overview of a concrete roof with a concealed membrane and visible rainwater outlets

System design

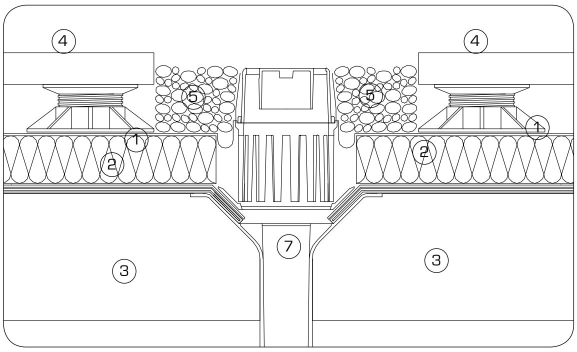
Bitumen has traditionally been used as a waterproof layer, applied while hot in liquid form onto a concrete roof slab. As it cools it hardens, forming an impervious membrane, but will soften again if heated by the effects of solar radiation. For this reason, in order to keep the material cool, bitumen membranes are concealed by smooth pebbles or paving slabs, usually with thermal insulation set between the bitumen and the pebbles or paving. Traditional bitumen roofs are usually laid in two layers, with an overall thickness of around 25mm. One of the limiting factors with bitumen is folding the material at a corner or edge. When the material turns through a right angle from the horizontal roof to a vertical parapet wall, it can pass through a maximum of 45° in a single fold. For this reason 45°angle fillets are used to make a 90° turn from roof to wall.

Modern bitumen-based membranes that are concealed beneath roof finishes are typically a combination of bitumen-based sheet mixed with synthetic rubber to give flexibility combined with a reinforcement to give dimensional stability and tensile strength. This reinforcement often allows the material to be folded through 90°, making its use considerably easier, where angle fillets are not required.

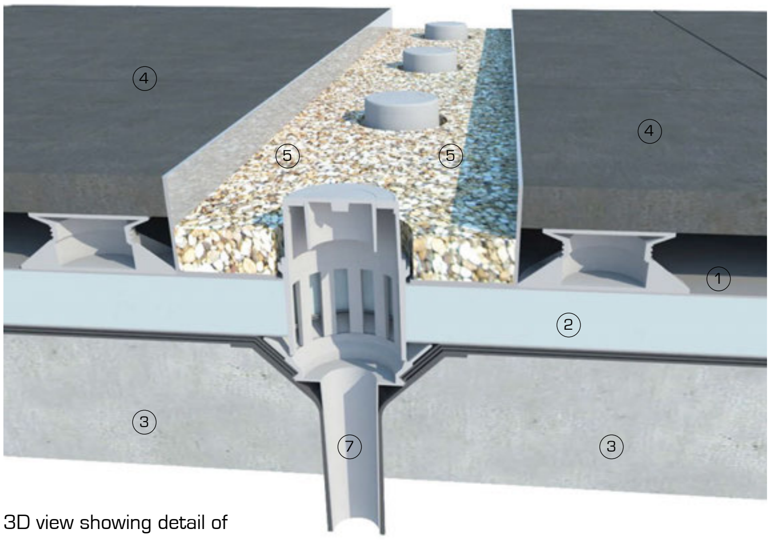
With the development of much thinner membranes in thermoplastics and elastomers, together with their competitive costs, there have been considerable efforts made by manufacturers over the past 20 years to make the bitumen layers thinner, to reduce the material required while enhancing its properties of strength and flexibility. This has been achieved by replacing the thick two-layer method with a mixture of thin layers, still applied in hot liquid form on site but reinforced with an elastomeric sheet, usually bedded between the layers. This is typically two layers, each 3mm thick with reinforcing layers bedded into the material. This allows the bitumen to accommodate both small amounts of movement at these junctions as well as the sharp fold in the material, creating a weakness in the membrane which might otherwise be damaged during the life of the building. An outer protective layer is added for vulnerable locations such as at gutters and at upstands.

System details

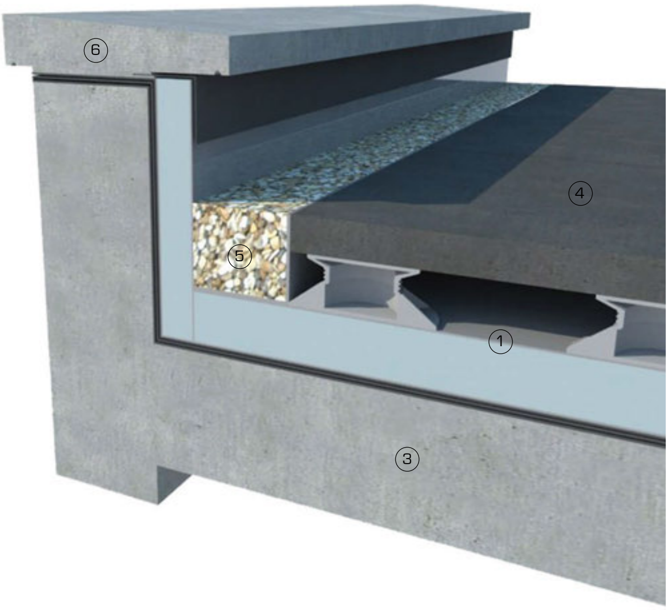
Concealed membrane roofs are typically in 'inverted' roof configuration with either open joints or sealed joints in the top layer that covers the thermal insulation, usually paving. In the open joint version the membrane, bonded to the concrete slab, is covered by a protection layer, with closed cell and rigid thermal insulation set on top. A polyester filter sheet is set on top, with paving or smooth pebble ballast on top to hold the insulation in place as well as to walk on. Pebbles are 20mm - 40mm diameter, while paving slabs are around 600 x 600mm in size and 30 mm - 40mm deep. In the sealed joint configuration, the bitumen membrane with its protection layer has a drainage layer on top, onto which is laid a minimum 65mm sand/cement screed, usually reinforced or made sufficiently

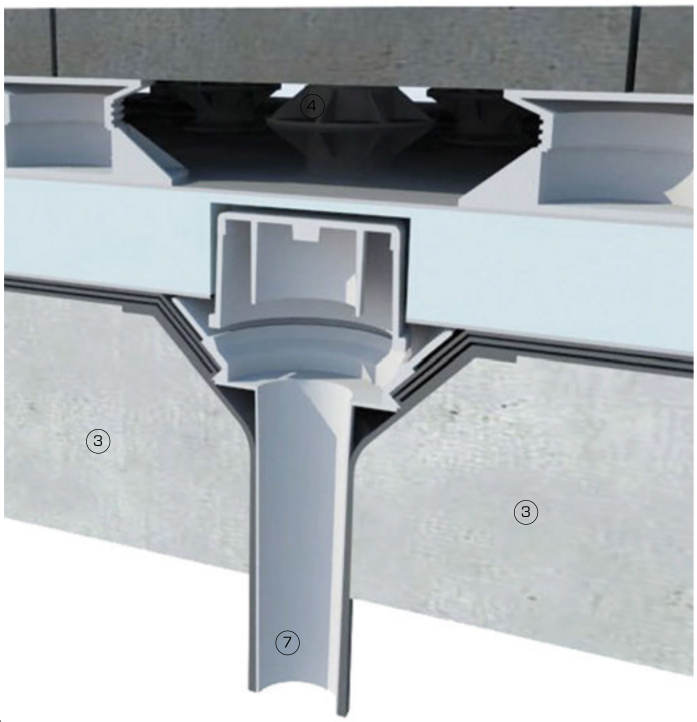


Vertical section 1:10. Rainwater outlet detail

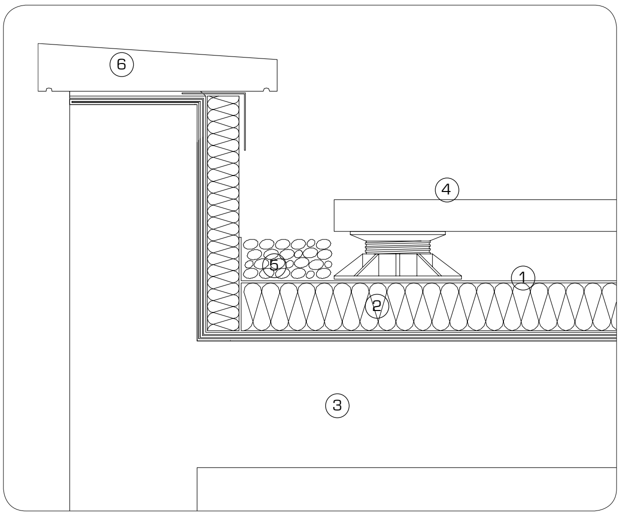


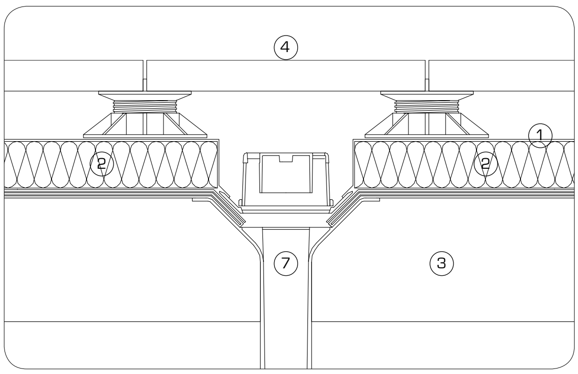
3D view showing detail of
rainwater outlet



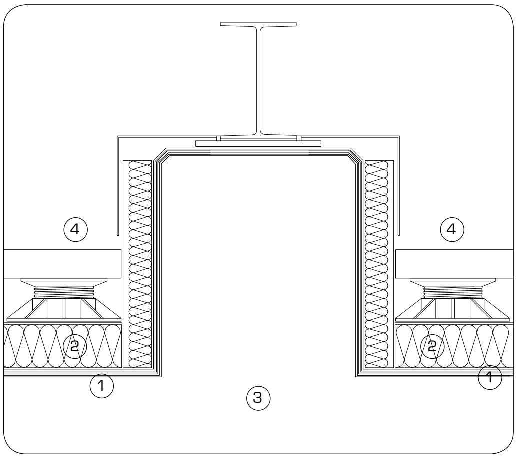


3D view showing details of parapet and rainwater outlet

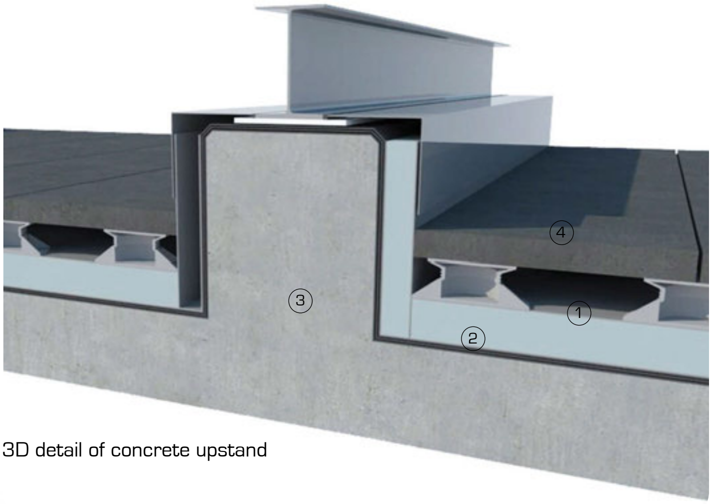




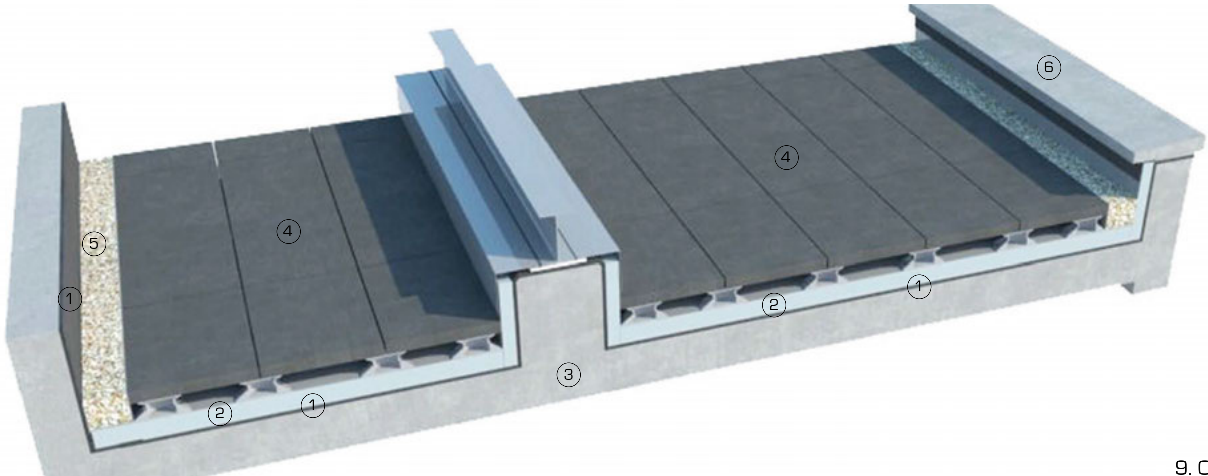
Vertical section 1:10 . Parapet and rainwater outlet details



Vertical section 1:10. Concrete upstand

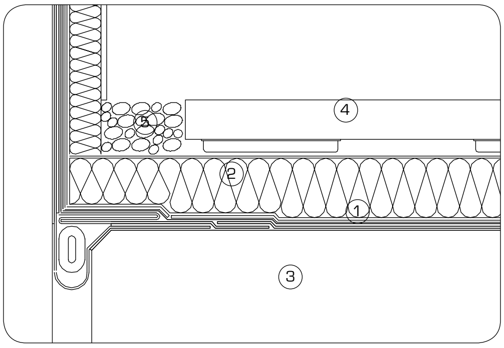


3D detail of concrete upstand

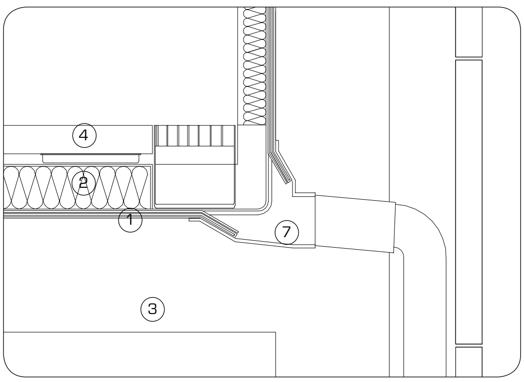


3D overview of a concrete roof with a concealed membrane and concrete upstand

Details
1. Waterproof membrane
2. Thermal insulation
3. Concrete deck
4. Paving slabs
5. Smooth pebbles
6. Parapet coping
7. Rainwater outlet
8. Slot drain
9. Opening for overflow



Vertical section 1:10. Junction of external wall and roof slab



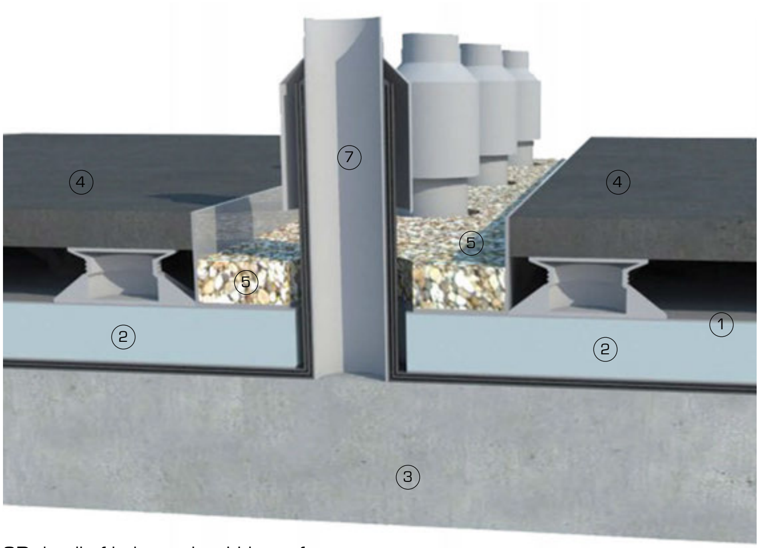
Vertical section 1:10. Two-way drain outlet

thick to avoid cracking both in the screed and the sealed paving above. Paving slabs or blocks are bonded to the screed with mortar and grouted.

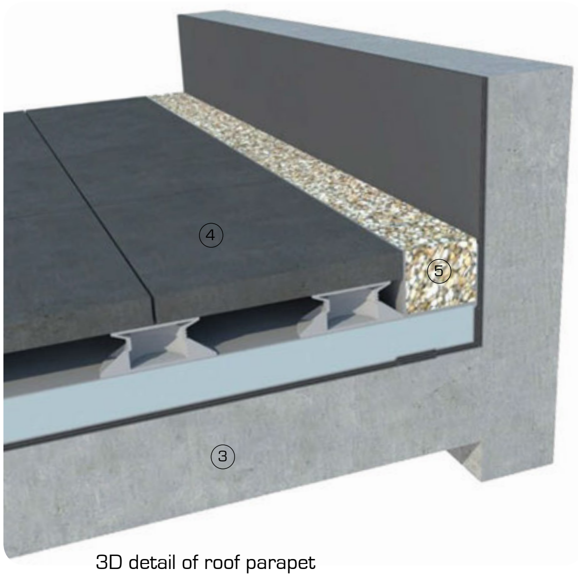
Expansion joints between concrete slabs of widths between around 10mm to 50mm are formed by stopping the material each side of the joint and setting a rubber-based strip that dips into the gap between the slabs, linking the membranes into a continuous seal. The joint is protected and reinforced with an additional layer, either flat and bonded on one side only, or formed as a folded, S-shaped cover that folds back over itself, held in place by an additional protection sheet on top. The gap between the membrane, dipped into the joint, and the reinforcement cover is filled with a foam backing rod or tube, as used in the glass joints of bolt fixed glazing. The material used for the reinforcement is either the same bitumen based material, or increasingly, a rubber-based strip.

The top of the joint is finished as level as possible with the adjacent areas of roof to allow water to drain freely from the roof. The reinforcing membrane is sometimes folded down into the gap, separated from the membrane below with a foam backing rod. It can be difficult to drain water from this groove at the edge of the slab unless water at this lower level can discharge into a rainwater outlet.

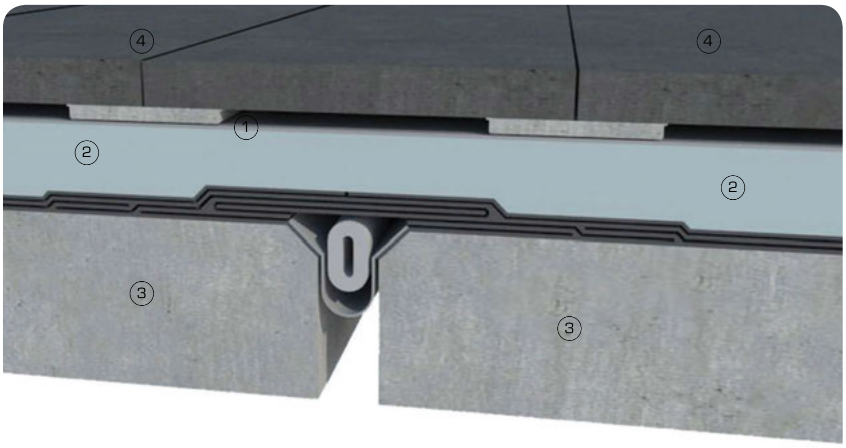
In forming parapet upstands, an essential requirement is to keep the waterproof membrane as well protected from the



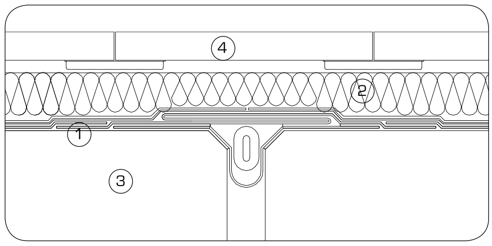
3D detail of balustrade within roof system



3D detail of roof parapet



3D detail of expansion joint in concrete slab

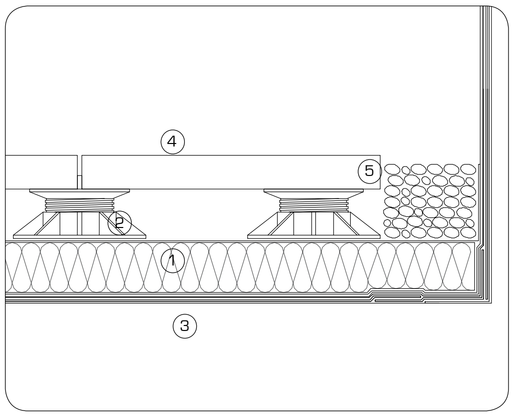


Vertical section 1:10. Expansion joint in concrete slab

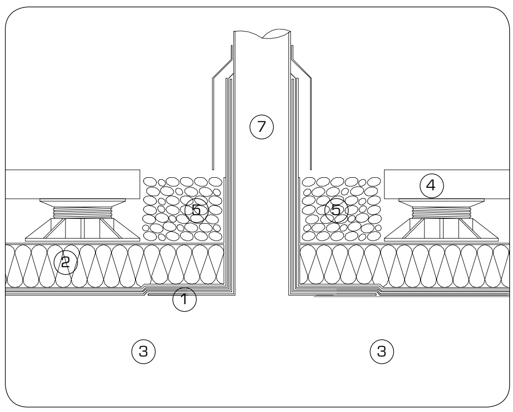
effects of the sun as elsewhere on the roof. For this reason, thermal insulation is applied to the inside face of the parapet, even if this has no direct benefit to the passage of heat through the building. The membrane is turned through a full 90° as shown in the drawings, but an angle fillet is required by some manufacturers to limit the angle of any fold to 45°. A reinforcing strip is usually added where a 90° fold is made.

Plinths which are formed as short columns for the support of roof-mounted mechanical equipment or balustrades are waterproofed in a similar way to a parapet upstand. The membrane is folded up through 90° from the roof level and is formed to cover the complete plinth. The thermal insulation extends across the complete plinth to prevent a thermal bridge through the roof construction.

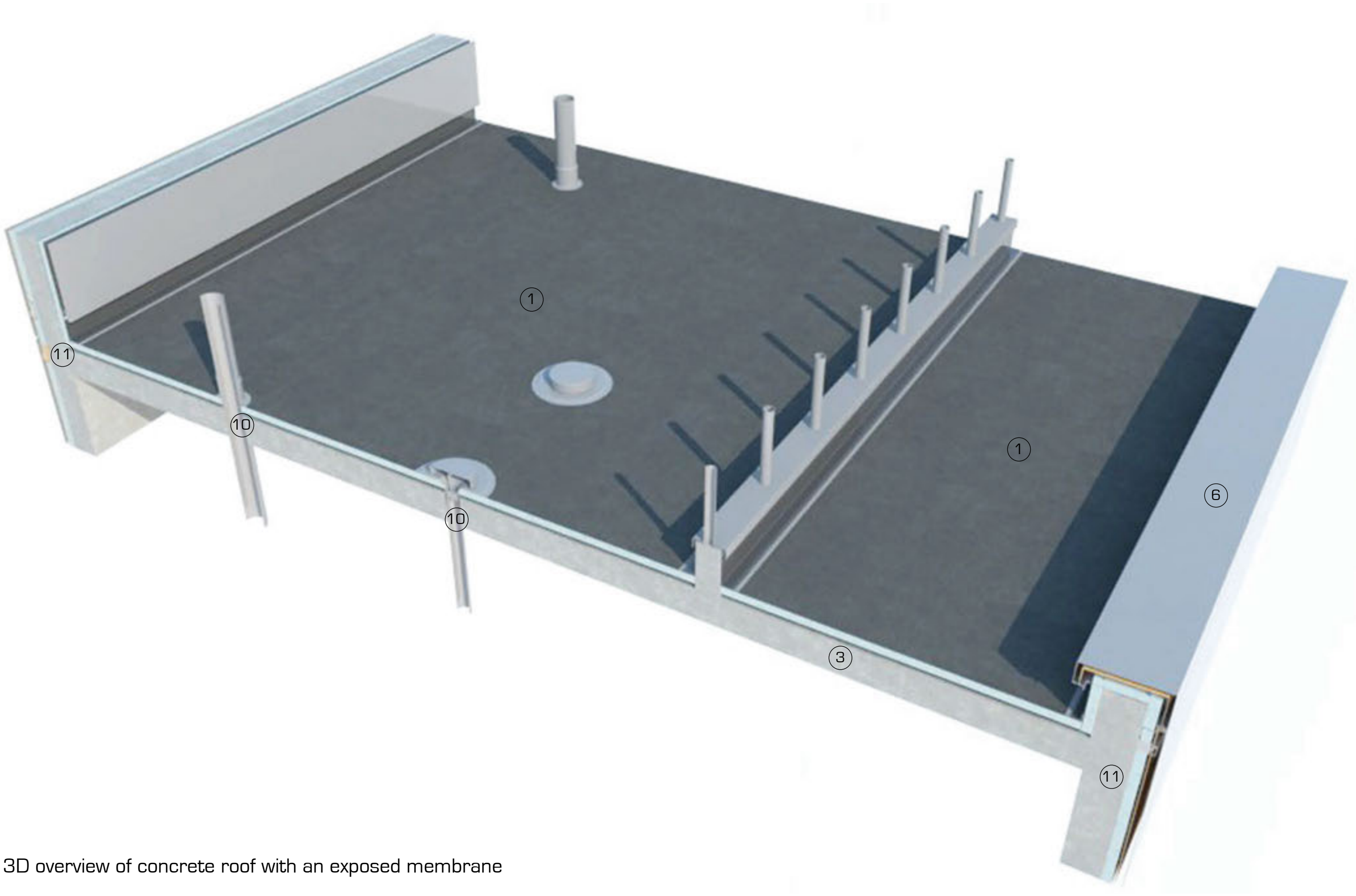
Rainwater outlets are set at the level of the waterproof membrane, drained at both the level of the sealed paving and the level of the waterproofing layer. The base of the rainwater outlet is fixed to the concrete slab. The waterproof membrane is dressed down into the top of the rainwater outlet and the upper part of the rainwater outlet is bolted down onto the part already fixed and sealed. The geotextile sheet is wrapped around the outlet to avoid dirt and debris being washed into the rainwater drainage system.



Vertical section 1:10. Parapet detail



Vertical section 1:10. Base of balustrade



3D overview of concrete roof with an exposed membrane

System design

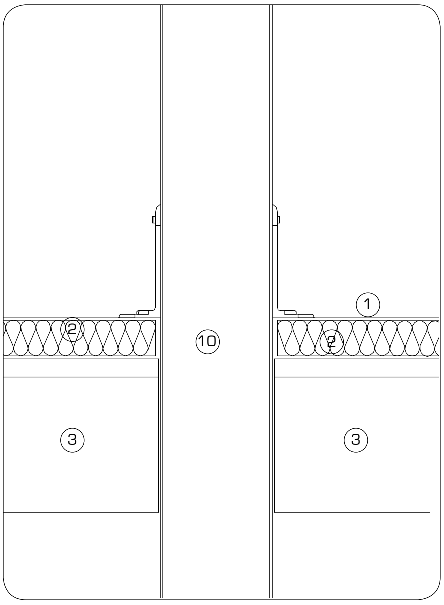
Exposed membranes have been used for flat roofs which are not visible from below, but this has changed in recent years as membranes are produced in increasingly smooth and regular finishes. Because of their lightweight nature, they are often used in conjunction with lightweight roofs such as profiled metal deck and timber. This section considers their use in concrete construction, though the same principles of waterproofing can be applied to these other materials.

The introduction of polymer-based membranes provided economic waterproofing materials that are more flexible than their bitumen-based predecessors. The increased flexibility of the new sheet materials allowed for greater amounts of movement between adjoining components and assemblies, allowing the detailing of junctions to be relatively straightforward in forming a reliable weathertight roof membrane. As a result of these developments, polymer modifications were also made in the earlier generation bitumen-based materials to make them more flexible, in order to compete with the polymer-based sheet materials. As a result there is now a wide range of exposed membrane materials available to suit different budgets and individual roof designs.

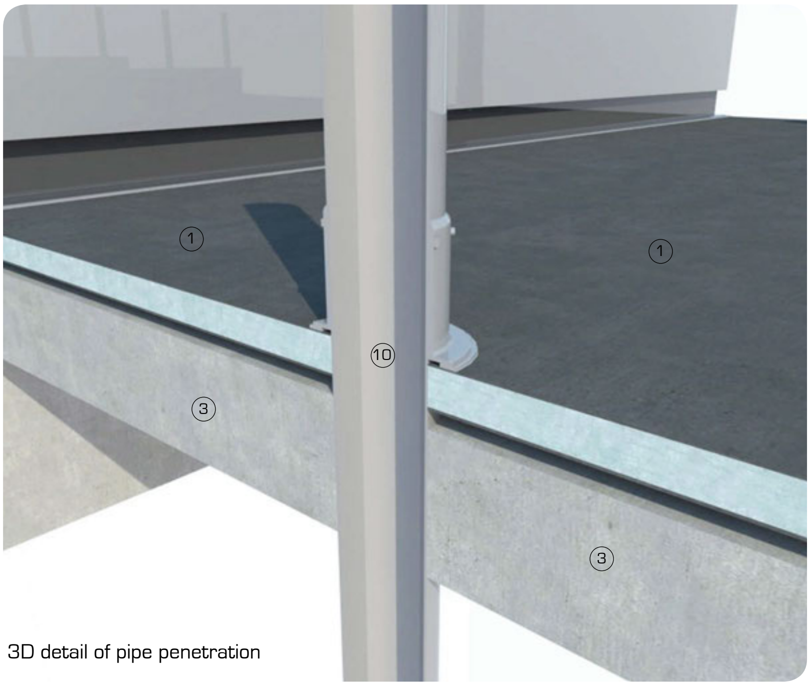
Polymer-based membranes have the main advantage of an ability to be cut and formed to complex shapes, allowing them to take up shapes precisely, sometimes pre-formed in the factory before being delivered to site. Single layer membranes are very practical on roofs with a large number of penetrations, typically in commercial buildings where mechanical ventilation equipment is regularly being modified or replaced during the lifetime of a building. Single layer membranes are made from either elastomeric materials, typically EPDM, or from thermoplastic materials, typically plasticised PVC (PVC-P). Elastomeric materials are very popular in the US while thermoplastics are preferred in Europe. EPDM (ethylene propylene diene monomer) is a flexible and elastic material that has the appearance of a synthetic rubber. EPDM is manufactured in the limited colours of black, grey and white.

Both elastomers and thermoplastics can be mechanically fixed, bonded or secured with ballast to the concrete deck beneath. Developments in these materials have led to them being used on timber decks and profiled metal decks in addition to the concrete decks discussed here. Both thermoplastic and EPDM membranes can be welded together to form a continuous waterproof sheet. While both material types were glued, there is an increasing use of hot air welding methods, which avoid the need for flame techniques or adhesive bonding methods that can be both slow and can damage adjacent work during their application. In hot air welding, a jet of heated air is used to soften the materials and weld them together, applied from a range of tools that are either hand held or fully automated, depending on the application.

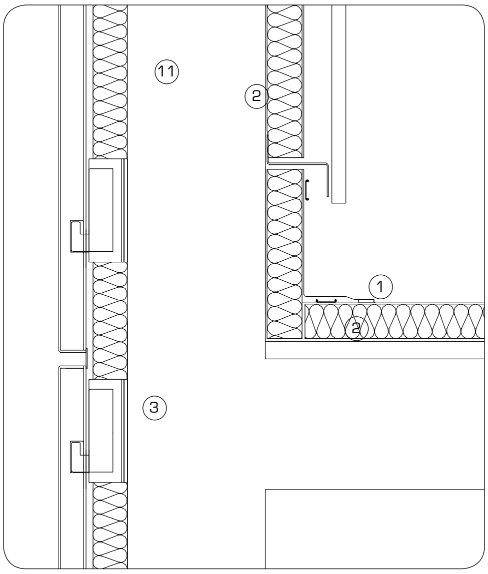
Membranes are reinforced with glass fibre sheet or polyester fabric. These layers are bonded into the material. The glass fibre provides dimensional stability, making it more stable for bonding to the substrate. The woven polyester fabric, used in tent membrane structures, has high tensile strength to resist wind loads.



Vertical section 1:10. Pipe penetration

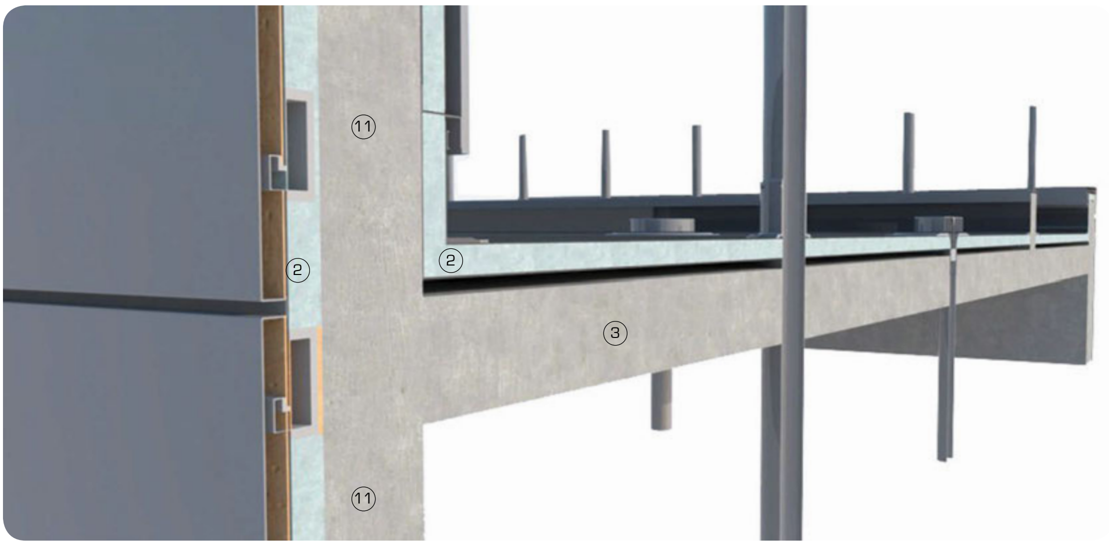


3D detail of pipe penetration



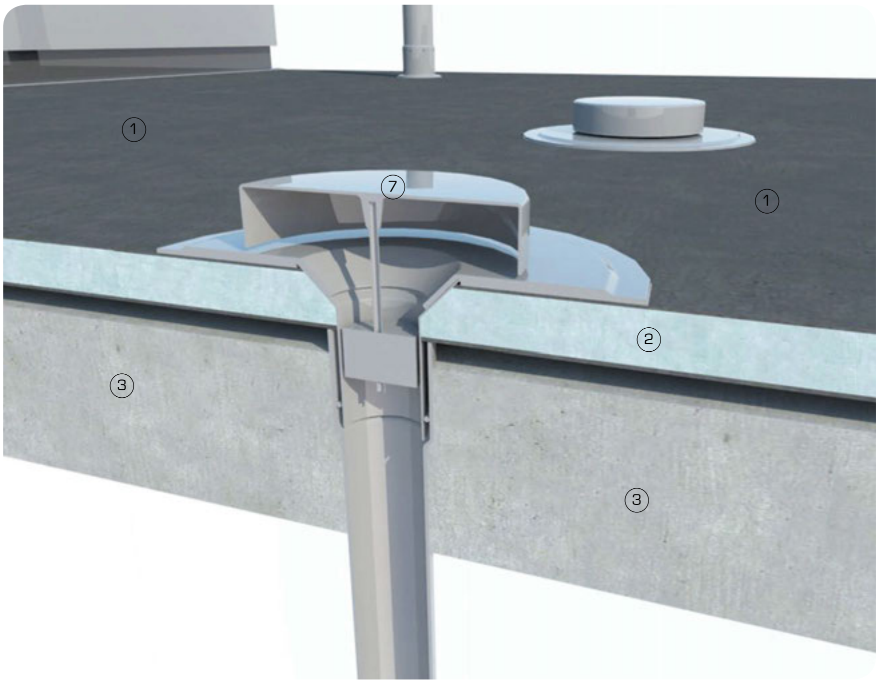
Vertical section 1:10 Junction of external wall and roof slab

3D detail of junction between roof slab and external wall.

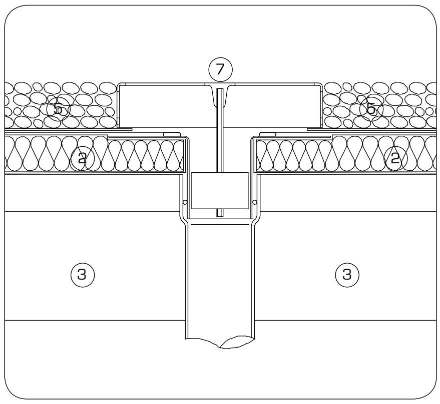


Details
1. Waterproof membrane
2. Thermal Insulation
3. Concrete deck
4. Paving slabs
5. Smooth pebbles
6. Parapet coping
7. Rainwater outlet
8. Opening for overflow
9. Balustrade
10. Pipe or duct
11. External wall
12. Rooflight

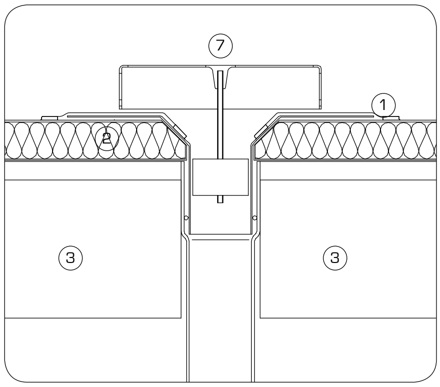
3D detail of junction between roof slab and external wall.



3D detail of rainwater outlet within exposed membrane roof



Vertical section 1:10. Rainwater outlet (balusted method)



Vertical section 1:10. Rainwater outlet (bonded method

A typical build-up for a single layer membrane is a concrete deck with a vapour barrier set on top, with thermal insulation above that, sealed on top with a single layer membrane. PVC-P membranes are typically 1.5mm - 3.0mm thick, while EPDM membranes are typically 1.0mm - 1.5mm thick.

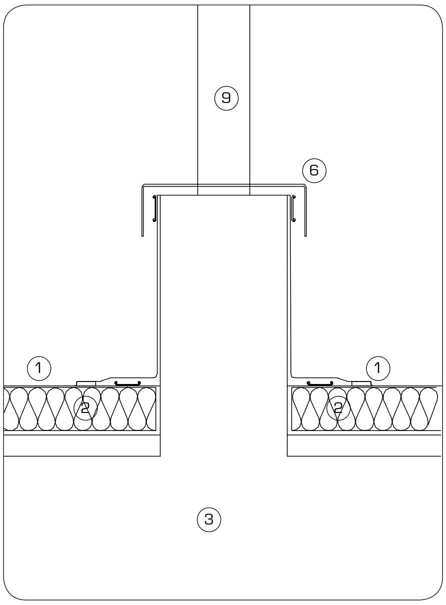
The mechanically fixed method is suited to applications with high wind uplift forces, as bonded systems tend to be limited by the bonding strength of the vapour barrier to which the membrane is itself bonded through the thermal insulation layer, which is typically made from expanded polystyrene board. The vapour barrier is loose laid on the concrete deck and thermal insulation is then mechanically fixed through this barrier to the deck beneath. The spacing of the fasteners varies with the design wind loads. A separating layer of glass fibre sheet is usually laid onto the insulation with an outer single layer membrane. The membrane is mechanically fixed with pressure plate bars, similar to those used in glazed curtain walling systems to hold the glass in place. Bars form strips of pressure plate to hold the roof build-up in place. The pressure plates are fixed by bolts at centres along their length to the substrate below.

System details
Membranes can also be secured by point fixings rather than by pressure plates. 50 - 75mm diameter rigid plastic discs are used to hold the build-up in place. These are set at centres to suit the design wind loads. The closed cell rigid insulation is typically made in panel sizes of 1200mm x 2400mm in thicknesses from 25mm to 100mm.

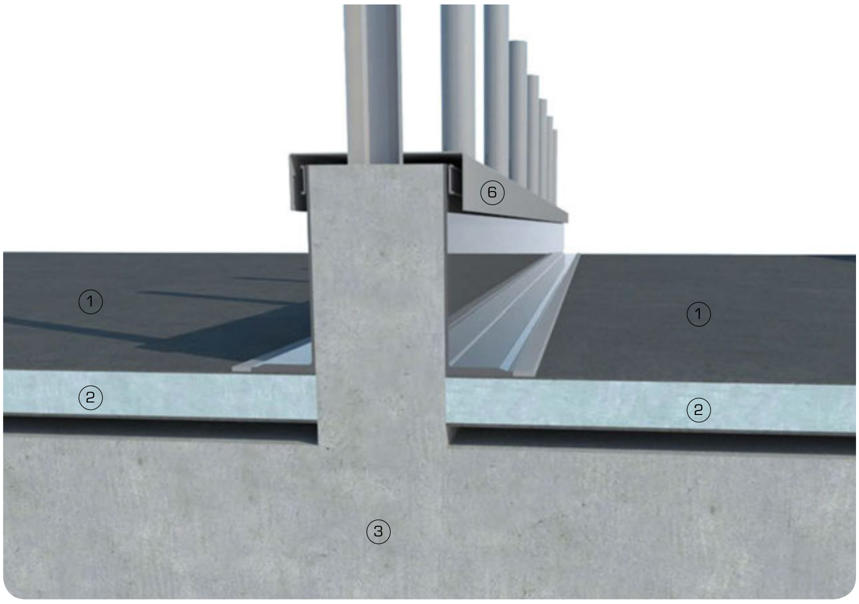
In the bonded fixing method the exposed membrane of the vapour barrier is usually bitumen-based and is bonded to the deck. Joints between the vapour barrier sheets are lapped to avoid any risk of vapour passing through the roof structure from inside the building. The thermal insulation is then bonded to the vapour barrier. Insulation can also be mechanically fixed with pressure plates to the concrete deck beneath. The membrane is then bonded to the insulation with a continuous layer of bonding adhesive on its underside. Some systems still bond the membrane at points only rather than across the entire surface of the membrane, but this is dependent upon the wind load and the proprietary system used.

Bonded membranes have a visually smooth appearance, making them suitable where the roof surface is seen from points around the building. This fixing method still requires mechanical fixing at the edges, and around openings such as rooflights.

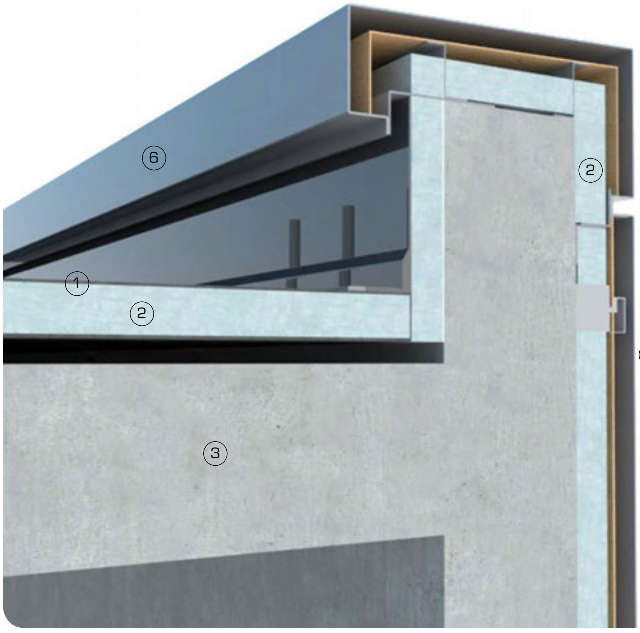
Membranes can be bonded or mechanically fixed to parapet upstands. The fixing method that is used on the main area of roof is usually continued on these vertical areas. With mechanical fixing the pressure plate can be fixed either to the upstand or to the flat roof area. The pressure plate forms a junction between the membrane sheet forming the upstand and the membrane sheet of the roof. Intermediate pressure plates are applied horizontally on the upstand when its height exceeds around 500mm, depending on the specific material used.



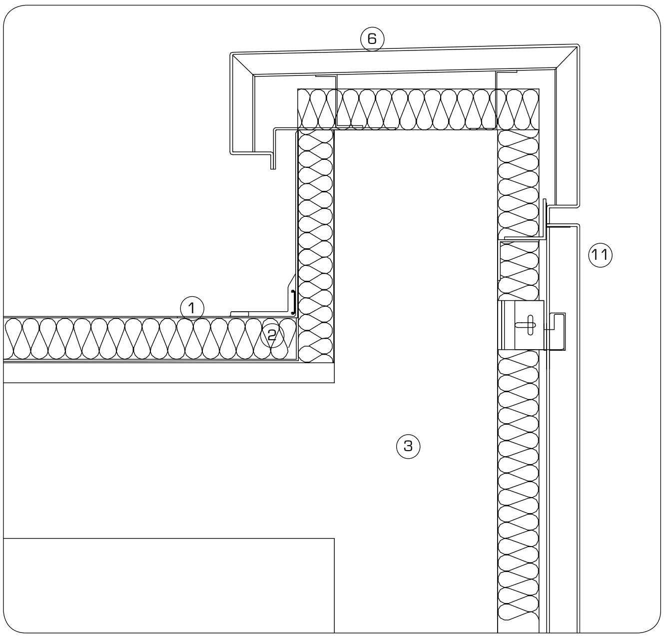
Vertical section 1:10. Upstand for balustrade



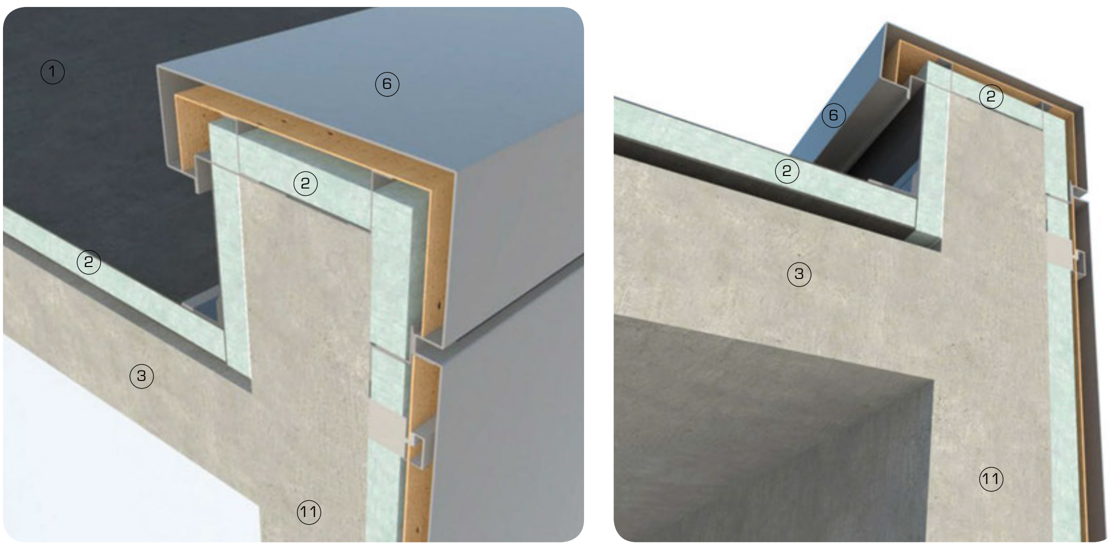
3D detail of upstand



3D detail of low parapet

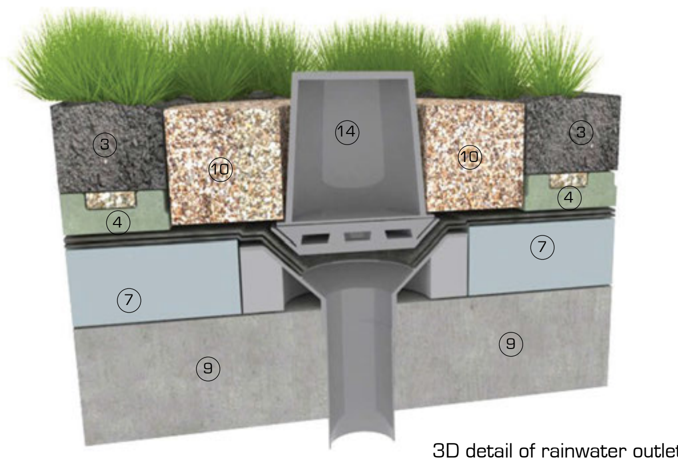


Vertical section 1:10. Low parapet

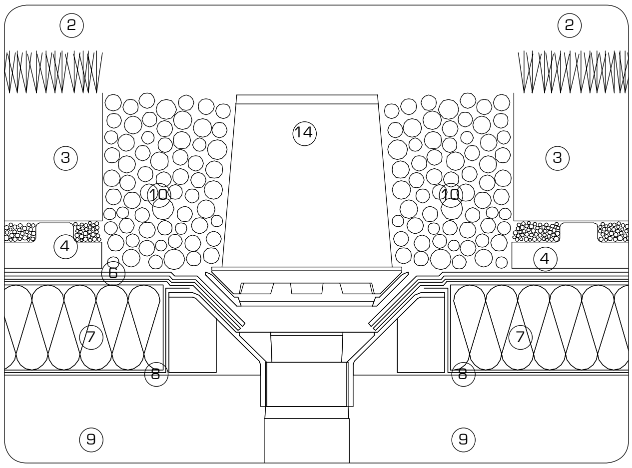


Details
1. Waterproof membrane
2. Thermal Insulation
3. Concrete deck
4. Paving slabs
5. Smooth pebbles
6. Parapet coping
7. Rainwater outlet
8. Opening for overflow
9. Balustrade
10. Pipe or duct
11. External wall
12. Rooflight

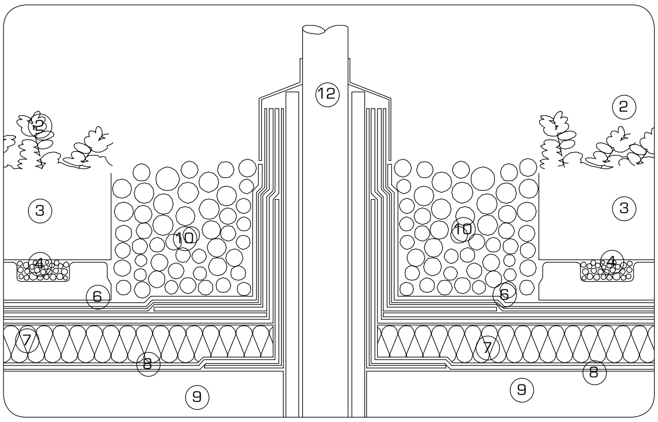
3D details of low parapet



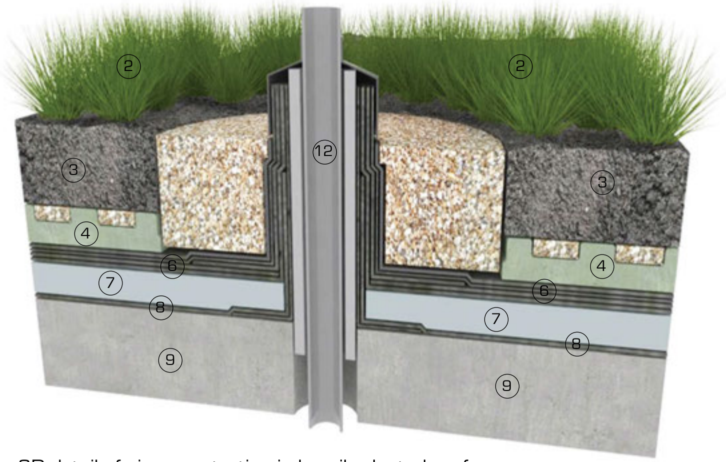
3D detail of rainwater outlet in heavily planted roof



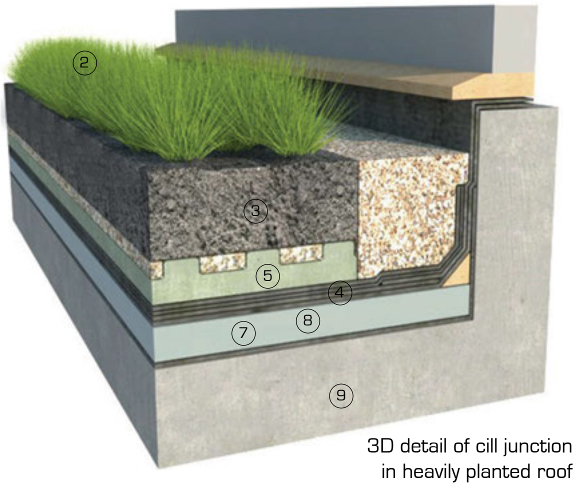
Vertical section 1:10. Heavily planted roof rainwater outlet detail



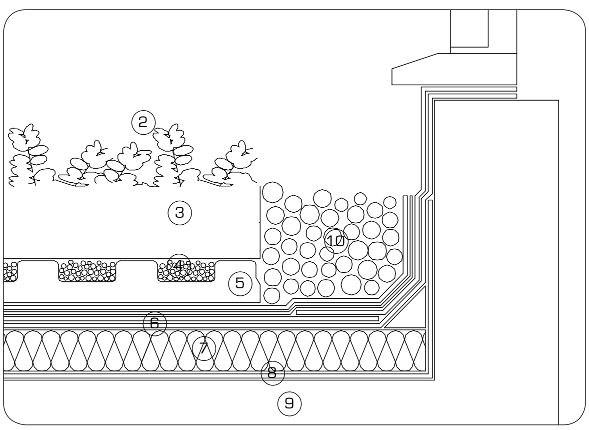
Vertical section 1:10. Heavy planting. Pipe penetration.



3D detail of pipe penetration in heavily planted roof



3D detail of cill junction in heavily planted roof



Vertical section 1:10. Heavy planting. Cill junction.

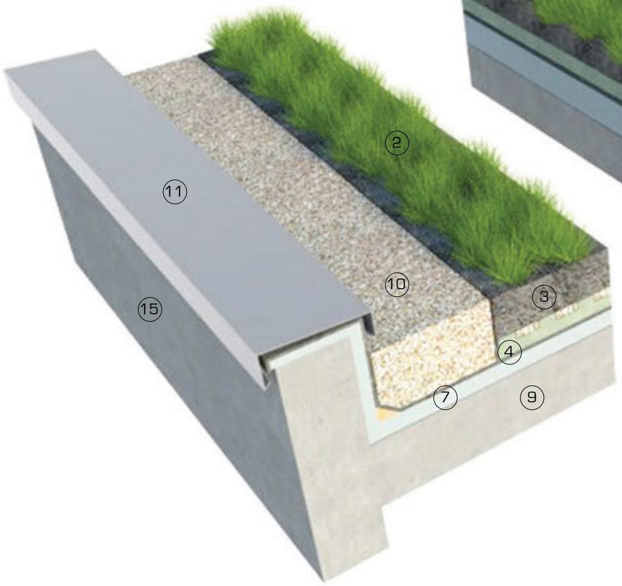
System design

Concrete decks used for planted areas can be waterproofed with either a concealed membrane or an exposed membrane as discussed in the previous sections. Planted roofs are of two types: light planted and heavy planted. Unlike other concrete roof types, planted roofs are not always insulated as they often form the roof of underground structures such as car parks, providing a planted roof at ground level.

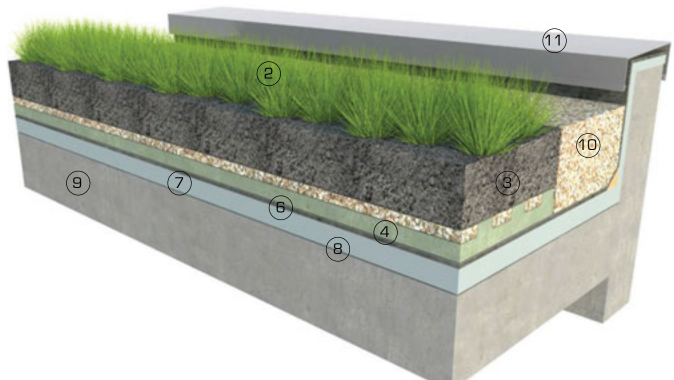
Light planted roofs have resilient plants that require little or no irrigation, and that will grow in a thin layer of soil or organic growing medium. They are not usually used on a roof accessible to building users, but are seen from vantage points around the building. Light planted roofs have plants and flowers that require little maintenance and do not usually have an irrigation system to supply water at controlled times, relying on rainwater and modest amounts of watering during maintenance at specific times of the year. These lightweight planted roofs suit a lightweight deck, such as a thin concrete shell, although profiled metal decks are commonly used as substrates. Maintenance access is provided by the pebble strips at the roof edges or by individual paving slabs that avoid the need to walk across the planting.

Heavy planted roofs permit a wide variety of plants, shrubs and trees to grow on a concrete roof deck. Due to the size and intensity of the planting they require an automated irrigation system, usually from pipes set into the soil that provide a trickle

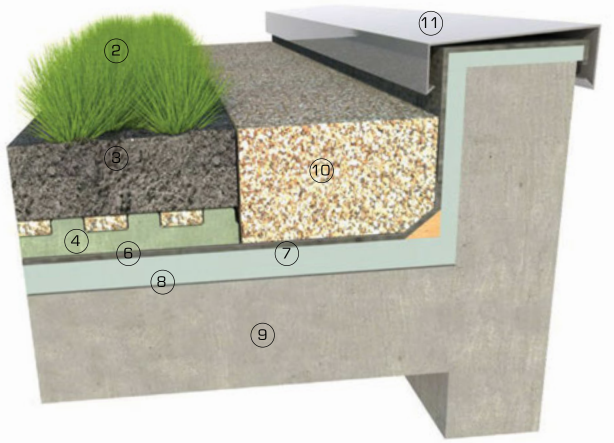
3D overview of concrete roof with heavy planting



Details
1. Light vegetation
2. Heavy vegetation
3. Soil/growing medium
4. Filter sheet
5. Drainage layer
6. Waterproofing layer
7. Thermal insulation
8. Vapour barrier
9. Concrete deck
10. Smooth gravel
11. Coping
12. Pipe/ duct
13. Supply pipe
14. Rainwater outlet
15. Wall cladding



3D views showing low parapet condition on heavily planted concrete roof

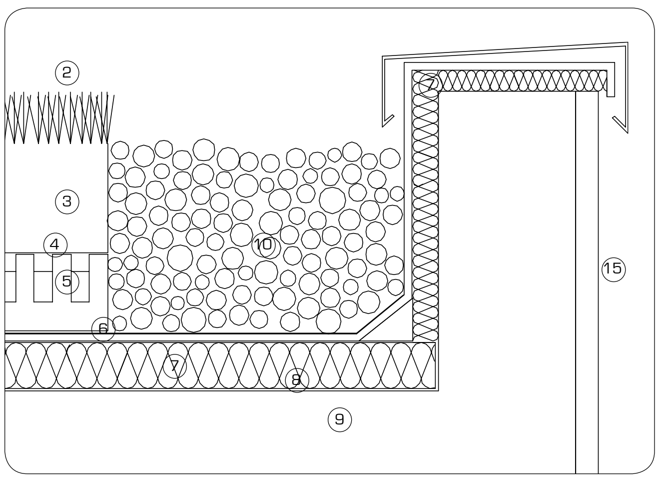


of water fed to the soil at specific times which may vary during the course of the year. Heavy planted roofs require regular maintenance, provided by paved paths or by areas of grass.

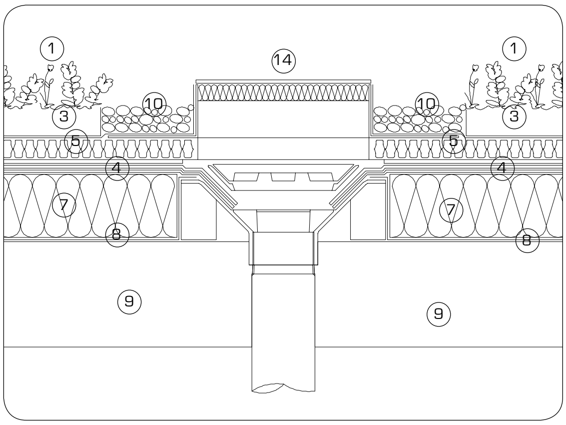
Both light planted and heavy planted roofs have drainage layers beneath the growing medium that hold water and release it back to the plants when required. This allows the soil depth to be much less than that which would be required for older landscaping methods, where the soil was expected to hold all the water. The reduced depth of soil allows planting to be considered for concrete roof structures that would require no significant strengthening to receive the added weight of soil. In terms of drainage it is estimated by manufacturers of proprietary systems that 50% to 90% of rainfall is retained in planted roofs, but this varies considerably with local climate conditions and rainwater drainage provision.

System details

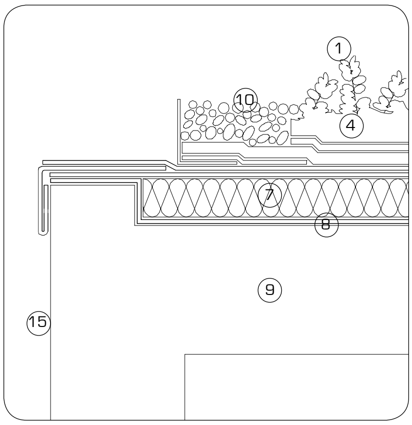
Both light planted and heavy planted roofs have a similar build-up, comprising typically a top layer of planting, with a growing medium or soil beneath. A filter layer is set underneath, and below this, a drainage layer and moisture mat. Beneath this lowest layer is set thermal insulation if required. Although planted roofs provide a limited amount of thermal insulation from the soil, in practice this is reduced due to the varying amounts of water held within the soil. A root barrier is set beneath the insulation to protect the waterproof membrane, that is the bottom layer, bonded to the concrete roof deck.



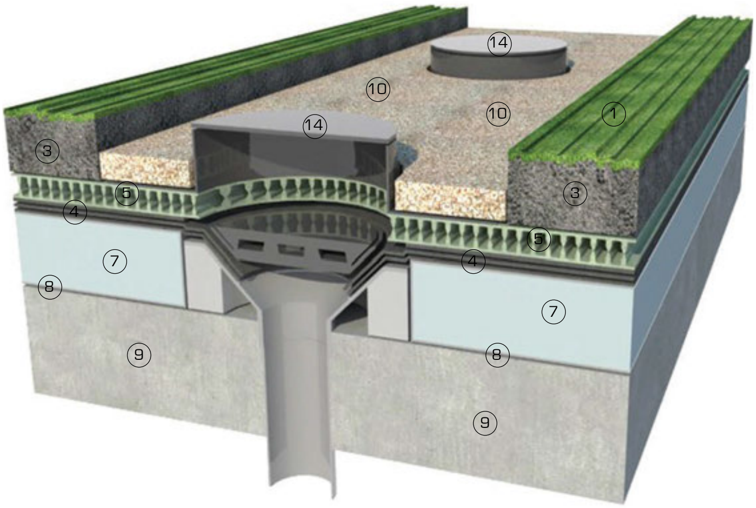
Vertical section 1:10. Heavy planting. Low parapet.



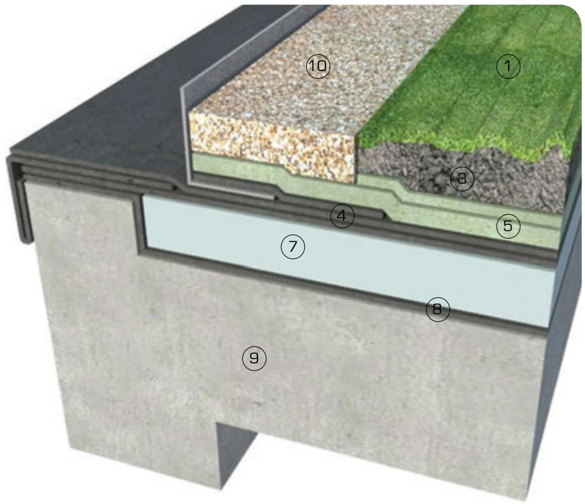
Vertical section 1:10. Light planting. Rainwater outlet



Vertical section 1:10. Light planting. Low parapet junction



3D detail of rainwater outlet in lightly planted roof



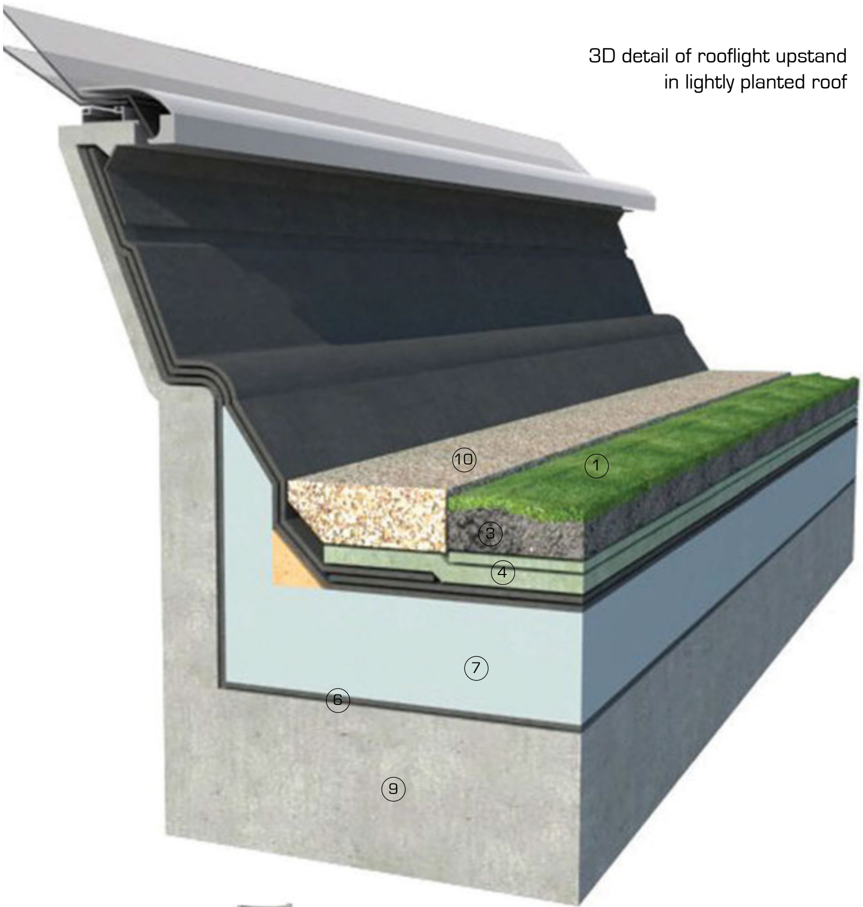
3D detail of low parapet in lightly planted roof

The root barrier is sometimes bonded to the waterproofing layer, usually when the complete build-up is a single proprietary system. To prevent the passage of organic matter and fine particles into the water drainage system, a filter sheet is set underneath the planting. This sheet is lapped up the sides of the planting where it meets an upstand, to the level of the planting.

The drainage layer beneath the filter sheet retains water that drains through the planting. Water is retained in profiled troughs in a typically polystyrene egg-crate shaped tray that releases water back to the planting. This method also performs satisfactorily on sloping concrete roofs. Excess water is drained away through gaps between the drainage trays. The egg-crate form allows aeration, permitting the soil to absorb the water stored here. In drier months, water diffuses up through the soil to the plant roots. A moisture mat is often set under this layer to catch water that runs off the drainage layer. The mat is made from a durable fibre that retains moisture and nutrients as well as serving as protection to the root barrier beneath. It is not used in inverted roof configurations. In inverted roofs, a root barrier is set immediately below the insulation to protect the waterproof membrane forming the lowest layer. This layer prevents planting roots from damaging the waterproofing. In warm roof construction, the waterproof membrane is set on top of the thermal insulation, positioning the insulation within the building envelope. A vapour barrier is set between the thermal insulation and the concrete deck. In this configuration a moisture mat is set between the waterproof membrane and the drainage layer above.

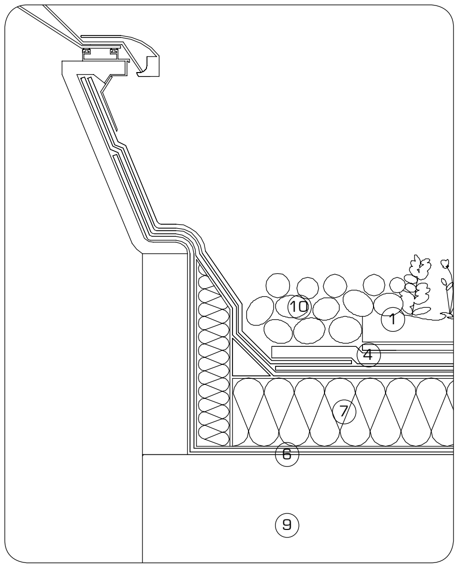
The soil depth in light planted roofs ranges from 50mm to around 150mm. Water is stored in the growing medium and drainage layer, making it efficient in mild, temperate climates. Light planted roofs can be grown on both nominally flat roofs and on sloping roofs with a pitch of up to 25° to 30°. Heavy planted roofs have a deeper drainage layer to provide greater water storage. The soil depth, in excess of 150mm, requires an automatic irrigation system to provide a reliable water supply coverage of the complete roof.

At upstands and eaves the same principles apply to planted roofs, as discussed in the previous sections. The waterproofing extends a minimum of 150mm above the level of the planting, providing a continuity from the roof membrane to the flashing at the top of the upstand or to the adjacent wall construction. Upstands for parapets and door sills, high walls and rooflights are formed by extending the waterproof filter sheet and root barrier up to a minimum of 150mm above the level of the soil or growing medium. The visible membranes and sheets are concealed with thermal insulation and typically either paving turned on edge, as per the paving used for adjacent access paving, or a metal sheet to match that of the parapet coping where a metal coping is used.



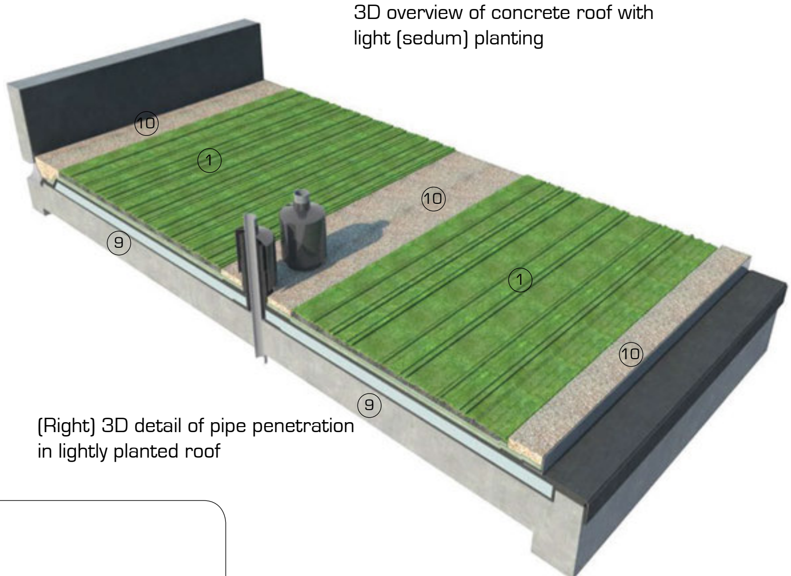
3D detail of rooflight upstand
in lightly planted roof

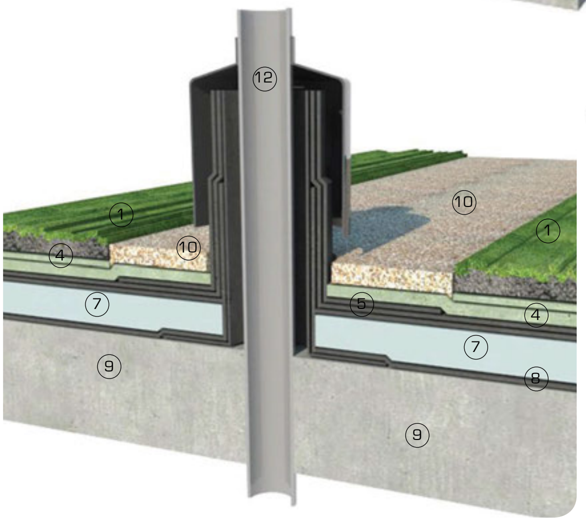
Details
1. Light vegetation
2. Heavy vegetation
3. Soil/growing medium
4. Filter sheet
5. Drainage layer
6. Waterproofing layer
7. Thermal insulation
8. Vapour barrier
9. Concrete deck
10. Smooth gravel
11. Coping
12. Pipe/ duct
13. Supply pipe
14. Rainwater outlet
15. Wall cladding



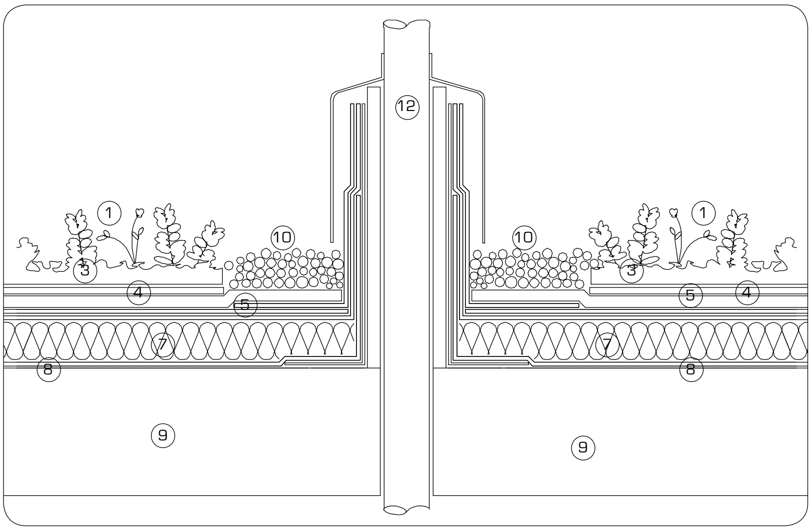
Vertical section 1:10. Light planting. Rooflight upstand

3D overview of concrete roof with light (sedum) planting

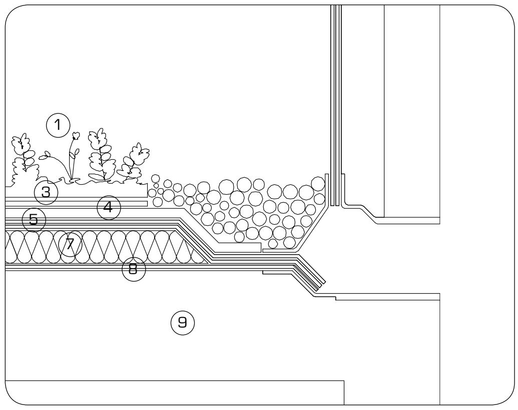




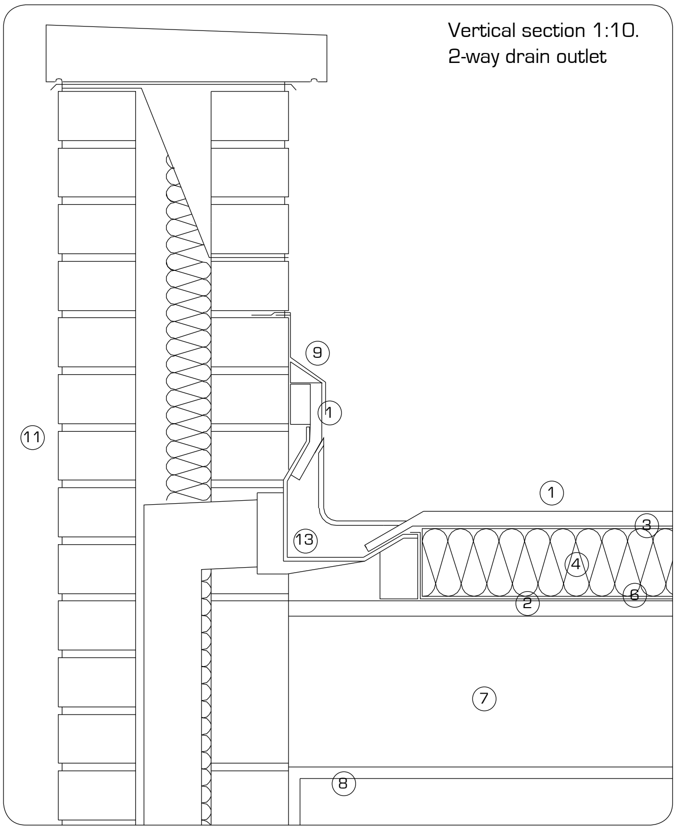
(Right) 3D detail of pipe penetration in lightly planted roof



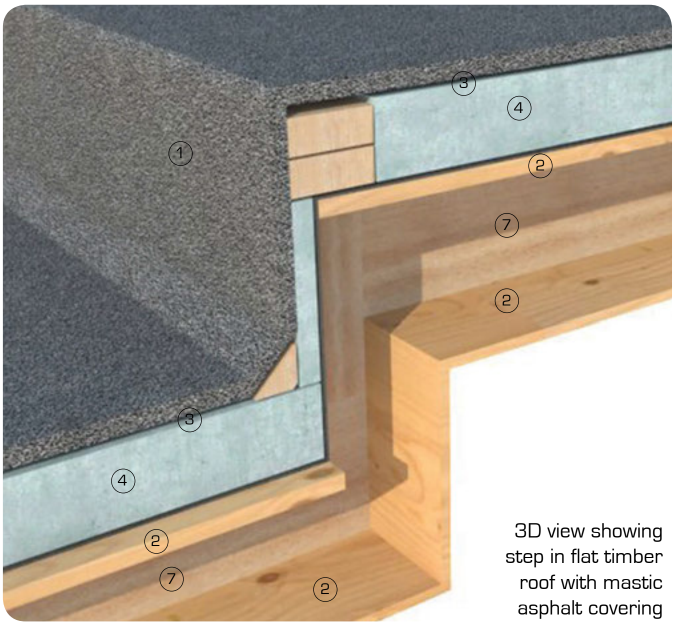
Vertical section 1:10. Light planting. Pipe penetration.



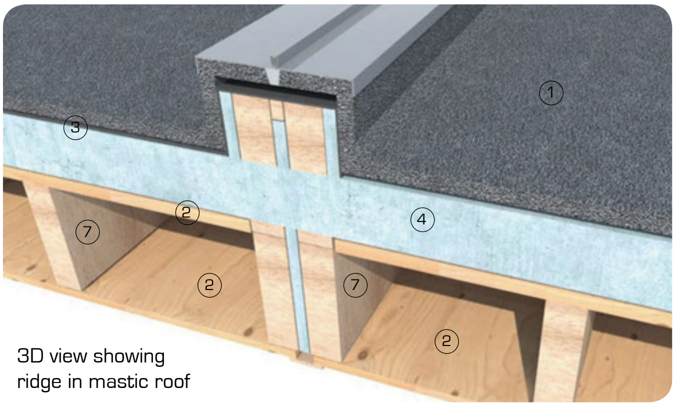
Vertical section 1:10. Light planting. two-way outlet



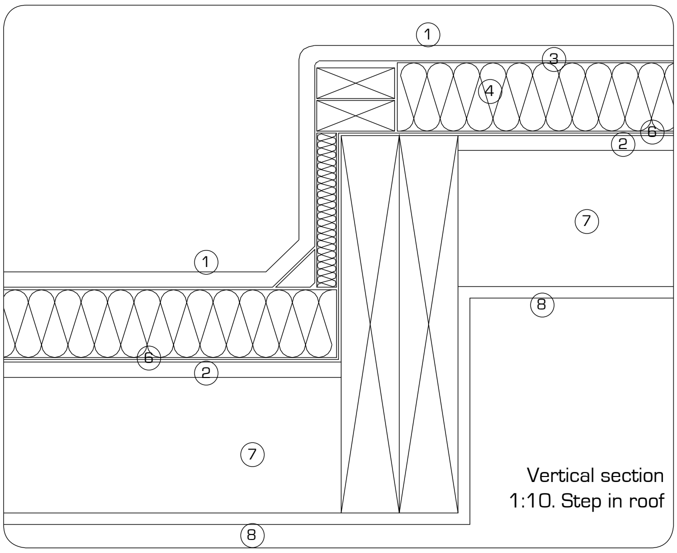
Vertical section 1:10. 2-way drain outlet



3D view showing step in flat timber roof with mastic asphalt covering



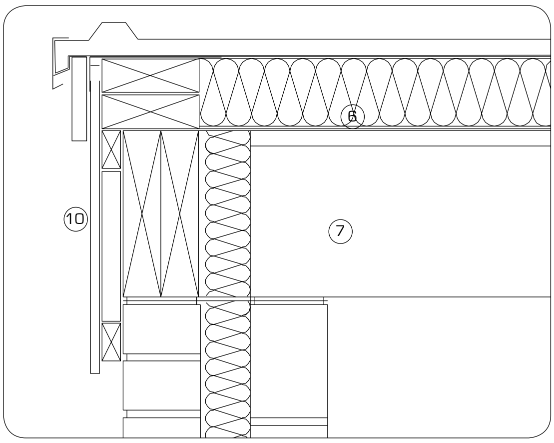
3D view showing ridge in mastic roof



Vertical section 1:10. Step in roof

Details

1. Mastic Asphalt
2. Plywood sheet or timber boards
3. Separating layer
4. Rigid thermal insulation
5. Freestanding timber upstand
6. Vapour barrier
7. Softwood joists
8. Drylining/drywall internal finish
9. Metal flashing
10. Fascia
11. External Wall
12. Expanded metal lathing
13. Rain water outlet/ other penetrations

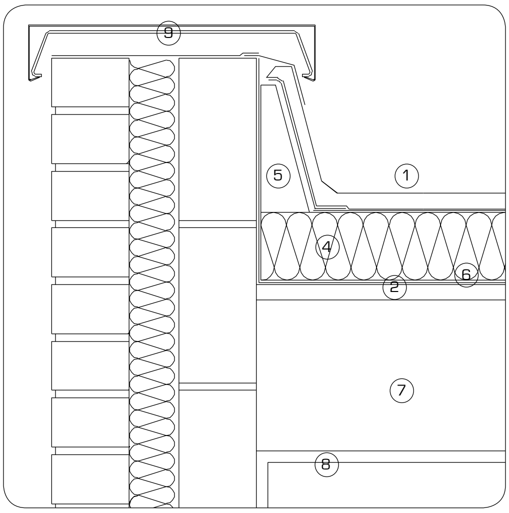


Vertical section 1:10. Eaves

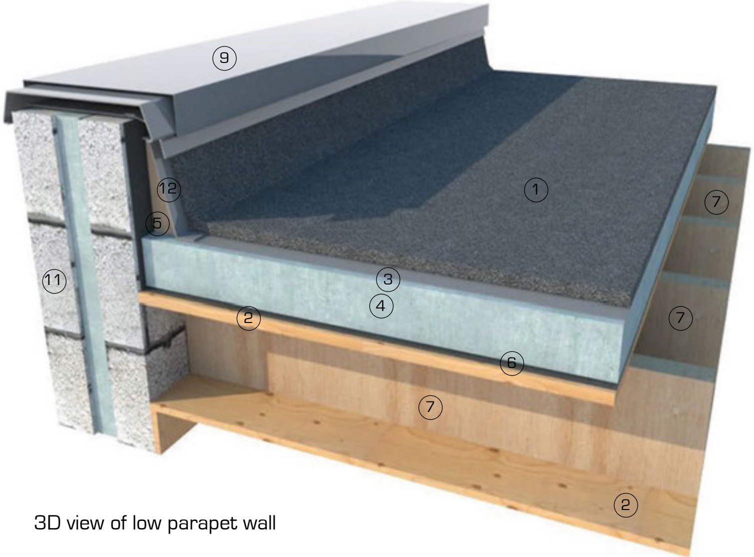
System design

This section discusses flat timber roofs that use the common combination of bitumen sheet-based membrane as a waterproofing layer in a warm roof. Although other membrane materials are used on flat timber roofs as both warm and cold roofs, typically formed in elastomeric and thermoplastic membranes, their application is discussed in the earlier section on exposed membranes in concrete roofs. The principles of detailing in that section can be similarly applied to timber roofs. Bitumen-based sheet can also be used in 'inverted roof', or concealed membrane configuration as described in that earlier section where the detailing is similar, but bitumen-based sheet is generally less robust than the membranes described in that section. Membranes applied to concrete decks are usually laid in hot liquid form and are reinforced to suit the specific conditions of folds and joints occurring within the structural deck. In this section the material is considered as an exposed and visible material on a relatively lightweight deck.

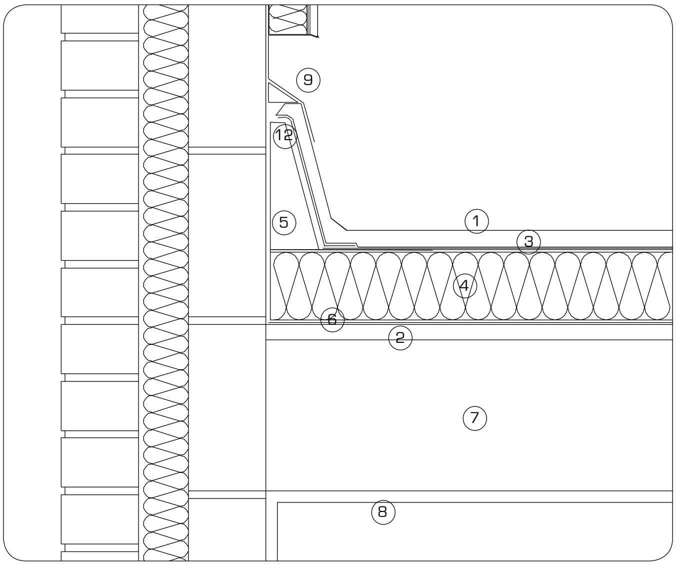
Bitumen sheet membranes are economic, and are often used with timber roof decks, which together provide an economic roof design for relatively small-scale applications, or designs with a complex geometry of low pitched roofs, as is often used



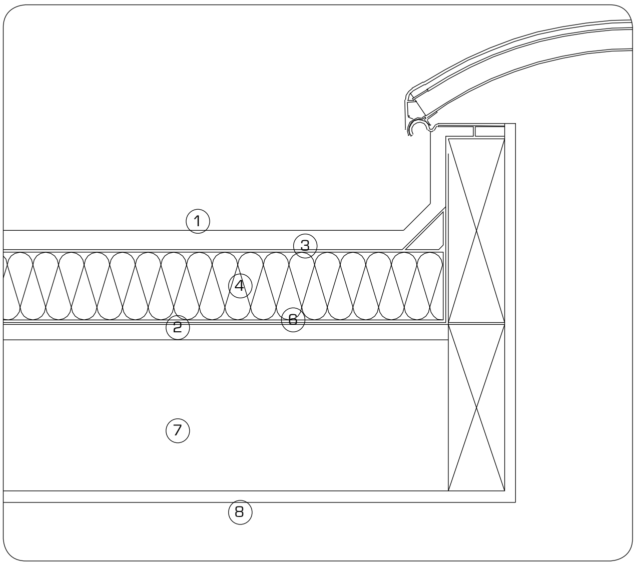
Vertical section 1:10. Low parapet wall



3D view of low parapet wall



Vertical section 1:10. High parapet wall



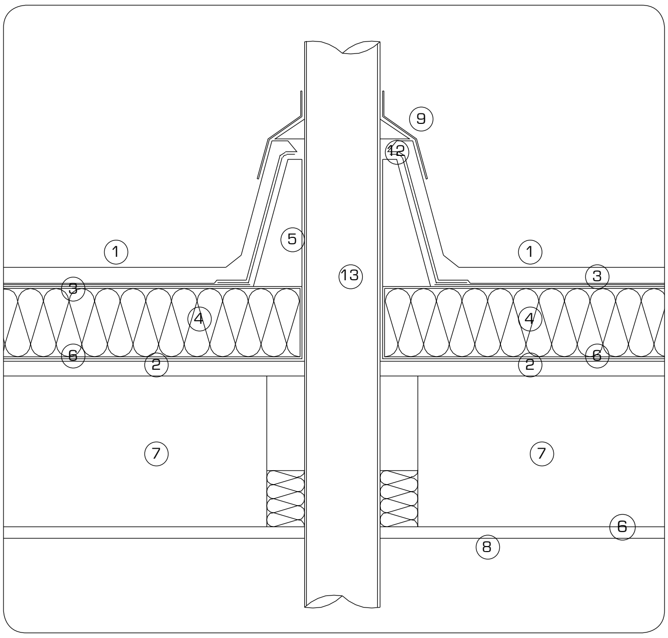
Vertical section 1:10. Roof light junction

in housing and in school buildings. Bitumen-based membranes have developed over the past 25 years to compete with the newer elastomeric and thermoplastic materials by increasing their flexibility and making them thinner, requiring less material, which helps to reduce their overall cost. Bitumen-based membranes can also be used with concrete and metal decks, and the principles here can be applied in a similar way to those roof deck types.

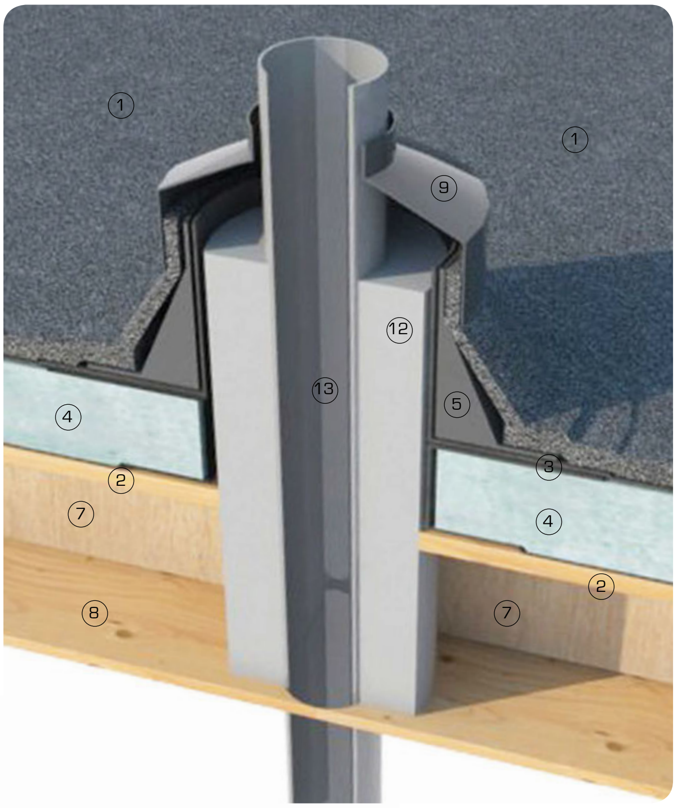
Bitumen-based sheet is manufactured in roll form in widths of around 1000mm, is black in colour, and is typically mixed with SBS (styrene-butadiene-styrene) polymers or with TPO (thermoplastic polyolefin) polymers. The addition of these polymers raises the melting point which ensures stability in hot weather as well as increasing the flexibility of the material at low temperatures (usually in winter in temperate climates) and enhancing the fire resistance of the material. Bitumen-based sheet often has a glass fibre reinforced upper face to provide greater dimensional stability and resistance to accidental damage, as well as a polyester reinforced core to increase tensile strength. These sheet materials are typically around 4mm thick, depending on the proprietary system used. Even with these additives, bitumen-based sheet is slowly oxidised by heat, making the material gradually more brittle which eventually results in cracks. The polymer additives reduce this effect, particularly the TPO additives that help to increase the life of the material, which can now be up to around 25 years. TPO-modified sheet can be exposed to the effects of the sun, requiring no additional solar protection, since the material provides better UV resistance than older-type bitumen-based membranes. SBS-modified sheet is usually covered with stone chippings or solar reflective paint to protect them from the effects of the sun.

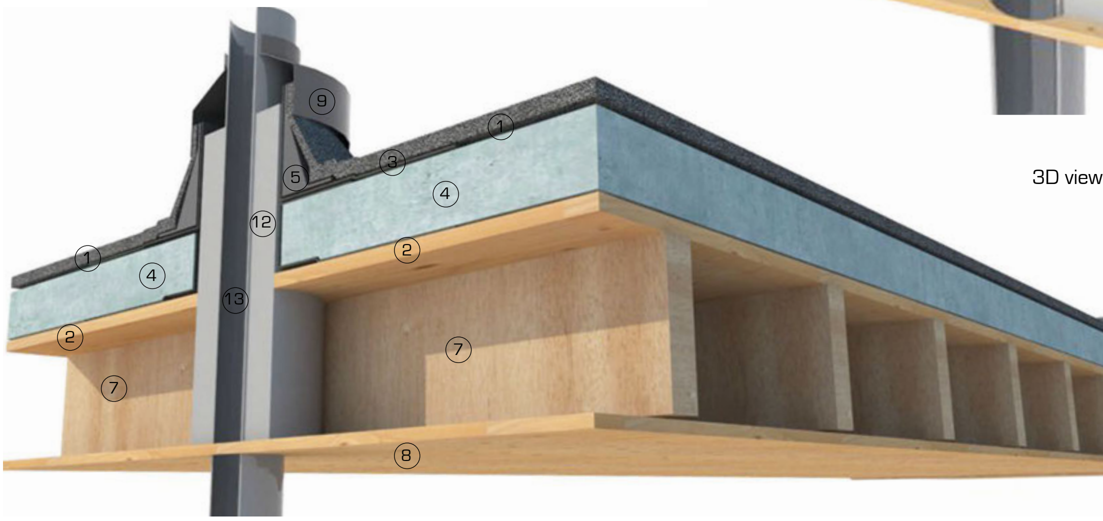
System details

Where plywood is used to form the structural deck of a timber roof, the joints between plywood boards are usually taped to provide a continuously smooth surface. On timber boarded decks, where this is not as practical a method, a thin layer of bitumen is laid onto the deck, applied typically in thick liquid form to seal the joints between the boards, the bitumen setting to form a smooth substrate. A vapour barrier is set onto the prepared timber deck, the barrier often being bitumen-based as part of a proprietary system. Rigid closed cell insulation such as polyurethane is bedded in hot bitumen onto the vapour barrier to hold the insulation securely in place. A loose laid perforated isolating layer is set onto the thermal insulation which is used to



Vertical section 1:10. Pipe Penentration





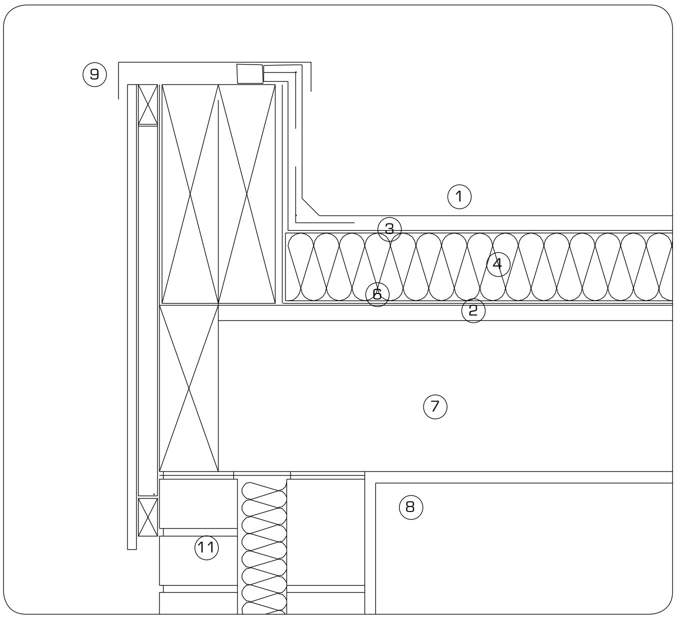
3D views showing pipe penetration in mastic roof membrane

allow the membrane and thermal insulation to release gases into the isolating layer which are formed as a result of bonding the bitumen to the insulation. The bitumen-based membrane is then bonded to the thermal insulation through the holes in the isolating layer.

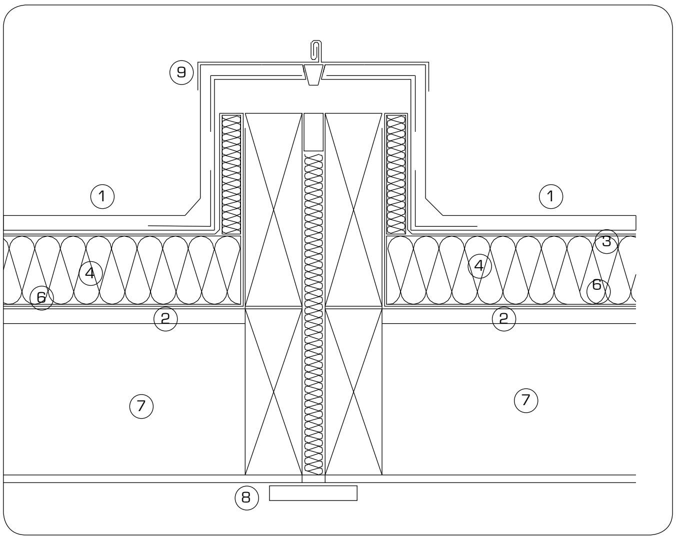
Resistance to UV radiation is provided by either a coating of fine stone chippings or by aluminium solar reflective paint applied to the visible surface of the bitumen-based sheet. As a result of providing this additional UV protection, these coatings have the additional benefit of reflecting heat, which has the effect of reducing the surface temperature of the roof below that which would otherwise be the case. Solar reflective paint gives the roof a metal appearance, which provides a visual alternative to the characteristic black colour of bitumen-based sheet. Membranes can also be provided with a solar protection layer during manufacture as part of a proprietary bitumen-based membrane system.

Bitumen-based membranes are fixed typically by either torching, bonding or mechanical fixing methods. With torching, a flame is used to melt an adhesive layer on the underside of the sheet so that the membrane adheres to the substrate. Sheets are lapped by around 100mm to ensure a water tight seal. Torches are usually gas fuelled, supplied from a small canister as part of a hand-held tool, or are supplied from a large gas cylinder set onto the roof to a variety of tools, either hand-held or wheeled, for larger scale applications.

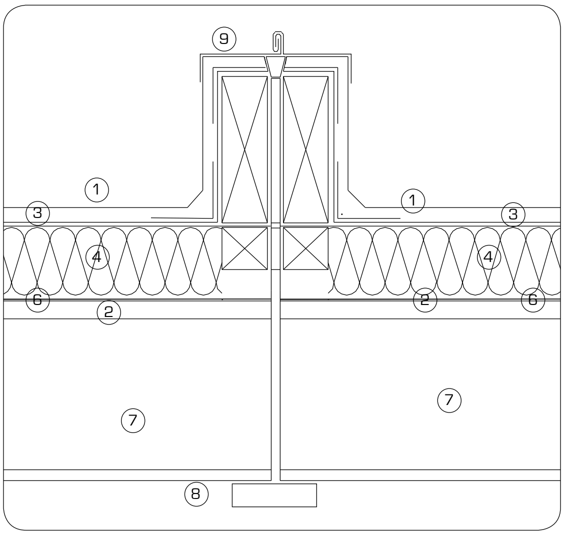
Upstands in bitumen-based sheets are formed by either fixing the sheet to the plywood face of a timber framed upstand, or to the face of the thermal insulation, depending on the configuration of the external wall. Where a timber roof deck meets a masonry wall, with the concrete block wall being clad in timber rainscreen panels, the bitumen-based sheet is shown fixed to the face of the upstand. With a low upstand, the membrane continues up the full height and extends across the top of the wall underneath the coping. The roof membrane is made continuous with the waterproof seal of the external wall, with the membrane terminating against the bitumen paint finish of the external face of the blockwork wall. The coping can be made from any impervious and durable material. A pressed metal coping, overhanging on both sides, provides additional protection to the membrane as it folds over the top of the wall.



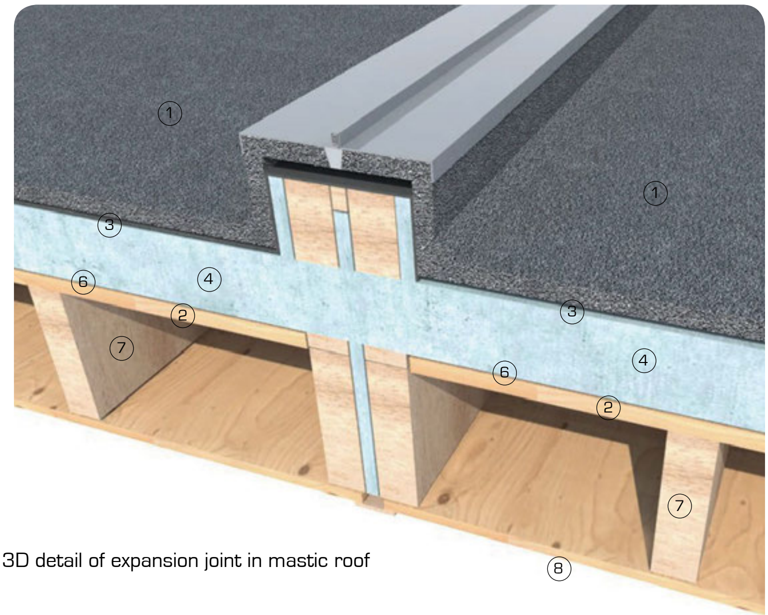
Vertical section 1:10. Eaves



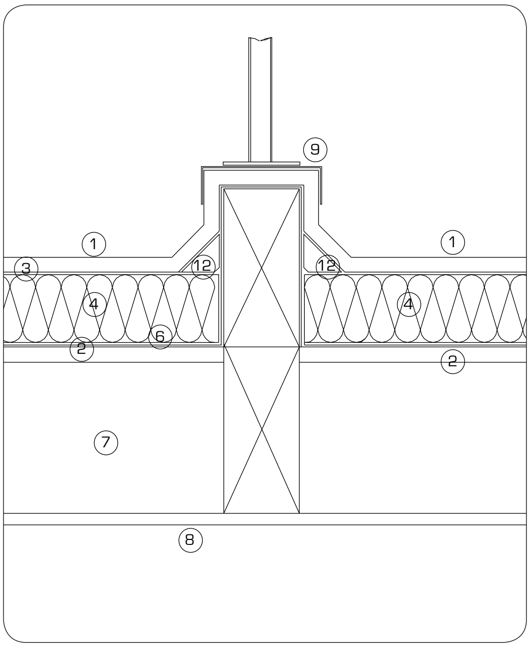
Vertical section 1:10. Expansion joint



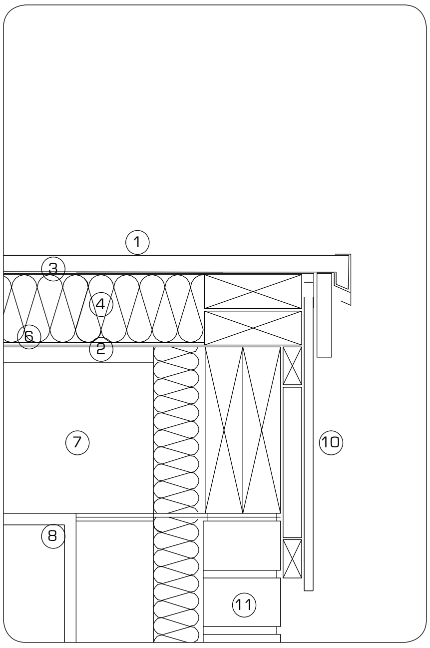
Vertical section 1:10. Expansion joint



3D detail of expansion joint in mastic roof



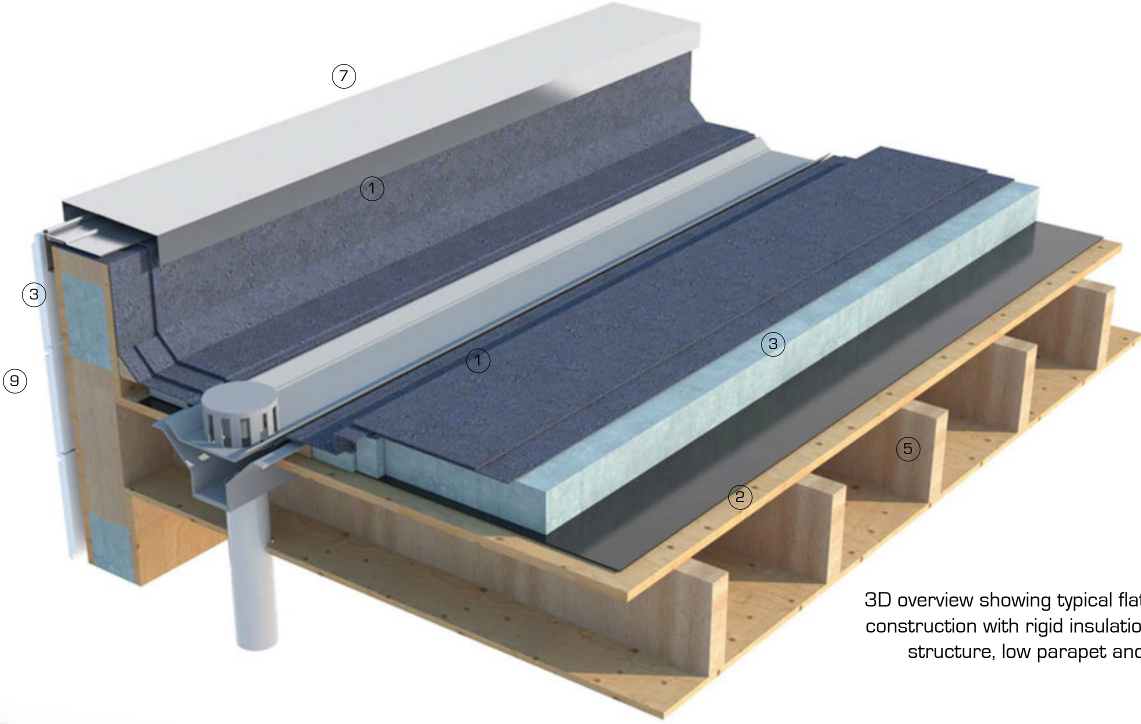
Vertical section 1:10. Balustrade



Vertical section 1:10. Eaves

Details

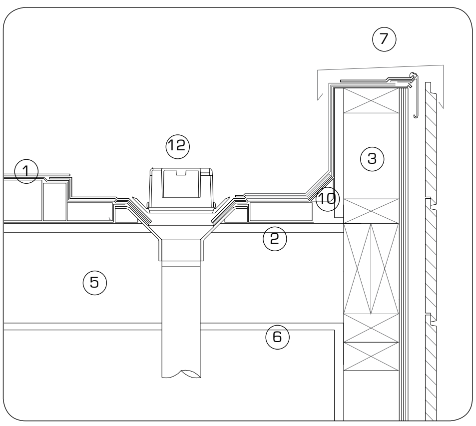
1. Mastic Asphalt
2. Plywood sheet or timber boards
3. Separating layer
4. Rigid thermal insulation
5. Freestanding timber upstand
6. Vapour barrier
7. Softwood joists
8. Drylining/drywall internal finish
9. Metal flashing
10. Fascia
11. External Wall
12. Expanded metal lathing
13. Rain water outlet/other penetrations



3D overview showing typical flat timber roof construction with rigid insulation above roof structure, low parapet and drain outlet

3D view showing drain outlet detail on flat timber roof arrangement

(Below) 3D view showing alternative drain outlet detail on flat timber roof arrangement

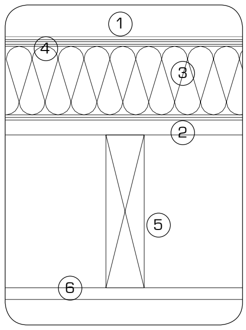


Vertical section 1:10. Low parapet wall with drain outlet

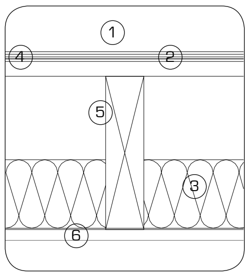
System design

Flat timber roofs are described as being in either 'warm' roof or 'cold' roof configuration. In the warm roof configuration, thermal insulation is set on top of the timber deck, which is protected by a waterproof layer set onto its upper face. A vapour barrier is set between the thermal insulation and the timber deck. The roof build-up is not required to be ventilated as the timber structure is maintained at near internal temperature conditions. In the cold roof configuration the waterproof layer is set directly onto the timber deck. Thermal insulation is set beneath the timber deck, in the voids between the timber joists and air is allowed to circulate in the void to provide ventilation that prevents the possibility of rot forming in the timber. A vapour barrier is set beneath the insulation, on the warm (in winter) side of the insulation, with a dry wall or internal lining board set below this. In both warm and cold roofs, the vapour barrier avoids the passage of damp air up into the thermal insulation where interstitial condensation can form that might damage the internal construction of the roof.

In a mastic asphalt waterproofed warm roof, thermal insulation is set on top of the timber deck, with an asphalt layer on top of this. A separation layer is set between the asphalt and the thermal insulation. A vapour barrier is set between the thermal

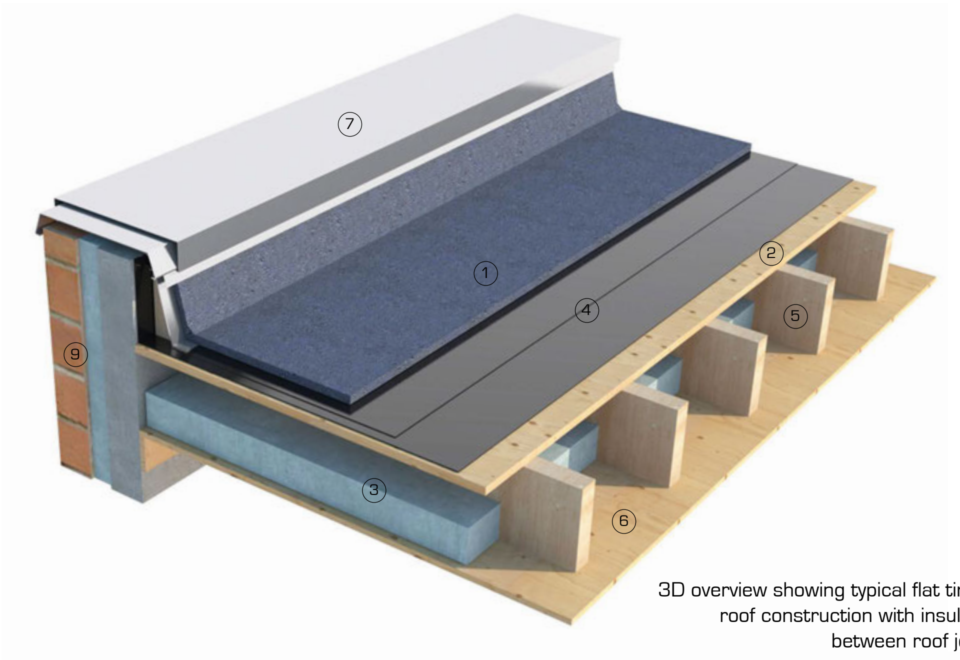


Vertical section 1:10. Flat roof with rigid insulation above roof structure

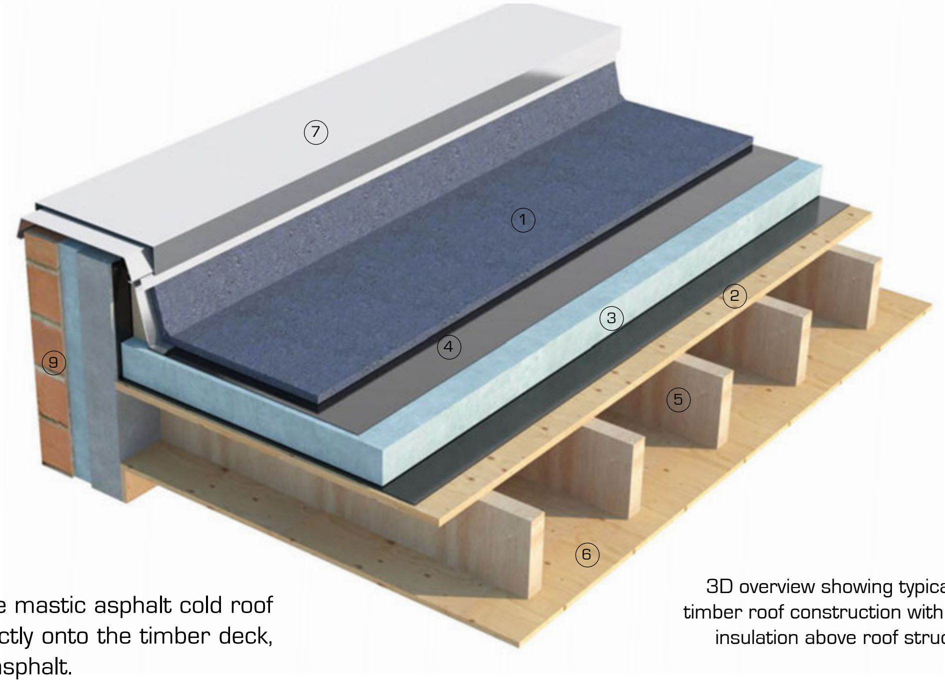


Vertical section 1:10. Flat roof with insulation between joists

Details
1. Bitumen based sheet
2. Plywood sheet
3. Rigid thermal insulation
4. Vapour barrier
5. Softwood joists
6. Dry lining/drywall internal finish
7. Metal Flashing
8. Timber upstand
9. External Wall
10. Angle fillet
11. Proprietary skirt flashing
12. Rainwater outlet
13. Paving bonded to bitumen based sheet



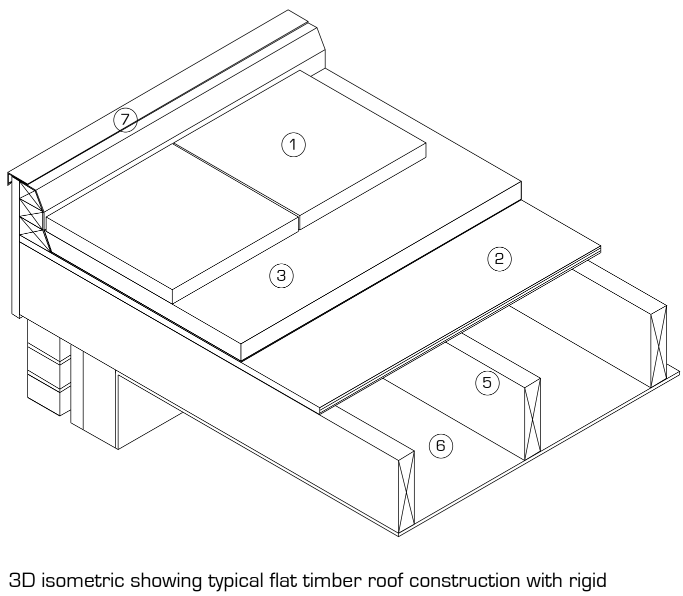
3D overview showing typical flat timber roof construction with insulation between roof joists.



3D overview showing typical flat timber roof construction with rigid insulation above roof structure

insulation and the timber deck. In the mastic asphalt cold roof configuration, the asphalt is set directly onto the timber deck, with a separating layer beneath the asphalt.

Mastic asphalt, used to form a continuous waterproof covering on flat or sloping roofs, has polymer additives in some types to provide stability at the relatively high temperatures experienced when exposed to the effects of the sun, as well as providing flexibility of the material at low temperatures, which allows it to take up movements in the substrate. Asphalt is applied in a hot liquid form on site, allowing it to form a homogeneous material at complex junctions such as at upstands, roof penetrations and changes in level. It was used more commonly 25 years ago, and its popularity is being challenged by single layer sheet membranes, which have greater strength, flexibility, a higher melting point and UV resistance. However, the use of this material is set to continue, mainly a concealed membrane, but its use as an exposed membrane is discussed here since this application is much more common in timber construction. Mastic asphalt is laid on rigid substrates, typically reinforced concrete decks, but its use as an exposed membrane on a timber deck is set to continue, particularly as a result of additives which make the material more flexible than was previously the case.



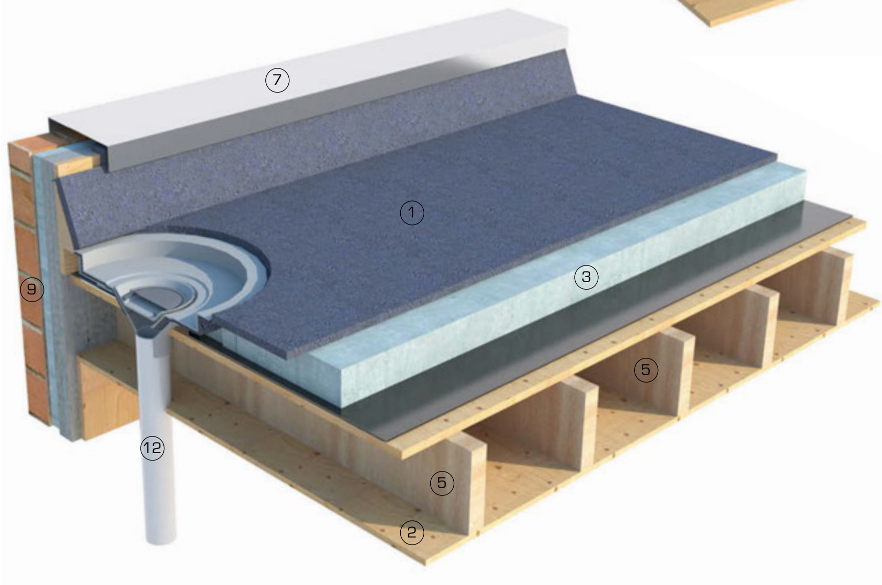
3D isometric showing typical flat timber roof construction with rigid insulation above roof structure

Timber roofs 2: flat roof: bitumen-based sheet

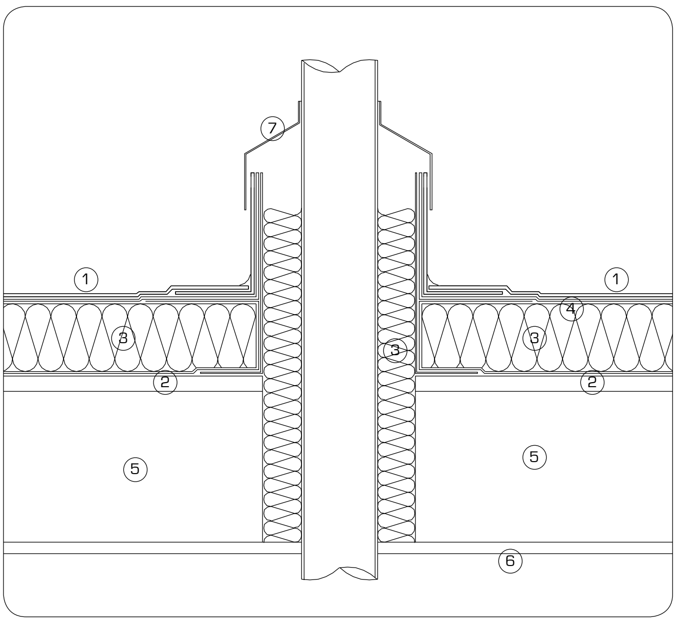
Details
1. Bitumen based sheet
2. Plywood sheet
3. Rigid thermal insulation
4. Vapour barrier
5. Softwood joists
6. Dry lining/drywall internal finish
7. Metal Flashing
8. Timber upstand
9. External Wall
10. Angle fillet
11. Proprietary skirt flashing
12. Rainwater outlet
13. Paving bonded to bitumen based sheet

3D view showing step in flat timber roof arrangement

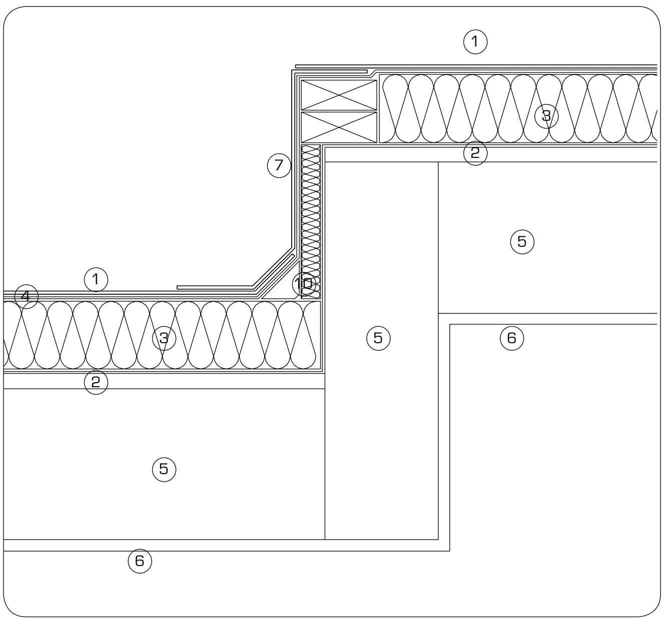
3D overview showing typical flat timber roof construction with rigid insulation above roof structure, low parapet and drain outlet



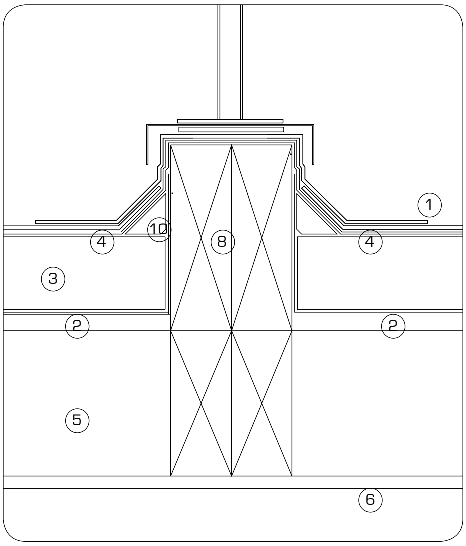
3D detail showing step in timber roof construction



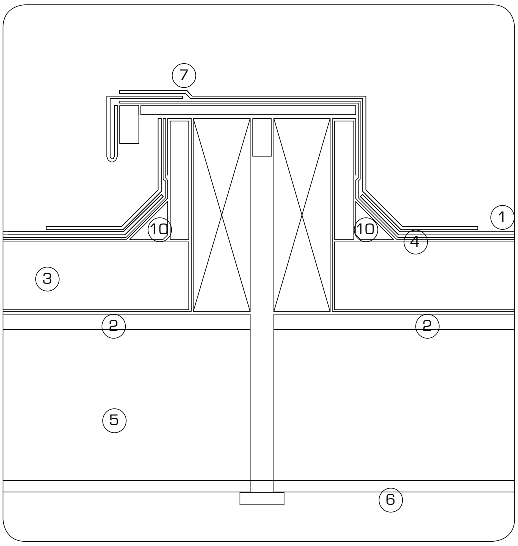
Vertical section 1:10. Pipe penetration and step in roof



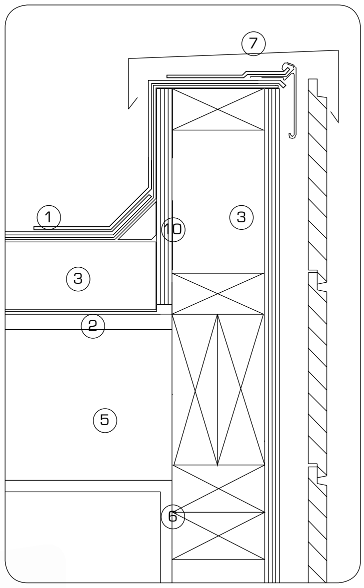
Vertical section 1:10. Step in roof



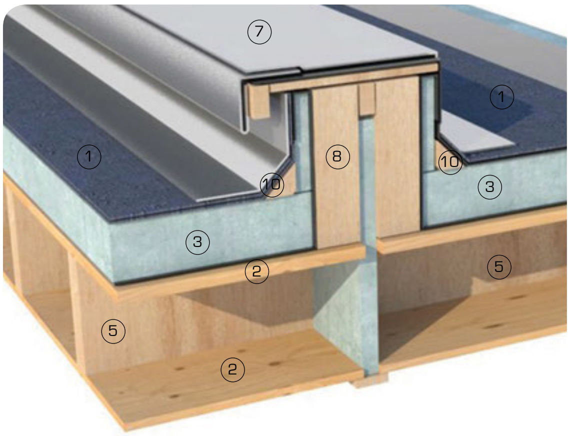
Vertical section 1:10. Balustrade detail

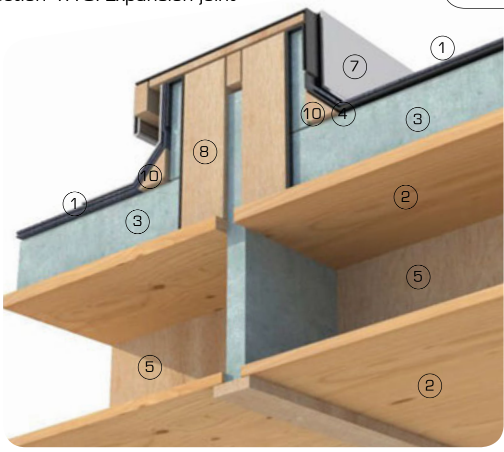


Vertical section 1:10. Expansion joint



Vertical section 1:10. Low parapet wall





(Left) 3D views showing expansion join in typical timber flat roof construction

In warm roof construction, a protective surface is usually applied to all exposed areas with a solar reflective paint, stone chippings or thin paving slabs which are bedded into the asphalt surface with a proprietary adhesive. A single layer of 10mm – 14mm stone chippings is used as permanent surface protection for asphalt. The chippings are usually bonded to the asphalt after the asphalt has cooled, with a bitumen solution to provide only a limited bond. This allows the chippings to be removed easily at a later date for repair and maintenance work.

System details

At upstands, where the asphalt is usually set vertically, or at a steep slope, the material is laid in three coats. The first coat is very thin in order to key in the substrate, then two further separate coats are applied to give an overall thickness of around 20mm. In forming an upstand, sheathing felt is fixed to the substrate, often a separate upstand fixed to the roof, as mentioned earlier. Expanded metal lathing, typically at 150mm centres, primed in bitumen, is fixed to the face of the sheathing layer, which provides a 'key' to which the asphalt will bond. Where the upstand is formed in lightweight concrete block, the surface is faced with either a sand cement render, or metal laths and sheathing felt is used as described.

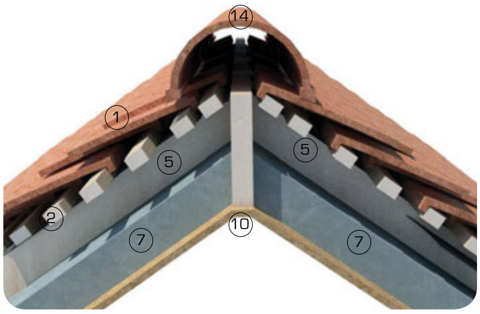
Trims to verges and eaves are formed with a GRP or aluminium trim in order to support the bottom edge of the asphalt. Some installations use no trim at all, but the edge becomes vulnerable to damage and can result in a visually uneven appearance. When the asphalt edge is terminated by a gutter, a metal flashing can be set under the bottom of the asphalt.

Verges can be formed by creating an asphalt upstand, built to a height of around 50mm to suit the expected flow from the roof. An alternative detail is to stop the asphalt at the edge of the roof and terminate in a metal strip so that the asphalt cannot be seen from below, but in practice it can be difficult to achieve a reliable seal between the asphalt and the metal trim.

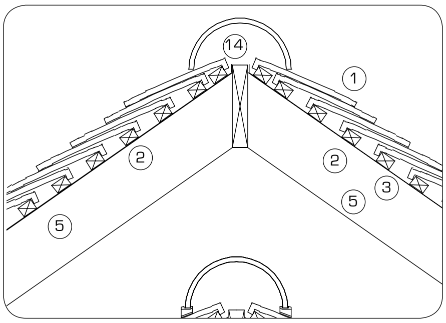
Penetrations through an asphalt covered roof are formed by extending the asphalt up by 150mm to create a collar round the material. The top of the asphalt collar has an apron flashing around it to protect the top of the asphalt. An alternative method of sealing a roof penetration is to form a complete upstand around the penetration which can be insulated to the top of the opening. An insulated metal panel can then be mechanically fixed and sealed, or bonded, to the duct or pipe creating the penetration. An additional secondary seal, formed typically with either EPDM or metal sheet, forms a secondary seal to this penetration.

Gutters can be formed to any shape created within the timber deck since asphalt can be laid to suit a complex geometry without the need for joints in the material. Where the gutter is formed as a parapet gutter at the base of the tiled roof, the asphalt is carried up over the tilting fillet of the tiled roof. Rainwater outlets are formed by setting the outlet at the level of the structural deck. The asphalt is stepped down with 45° folds down into the rainwater outlet, and the metal grating and cover is fixed down onto this. The sheathing felt extends up to the edge of the rainwater outlet.

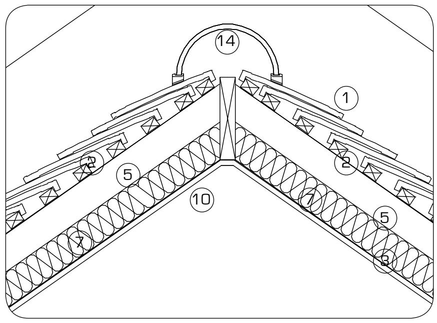
3D view of ventilated roof with terracotta tiles



3D view of ventilated roof with terracotta tiles



Vertical section 1:20. Unventilated roof



Vertical section 1:20. Ventilated roof

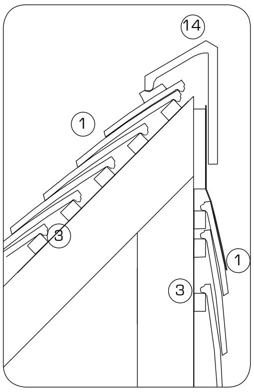
System design

Clay tiles for roofs are most commonly made from clay or concrete. In the clay type natural clay is mixed with additives such as quartz, mica, iron oxide and crystalline aluminium oxide. Clay tiles are fired in a kiln at around 1100°c to make the material both rigid and resistant to moisture penetration. Plain tiles are used on pitched roofs ranging from vertical tile hanging to pitches as low as around 35° above the horizontal. Interlocking tiles, with grooves and complex laps can be used in down to a minimum pitch of 22.5° above the horizontal. Concrete tiles are made from aggregate and Portland cement which are mixed together and then cured in temperature-controlled chambers in the factory. Their appearance tends to imitate those of traditional clay tiles in both shape and variety of colour, but large interlocking tiles are available in sizes that are difficult to achieve in clay. In common with clay tiles, concrete plain tiles are used in roof pitches down to 35° above the horizontal. An advantage of concrete tiles over clay tiles is that some concrete interlocking tiles can be used for pitches as low as 12.5° above the horizontal.

Both tile types are fixed to timber battens set horizontally, that is, at right angles to the direction of the slope. The battens are fixed onto roofing felt, which forms a second line of defence and a full weathertight barrier to the roof. The roofing felt is set on timber rafters (sloping timbers) or full timber trusses. The tiles provide the first line of defence against rainwater penetration as well as protecting the roofing felt from direct windblown rain, the effects of the sun, as well as protecting the felt from accidental damage. Many tile shapes and profiles are available which have been developed from historical examples. The design life for tiled roofs in both clay and concrete types is around 30 years but they are actually expected to last for around 100 years.

Like flat roofs, pitched roofs are formed as either warm roofs or cold roofs. In the cold roof, horizontal joints are insulated and the void is ventilated to ensure that any condensation forming in the roof void can escape, which avoids damage to both the timber and the thermal insulation. In recent years it has become more common to use a vapour permeable membrane or 'breather' membrane as the underlayer to the tiling instead of waterproof roofing felt. This is done to avoid ventilating the roof void, which can become very damp in temperate climates during winter.

In the warm roof, the sloping rafters are filled with thermal insulation in order to allow the internal space of the roof void to be used. As with the cold roof, a vapour barrier is set between the thermal insulation and the internal dry wall lining. A vapour permeable membrane is set on the outside face of the sloping rafters as an underlay to the tiling. If the insulation completely fills the void between the rafters, then this breather membrane serves to allow moisture trapped within the construction to escape. If the thermal insulation does not fill the void, and is set against the internal dry lining, then the void between the insulation and the breather membrane is ventilated at the ridge



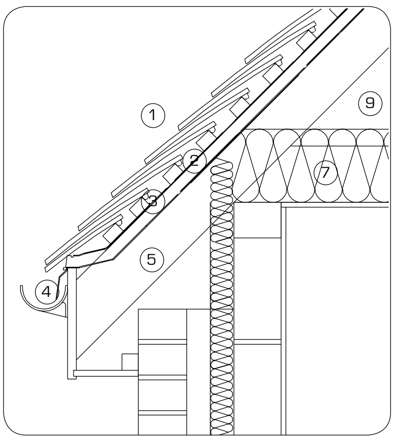
Vertical section 1:20. Ridge detail for ventilated roof

3D view of timber shingles on timber roof construction

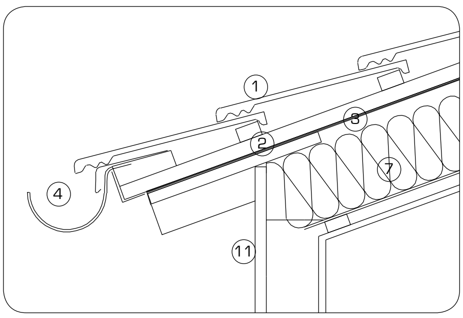
3D view of timber shingles on timber roof construction

Details

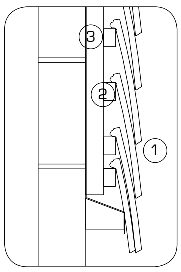
1. Roof tiles, slates or shingles (tiles shown)
2. Softwood battens
3. Roofing felt
4. Gutter
5. Softwood rafter
6. Ventilation void
7. Thermal insulation
8. Vapour barrier
9. Softwood joist
10. Dry lining/drywall internal finish
11. Soffit board to conceal rafters but allow ventilation to air gap behind
12. Fascia board
13. Supporting wall (brick cavity wall shown)
14. Ridge capping (ridge tile shown)
15. Metal flashing
16. Standing seam sheet



Vertical section 1:20. Eaves detail



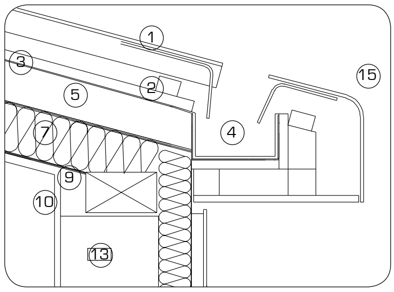
Vertical section 1:20. Eaves detail for profiled tile



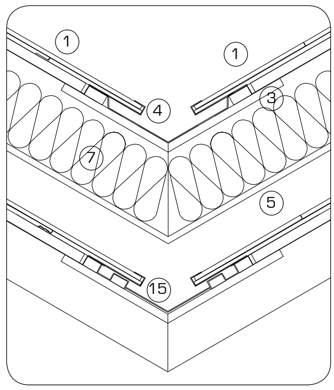
Vertical section 1:20. Tiles applied to vertical wall

3D view showing slate tiles on unventilated timber roof at ridge

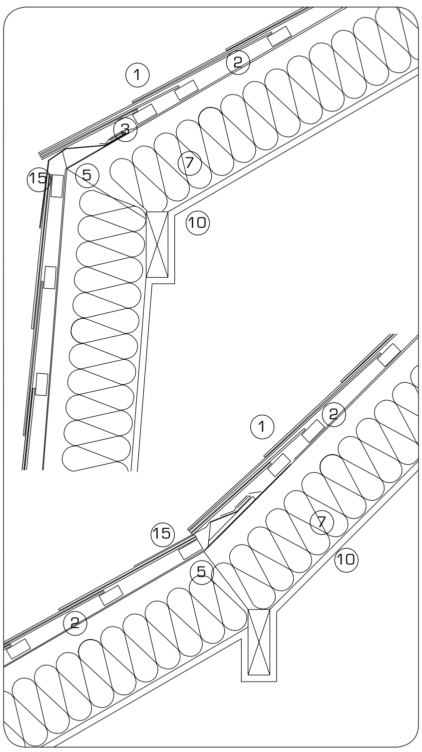
3D section through slate tiles on unventilated timber roof showing valley and fold details



Vertical section 1:20. Eaves detail. Standing seam roof covering



Vertical section 1:20. Valley details for ventilated and unventilated roof



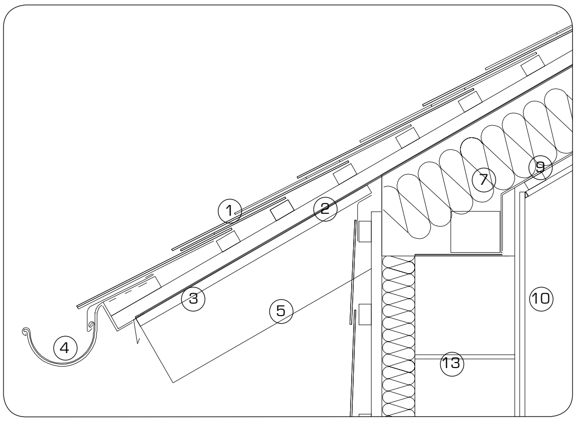
Vertical section 1:20. Internal fold

and at the eaves. Where a breather membrane is used, the cavity between the outside face of the membrane and the tiles is increased from 25mm to 50mm with counter battens to allow the air within the void to move more freely, ensuring that vapour being released to the outside can be dispersed easily.

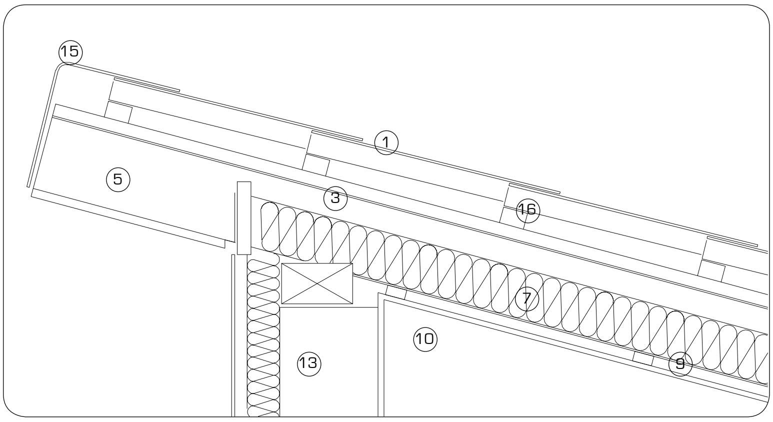
System details

Both plain tiles and interlocking tiles are terminated at their base with a gutter. In order to maintain a constant pitch of tiles down to the gutter, the bottom row of battens is raised up on a wedge-shaped timber profile called a tilting fillet. This allows the underlay to meet the underside of the bottom tile, and drain both rainwater running down the tiles as well as any moisture running down the underlay into the gutter. A ventilator, typically in PVC-U, is set between the bottom tile to ventilate either the roof void in a cold roof, or the cavity between the underlayer and the tiles in a warm roof configuration.

In the cold roof version the proprietary ventilator is set beneath the underlayer. Fresh air is allowed to flow into the ventilator set beneath the bottom tile and is released into the roof void without affecting the thermal insulation of the roof at ceiling level, which is continuous between wall and roof. In the warm roof version, a ventilator set between the bottom tile and the felt underlay



Vertical section 1:20. Eaves detail of slate tile



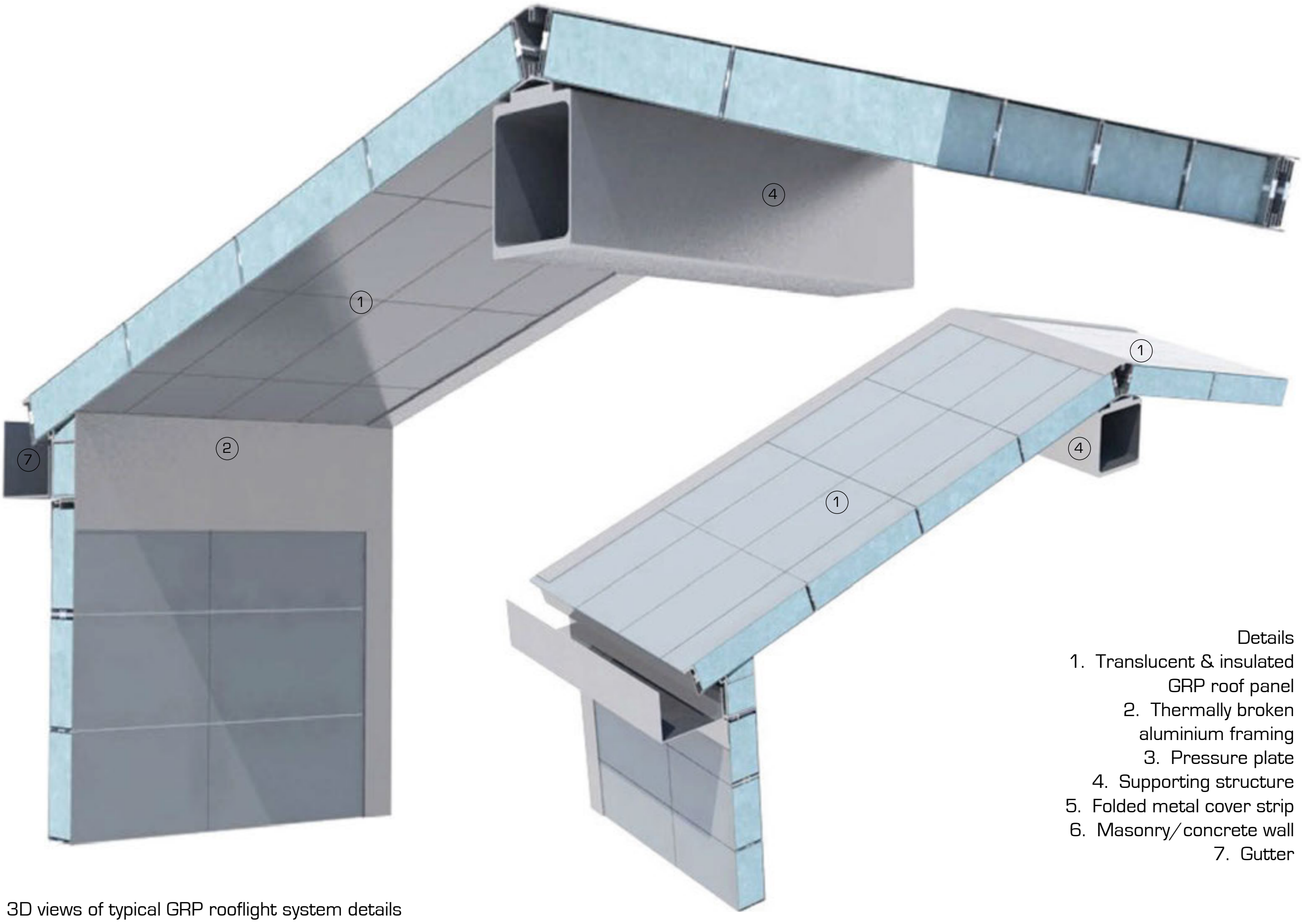
Vertical section 1:20. Ridge detail. Metal tiles on timber roof

3D section through standing seam roof on timber structure

introduces air into the void between the tile and the breather membrane. The thermal insulation either continues to the fascia board, then returns horizontally back from a continuity with the wall insulation, or alternatively the wall insulation continues vertically until it reaches the sloping insulation set between the rafters. In the second version, the void forming the fascia and soffit immediately beneath it is in 'cold' roof configuration and is required to be ventilated in order to avoid damp, stagnant air from damaging the timbers.

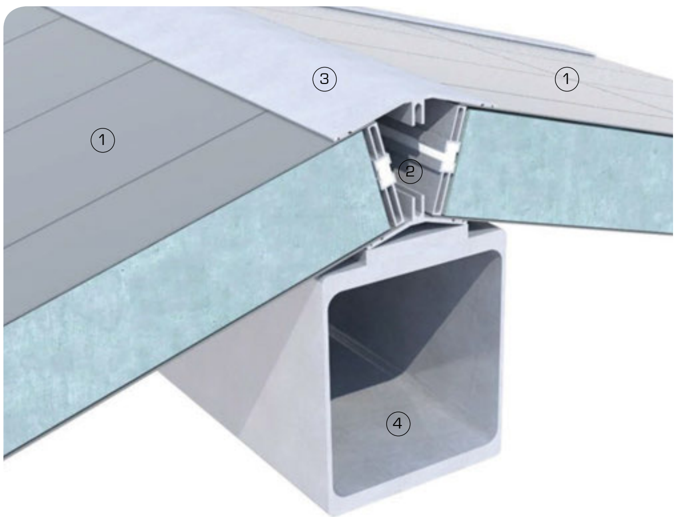
Where a sealed ridge is required, ridge tiles are either bedded in a sand cement mortar, or are dry fixed with metal screws, typically stainless steel, where a rapid installation is required. For ventilated ridges, proprietary fixings usually made in PVC-U with ventilation slots are used to ventilate either the batten cavity between the underlay and the tiles, in a warm roof, or the roof void in a cold roof configuration. Where the batten cavity is ventilated the cavity is sealed across the ridge. Air is allowed to pass through a gap between the bottom of the ridge tile and the roof tile immediately beneath; the gap being formed by the PVC-U ventilator. Where the complete roof void is vented to the outside in a cold roof, a gap of around 10mm in the underlay is formed at the ridge.

Details
1. Roof tiles, slates or shingles (tiles shown)
2. Softwood battens
3. Roofing felt
4. Gutter
5. Softwood rafter
6. Ventilation void
7. Thermal insulation
8. Vapour barrier
9. Softwood joist
10. Dry lining/drywall internal finish
11. Soffit board to conceal rafters but allow ventilation to air gap behind
12. Fascia board
13. Supporting wall (brick cavity wall shown)
14. Ridge capping (ridge tile shown)
15. Metal flashing
16. Standing seam sheet

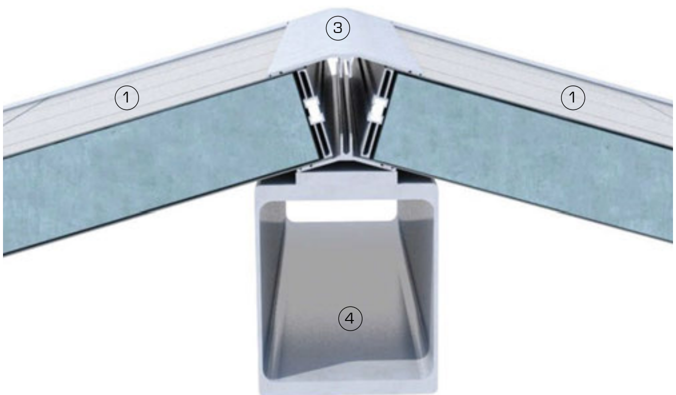


Details
1. Translucent & insulated GRP roof panel
2. Thermally broken aluminium framing
3. Pressure plate
4. Supporting structure
5. Folded metal cover strip
6. Masonry/concrete wall
7. Gutter

3D views of typical GRP rooflight system details



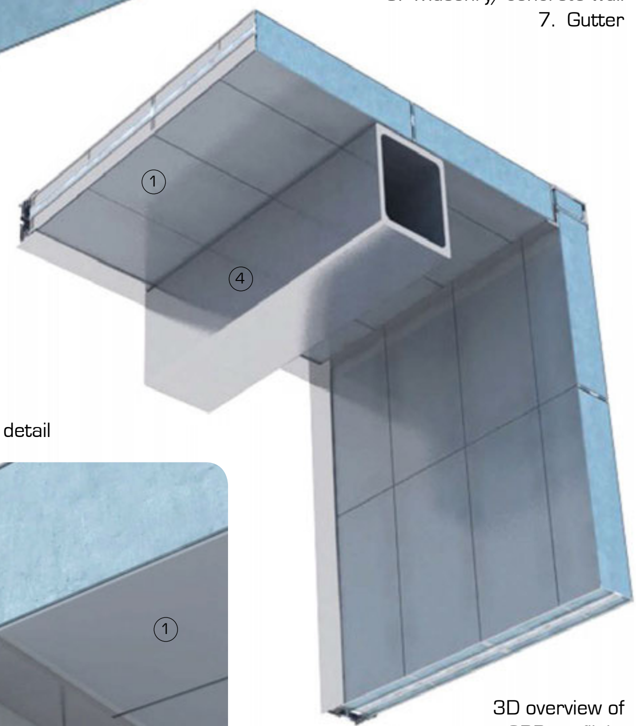
3D views of typical ridge detail



3D view of typical gutter/eaves detail

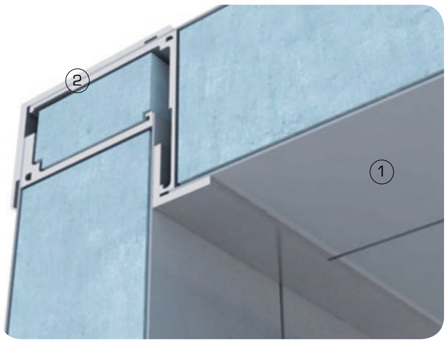
Details
1. Translucent & insulated GRP roof panel
2. Thermally broken aluminium framing
3. Pressure plate
4. Supporting structure
5. Folded metal cover strip
6. Masonry/concrete wall
7. Gutter

3D overview of GRP rooflight



3D overview of GRP rooflight

3D view of typical edge detail



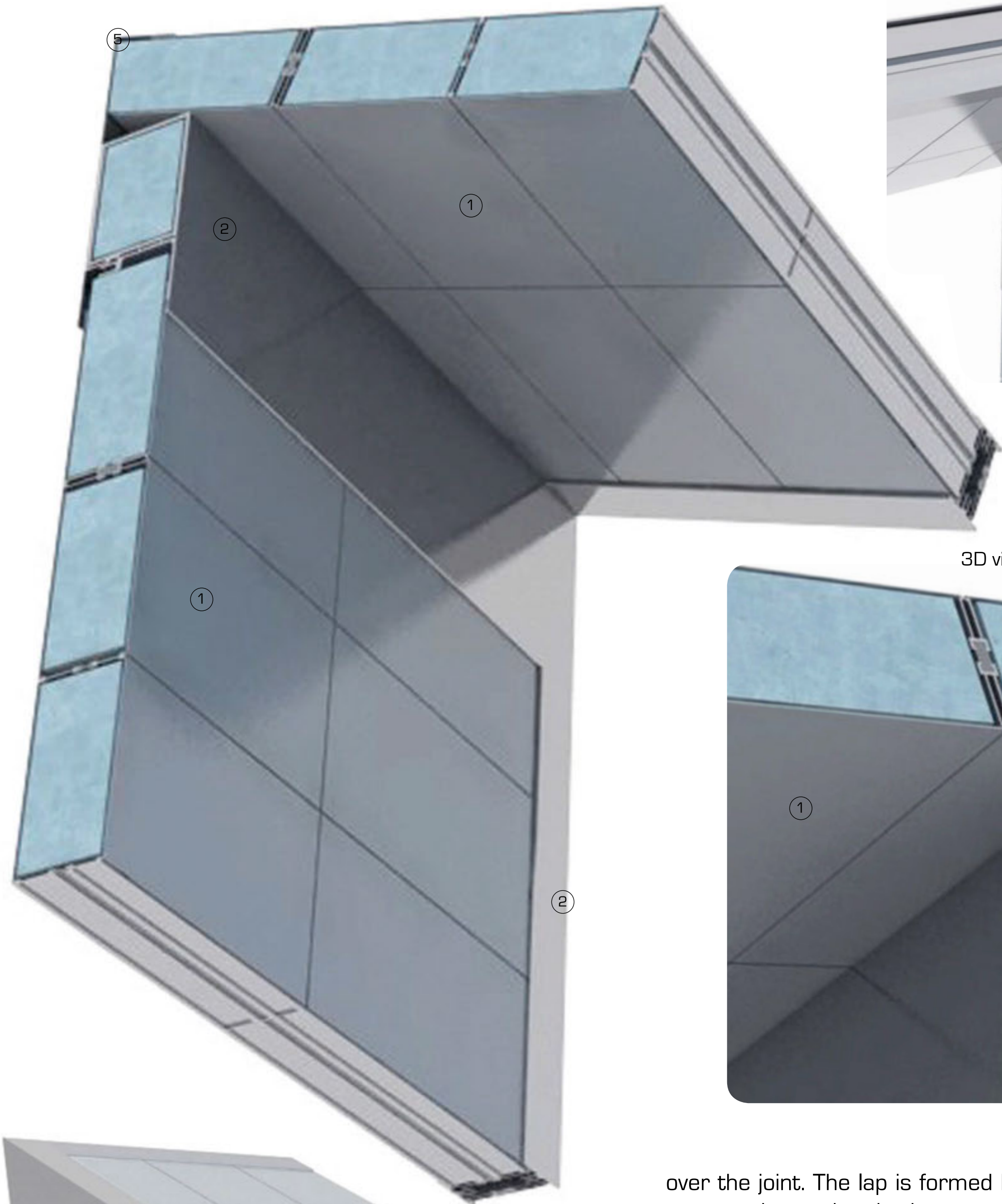
System design

Glass reinforced polyester (GRP) is used in the form of thermally insulated panels to form translucent rooflights which are robust and economic when compared to an equivalent glazed rooflight with double glazed units. The advantages of GRP over glass are its strength, lightness and flexibility as well as the material's high resistance to impact damage. GRP is a composite material formed by reinforcing flexible fibreglass mat (or fibres) with thermosetting polyester resins that provide high tensile and compressive strengths. The material is not combustible, making it a suitable material for rooflights as well as an opaque roof cladding material. While GRP rooflight systems do not usually achieve the high levels of resistance to wind blown rain of internally drained and ventilated curtain walling systems, they are robust and economic, making them ideal where translucency is required rather than the transparency provided by glass panels.

Rooflights are made from GRP sheet which is bonded to an aluminium carrier frame around its edges. Thermal insulation set into the void is usually bonded to the outer GRP facing sheets to provide true composite action between the GRP skin and the insulated core. Like metal composite panels, GRP panels increasingly have a thermal break introduced into the framing to reduce the possibility of condensation forming on the underside of the panel in temperate climates as well as to improve the overall thermal insulation value of the rooflight. Thermal breaks are usually made from an extruded polymer that has a much lower thermal conductivity than aluminium, and are bonded to the extrusion in the manner of glazed curtain walling or are clipped to it and secured in place by self tapping screws that hold the pressure plate in position.

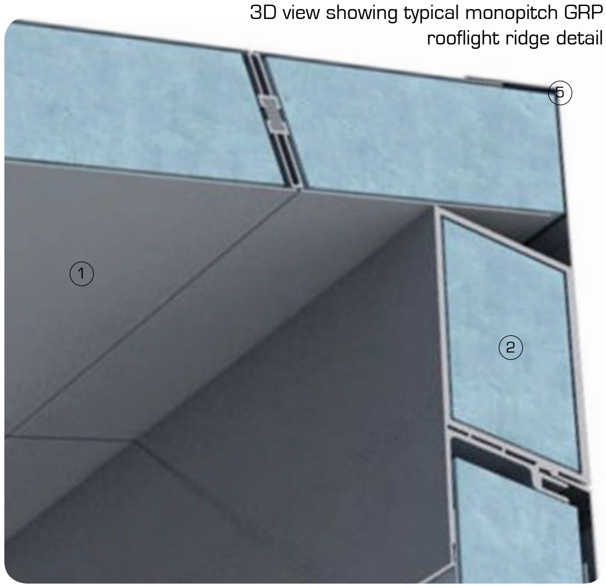
In small rooflights, up to around a 3000mm span, GRP composite panels require no additional support, while those of greater span use an additional aluminium or steel frame beneath to support the composite panels over the greater span. Panel sizes vary with the proprietary system and with the individual rooflight design. Typical panel sizes range from around 400mm x 800mm to 800mm x 3000mm. GRP rooflight panels use a lightweight framing system rather than a lapped junction or raised edges providing a standing seam type joint used in metal composite panels. These make their appearance more refined, since the framing is very visible in translucent GRP panels, unlike their metal equivalent. An extruded aluminium T-section forms the support to the panels on all four edges, with an extruded aluminium pressure plate being used to hold the panels in place on the outer face of the GRP panels. Most support frames are now internally drained and ventilated to provide a second line of defence against rainwater penetration. The outer seal is provided by an extruded EPDM gasket clipped into the aluminium extrusion. Proprietary tapes are also used but are more dependent upon good workmanship on site than gaskets, which are fixed to the pressure plate in factory conditions.

Pressure plates for panel joints running down the slope are set over the joint between the panels in the manner of glazed curtain walling. Joints running across the slope sometimes have pressure plates with lapped joints, in order to avoid water building up on the upper side of the joint and being unable to run



3D view showing typical monopitch GRP rooflight

3D view showing typical monopitch GRP rooflight ridge detail



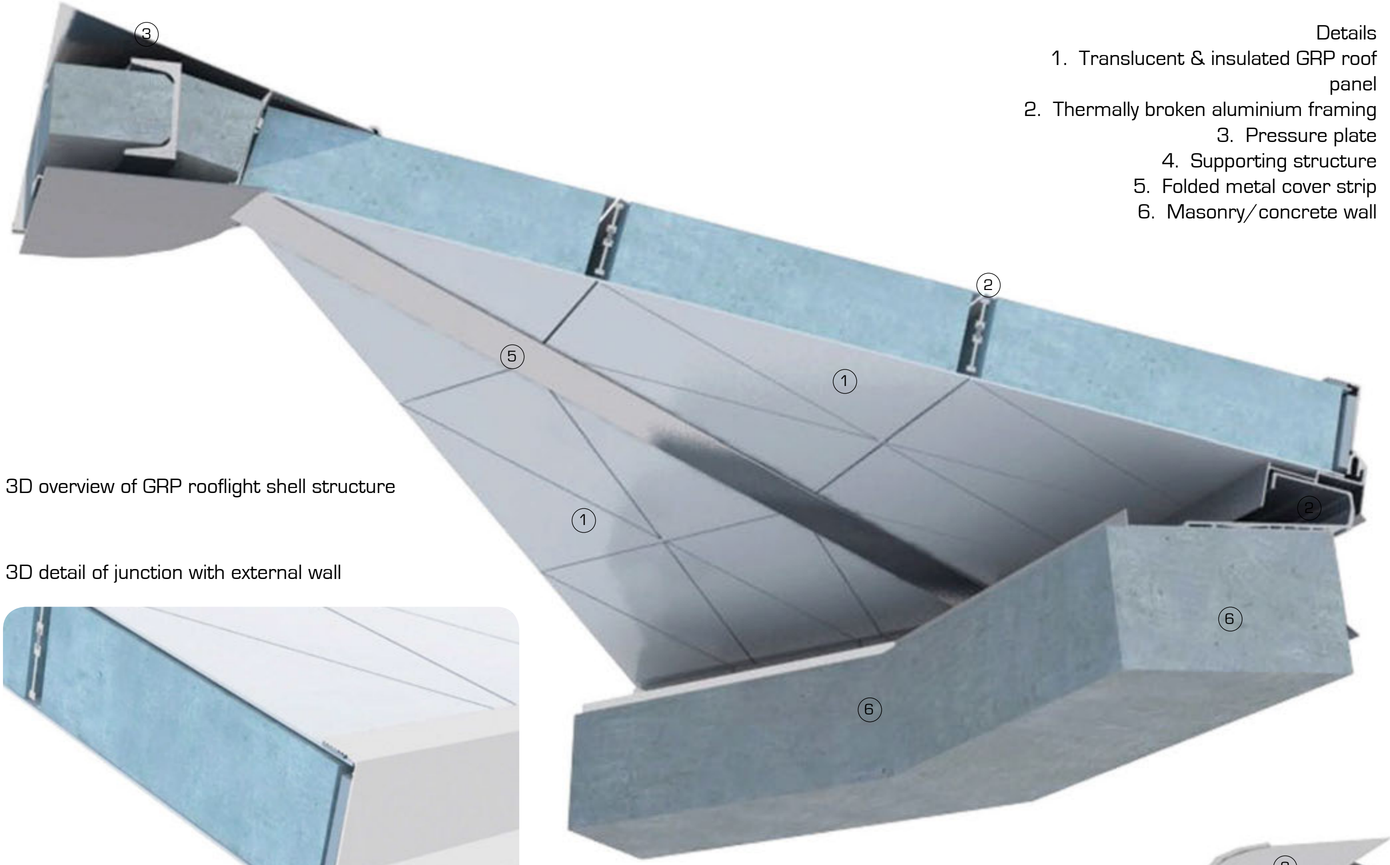
3D view showing typical monopitch GRP rooflight ridge detail

over the joint. The lap is formed by setting an aluminium strip or extrusion under the bottom edge of the panel, which laps over the top of the panel below. In addition to these standard junctions which form part of proprietary systems, panels are jointed with folded metal sheets, where unusual junctions are to be formed. An inner metal sheet is bonded to the junction of the panels to provide an inner seal and vapour barrier.

System details

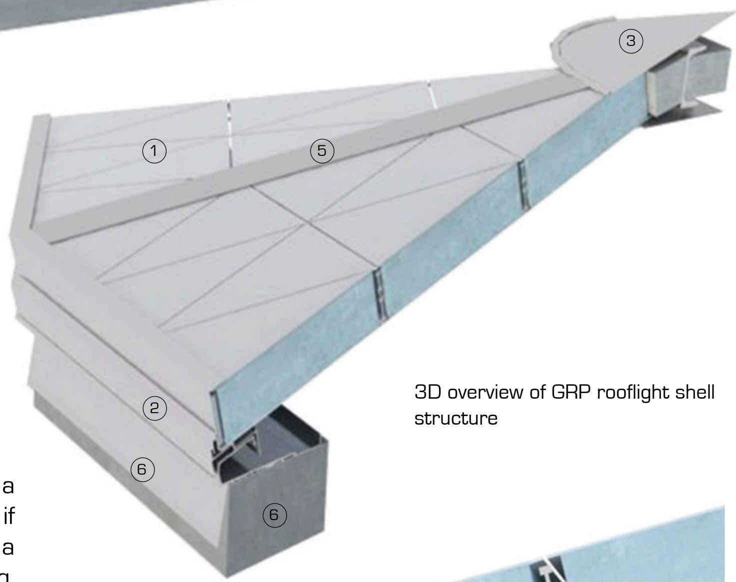
When a rooflight terminates in an eaves, an intermediary aluminium extrusion or folded sheet is used to form the junction. An outer EPDM or extruded silicone seal is used as an outer line of defence against rainwater penetration at the junction with the GRP roof panel. Drainage slots formed in the bottom of the aluminium closer piece drain away any water that passes through the outer seal. These drainage slots also take away any water to the outside from the drainage channels within the joints between panels that run down the slope of the roof. The GRP panel beneath the closer piece that forms a vertical part of the rooflight is formed by setting the panel behind a vertical aluminium strip that forms a lapped joint over the top of the panel, avoiding the possibility of rainwater passing through the joint. The gap between the aluminium closer and the GRP panel

Details
1. Translucent & insulated GRP roof panel
2. Thermally broken aluminium framing
3. Pressure plate
4. Supporting structure
5. Folded metal cover strip
6. Masonry/concrete wall



3D overview of GRP rooflight shell structure

3D detail of junction with external wall

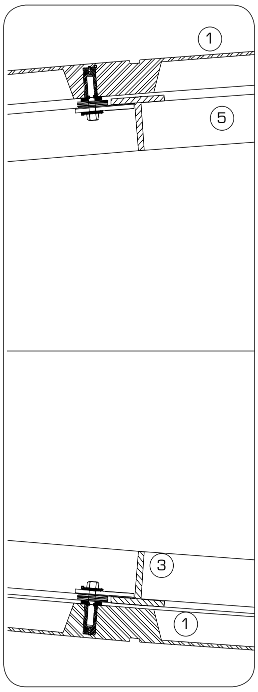


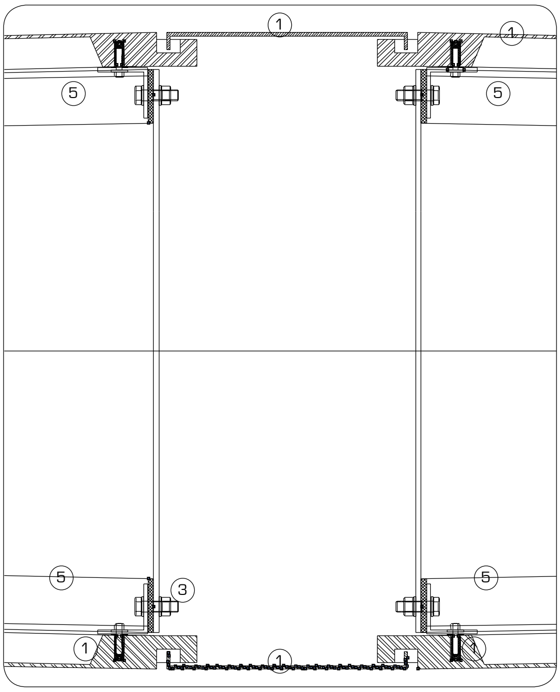
3D overview of GRP rooflight shell structure

is sealed with either an EPDM gasket, a proprietary tape or a silicone sealant. A metal gutter is fixed to the metal closer if required, but this is usually exposed unless it forms part of a fascia, such as the curved eaves used in profiled metal roofing, for example. In smaller rooflights the rainwater typically runs off onto the surrounding area of the flat roof.

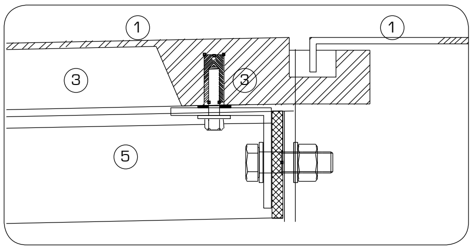
The gable ends of sloping GRP rooflights are formed with an aluminium flashing that is bonded, or mechanically fixed and sealed, to the metal edge frame to the side of the GRP panel forming the sloping panel, and to the top of the triangular-shaped vertical end panel. The sloping panel extends slightly forward of the vertical panels to give a thin edge to the roof, but alternatively the roof can terminate in a sharp edge, with a folded aluminium sheet or angle closing the gap between the panels. As with other panel to panel junctions, a waterproof membrane is set on the underside of the outer metal flashing as a second line of defence against rainwater penetration. The void between the panels is filled with mineral fibre quilt-type thermal insulation, which has the flexibility required to fill the irregular-shaped voids between GRP panels. An additional aluminium angle is used at the junction of the inner face of the panels to provide an additional seal and vapour barrier.

3D detail of junction with external wall

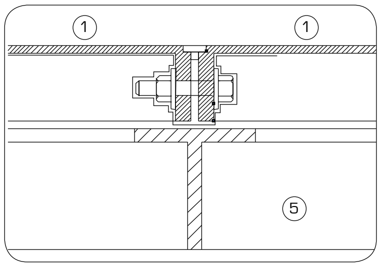




Vertical section 1:10. Panel to panel junction

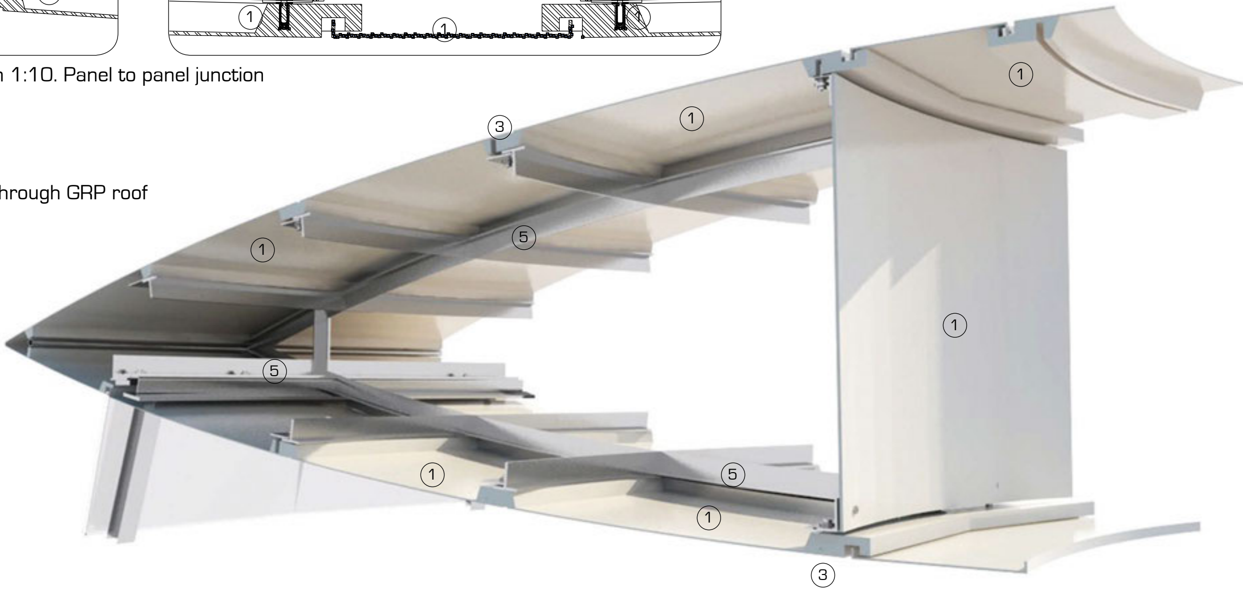


Vertical section 1:5. Panel to panel junction



Vertical section 1:5. Panel to panel junction

3D section through GRP roof panels



System design

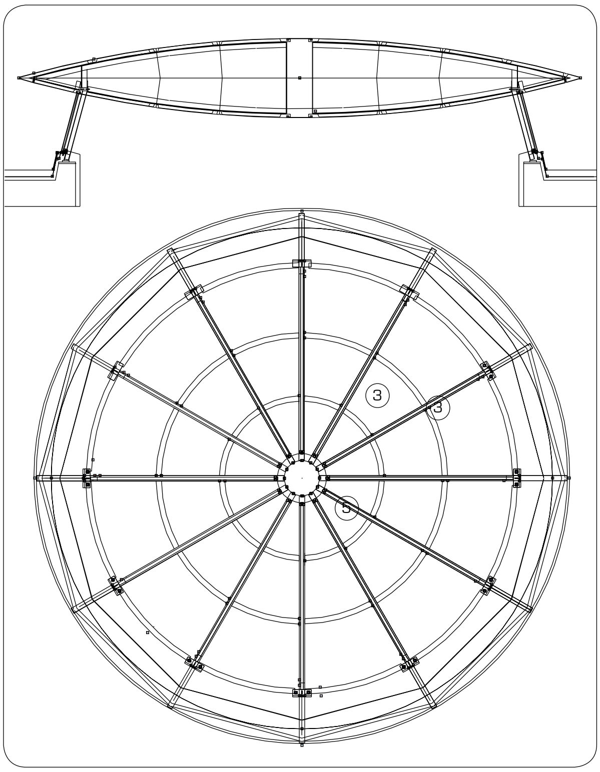
While glass reinforced polyester (GRP) rooflights, discussed in the previous section on rooflights, are made as panels which are joined to form translucent rooflights, opaque GRP panels can be made as monolithic, self-supporting shells, usually made from panel segments which are brought to site and bolted together. The segment sizes of GRP shells are made in sizes which are suitable for transportation by road, usually set upright on a trailer. The shells can then be lifted by crane into place as a completed assembly, which makes them quite different from roof structures in other materials.

The example shown is of a small shell for a rooflight. The shell consists of a set of segmented panels which are bolted together to form a roof shell of approximately 7.0 metres diameter, supported by an additional frame. Panels are made in a mould, usually from a single segmented panel type to form a complete rooflight. Moulds are usually made from plywood to create the shape and are then finished in GRP to create the negative shape of the panel being formed. GRP panels are fabricated by first applying a release agent to the mould to allow the finished panel to be removed easily, then thermosetting polyester resins are applied to the face of the mould with flexible fibreglass mat being laid into the resin, usually with rollers. The process of fabricating GRP panels is very labour intensive, but requires no expensive equipment, making panel production a craft-based technique rather than an industrial process. When the panels are released from the mould they are trimmed along their edges and ground smooth where necessary. An alternative method is to apply a mixture of resin and glass fibre particles as a spray directly into the mould. The mixture is applied to a thickness of 3mm to 5mm depending on the panel size required.

In the example shown, GRP panels are supported by a light metal frame beneath. The frame comprises steel or aluminium T-sections which are welded together to form a structure that supports the complete outer skin. The frame has curved members that radiate from the centre at the top to the edge and from the centre at the lowest point of the structure, back to the perimeter. The radiating 'spokes' of the wheel are held in place by T-sections that, in plan, form concentric circles. This 'bicycle wheel' form is supported near its perimeter by a metal ring beam that is set immediately above the glazing beneath the GRP roof. The ring beam is supported by posts that are fixed to the roof deck beneath.

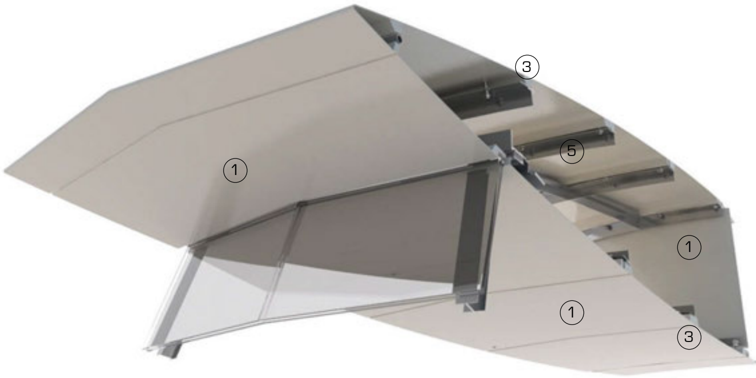
Details
1. GRP shell panel
2. GRP outer cladding panel
3. GRP structural rib
4. GRP thin panel with
   honeycomb core
5. Mild steel or aluminium frame

3-D overview of GRP shell



Horizontal and vertical sections 1:50.
Generic example of roof geometry

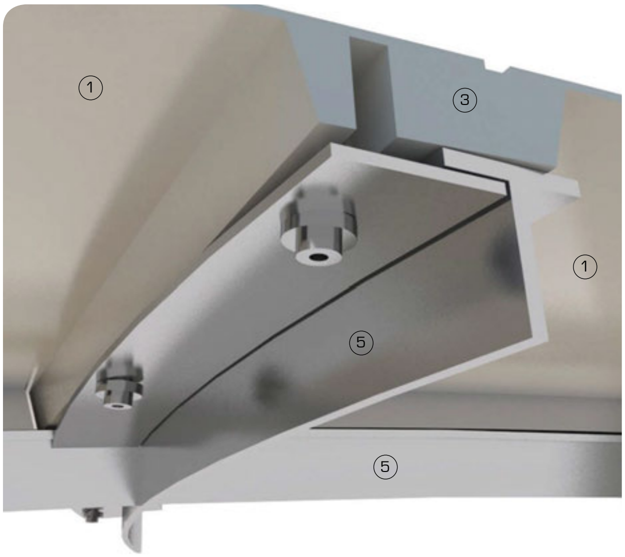
3D views of underside of roof



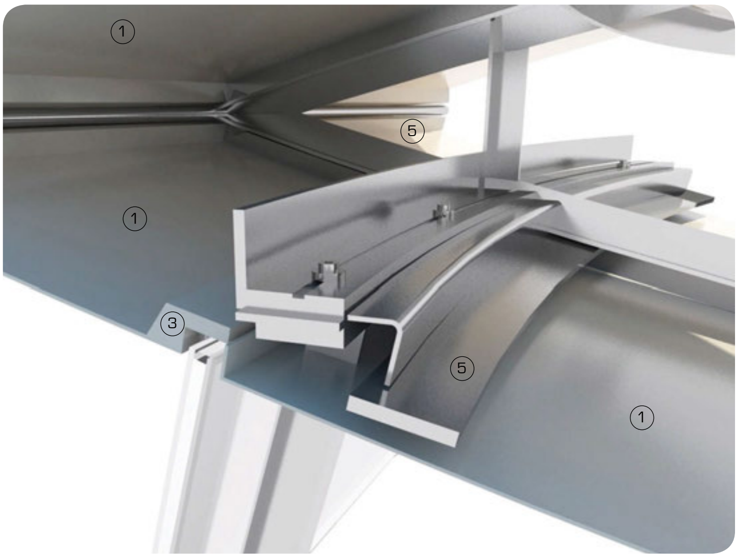
3D section through roof assembly

3D overview of GRP shell

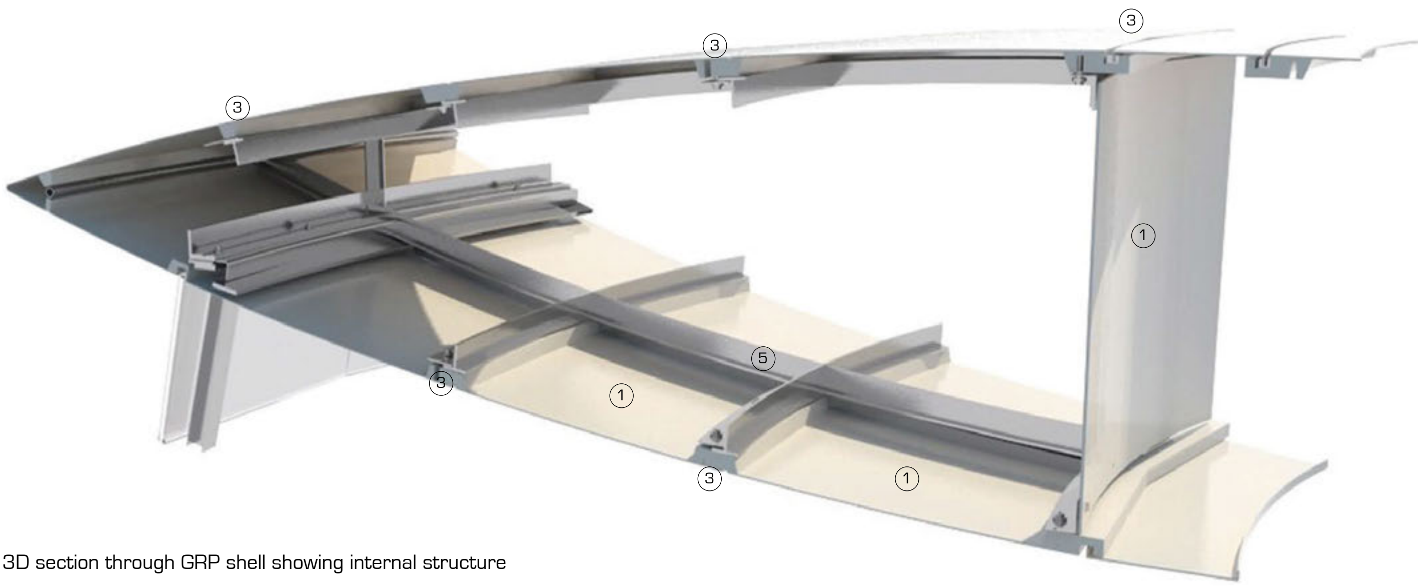
Details
1. GRP shell panel
2. GRP outer cladding panel
3. GRP structural rib
4. GRP thin panel with honey comb core
5. Mild steel or aluminium frame
6. Mild steel or aluminium truss
7. GRP flashing
8. Waterproofing membrane
9. Metal fixing bracket
10. Thermal insulation



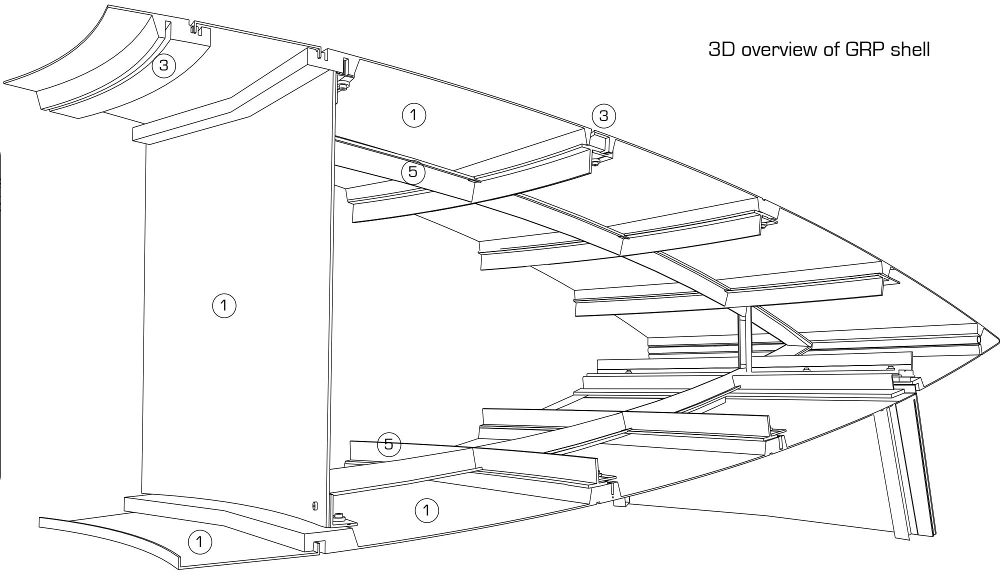
3D detail of GRP panel connection



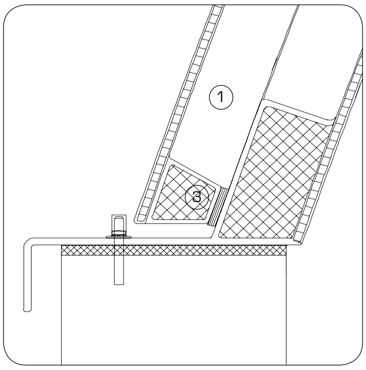
3D detail of GRP panel connection to supporting aluminium frame



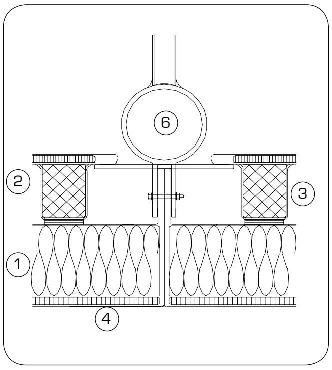
3D section through GRP shell showing internal structure



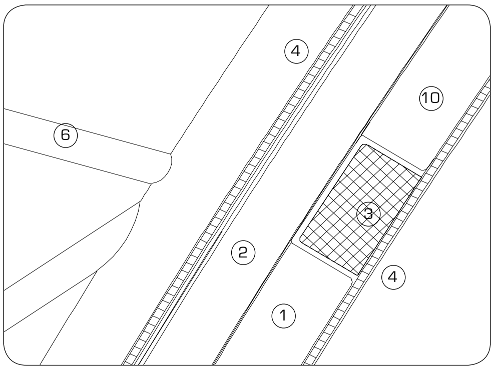
3D overview of GRP shell



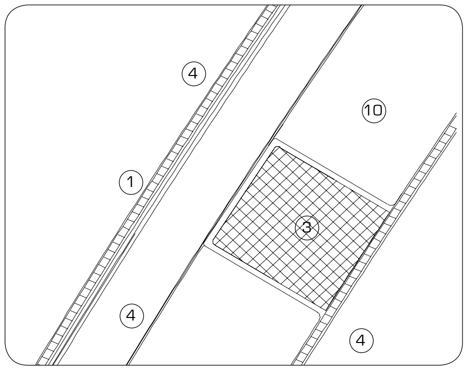
Vertical section 1:10. Junction at base



Horizontal section 1:10. Panel to panel junction



Vertical section 1:10. Panel to panel junction



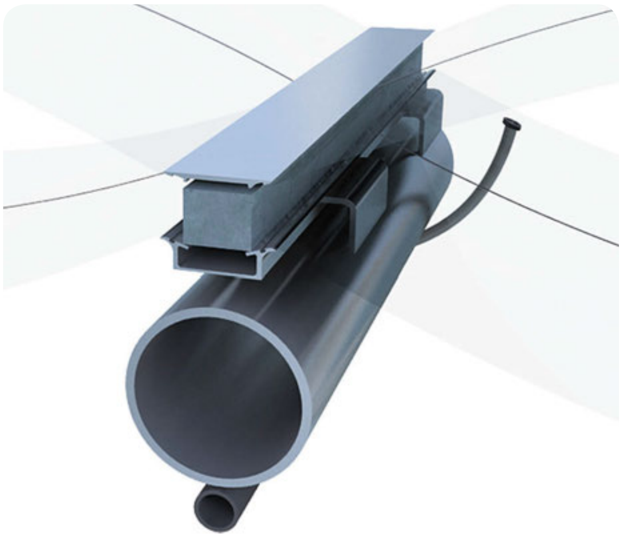
Vertical section 1:10. Panel to panel junction

System details

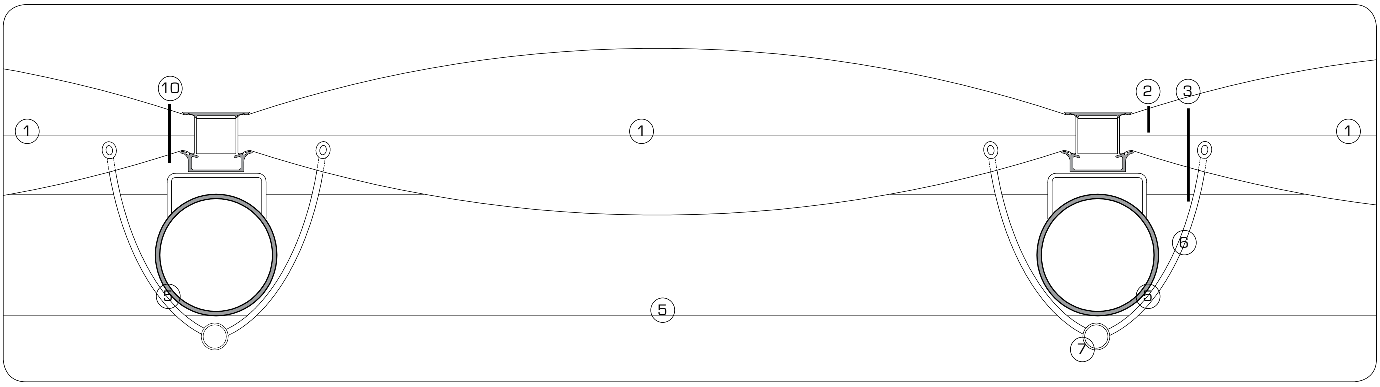
The metal frame is clad in prefabricated GRP panels which are bolted to the support frame on their internal face in order to avoid visible fixings. Panels are made with an outer skin of GRP around 5mm thick, with an overall panel depth of around 45mm for the panels sizes shown of 3500mm long and 1800mm wide. The GRP panels are stiffened by concentric ribs, around 120mm wide, but ribs on the edges are thin in order to facilitate their bolting together. Panels are secured with bolts which are fixed through the metal support frame into reinforcing ribs at the edges of the GRP panels. Joints between GRP panels are formed by butting panels up to one another and sealing the gap between the panels. The seal is formed in a continuous step profile on the long edges of each panel that creates a continuous groove at the joint between panels. The groove is filled with a lamination of glass fibre and resin to fill the groove to the level of the top of the panels. The external face of the GRP is then ground smooth, usually by a hand-held grinder, to achieve a uniform, smooth surface that conceals the joint lines. Finally, a paint finish is applied, usually as a spray, to give a smooth and reflective finish. Where pigments are applied to the top coat, or 'gel' coat, in the factory, a more limited range of colours is available. Thermal insulation is set on the underside of the shell, being bonded to the inner face of the GRP panels in order to achieve continuity of insulation.

Alternatively, the glass fibre ribs that form part of the shell to provide it with integral structural stability, could be made around 200mm deep to avoid the need for an additional steel frame. Panels would be bolted together to form a self-supporting GRP shell. Ribs would be made in solid GRP in order to allow them to be bolted together easily. Panels are joined and sealed on their external face in the same way as the example shown. Where panel segments converge at the top of the shell, a separate centre panel is used to create a smooth external finish. A central external panel avoids the difficulty of bringing up to 16 panels together at a single point which would make it difficult to achieve a smooth transition from one side of the shell to the other. In the example shown, a shadow groove is set around the joint between the central panel and the segments in order to avoid any misalignment between segmented panels from being visible. The perimeter joint of the panel can be filled and sealed using the method described earlier, with additional grinding required on site to ensure a smooth finish.

The internal part of the shell, on its underside, has the same panels with the same finish but without any thermal insulation, which is typically set around the outer edge of the shell in order to keep temperatures within the void close to those within the building. Close to the edge of the shell, on the underside, the joint between the top panel, which curves around the edges, and the adjacent panel underneath, has a groove formed along the joint to serve as a drip. Windblown rain will still be pushed along the underside of the soffit panel, but the drip reduces the amount of water that runs down to the glazing below.



3D views showing joint between ETFE cushions showing air supply pipes



Vertical section 1:20. Connection between ETFE cushions

System design

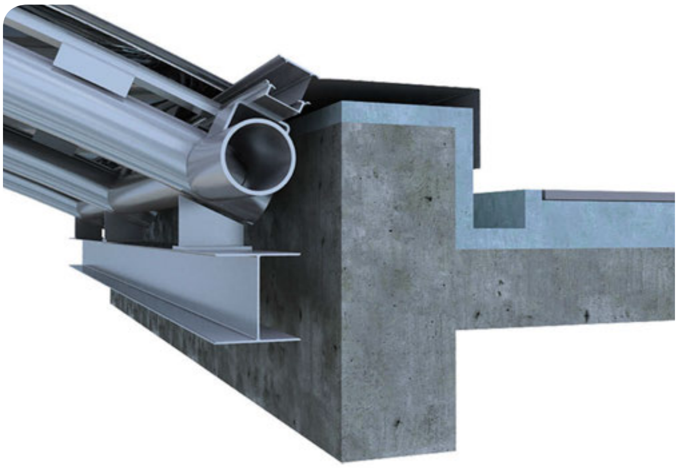
Fabrics used as roof membranes have the advantage of being light in weight, strong in tension and durable, and have the ability to be cut to different shapes and joined together economically, which is difficult to achieve so easily with metal and is very expensive to achieve with curved glass. Roof membrane fabrics are used in tension structures, either by stretching the material, or 'prestressing' the membrane, between structural supports or, alternatively, by supporting the material pneumatically in inflated structures. The use of fabric membranes in prestressed roofs is discussed in the next two sections on single layer fabric membranes. This section considers ETFE cushions, also called 'pillows' or 'foils', which are the most common application of inflatable fabric roofs.

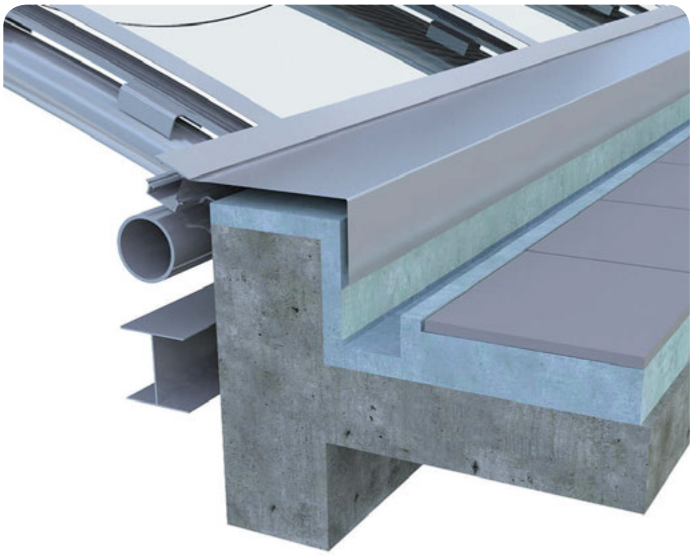
Although large scale self-supporting inflatable roof structures are in use, particularly for covering sports stadiums, they remain structurally stable only while air is being supplied to the structure. If the air supply is interrupted, the complete roof structure deflates. In smaller scale applications, air-filled cushions remain in place when the air supply fails or is switched off when used as non-loadbearing panels. This type, where ETFE sheet is used to make panels formed as air-filled 'cushions', provide highly transparent, lightweight and resilient roofs that have thermal insulation values similar to those of double glazed units. The complete ETFE cushion assembly is supported by a structural frame beneath, with mild steel, aluminium and laminated timber all being used to suit the design.

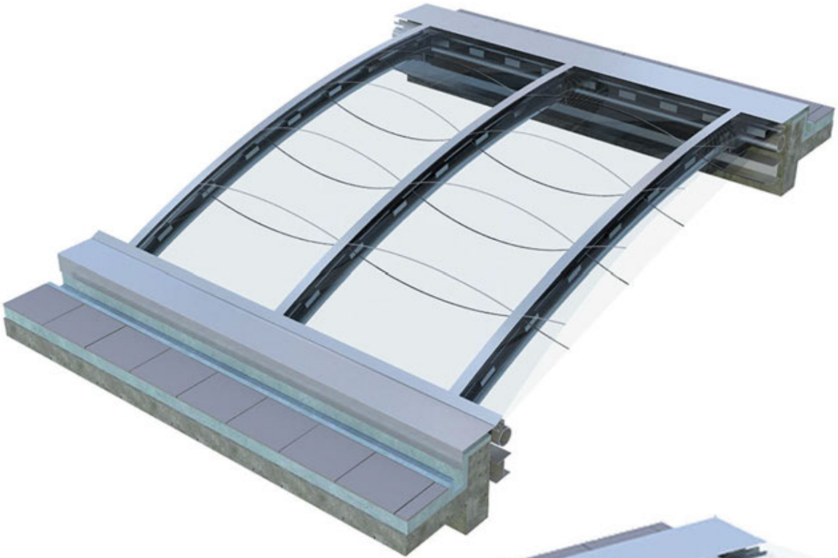
ETFE cushions usually consist of a minimum of two layers of ETFE sheet which are set back to back to form a flat panel and are sealed at the edges. The void within the cushion-shaped panel is inflated with air to a pressure that varies with cushion size and the manufacturer's proprietary system to provide structural stability to the panel. The increased air pressure stretches, or 'prestresses', the outer membranes, giving ETFE cushions their characteristic curved shape. The cushions are held in place by clamps that form a frame around the cushions in the manner of glazed rooflights. The clamping frames are then supported by a mild steel structure formed typically as box sections or tubes. Cushions typically have three layers that form two chambers. The two chambers are linked by a hole formed in the middle (flat) membrane in order to allow air to pass to both chambers from a single air supply, and to ensure that the air pressure in both chambers remains equal. This three-layer cushion provides a U-value of around 2.0 W/m2K, which is similar to a double glazed unit used in glass roofs.

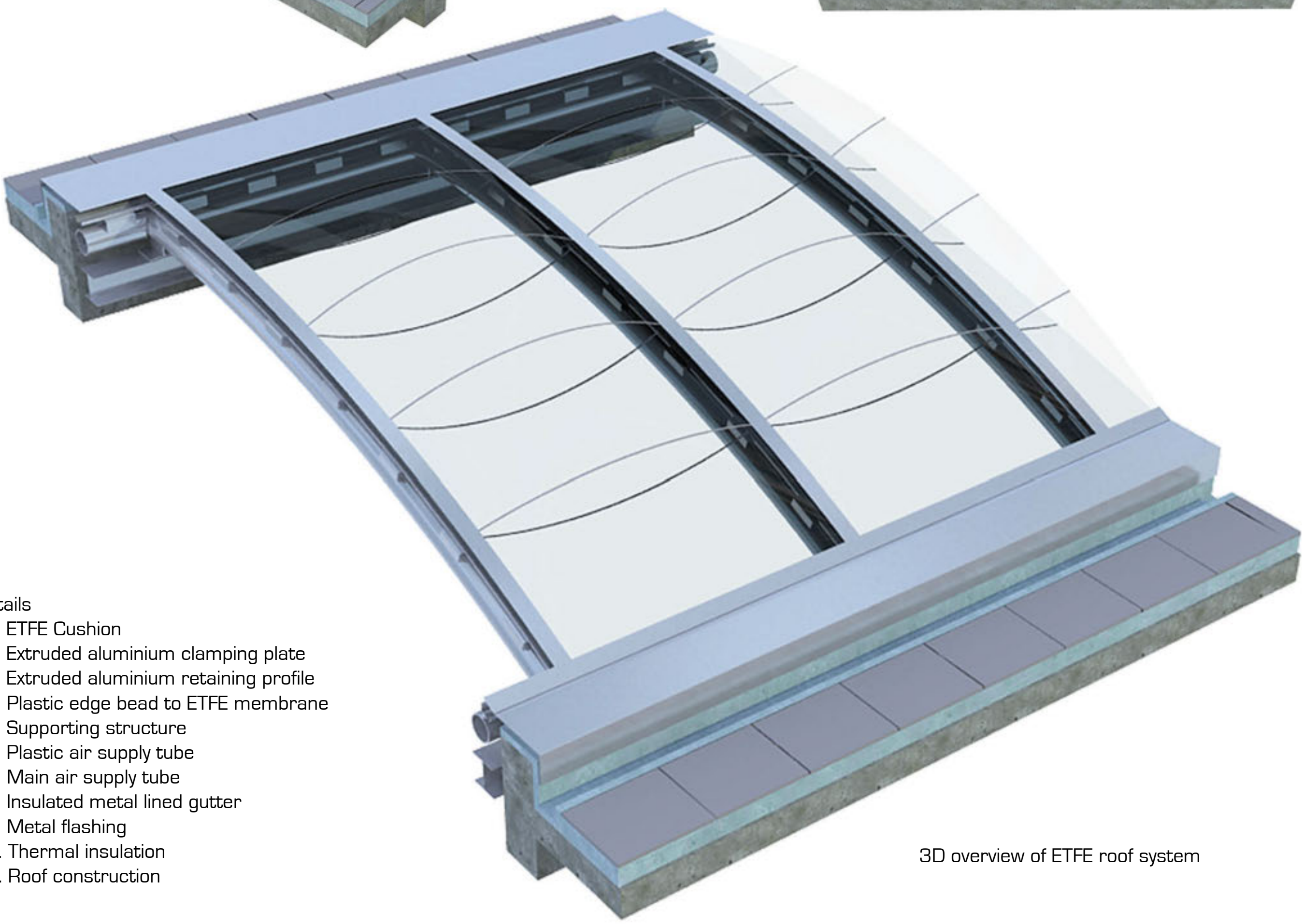
System details

Air is supplied to cushions from rubber pipes or flexible plastic pipes that are connected to the underside of the cushion near the clamping assembly. Pipes are usually of around 25mm diameter, and are connected to a larger pipe that supplies the air to all the cushions either side of a single structural support. This main pipe is also usually made from plastic and can be concealed within the supporting structure, being only up to a diameter of around 60mm. The air supply, which maintains the air pressure within the cushions at a constant level, is supplied by electrically powered fans with air filters (to





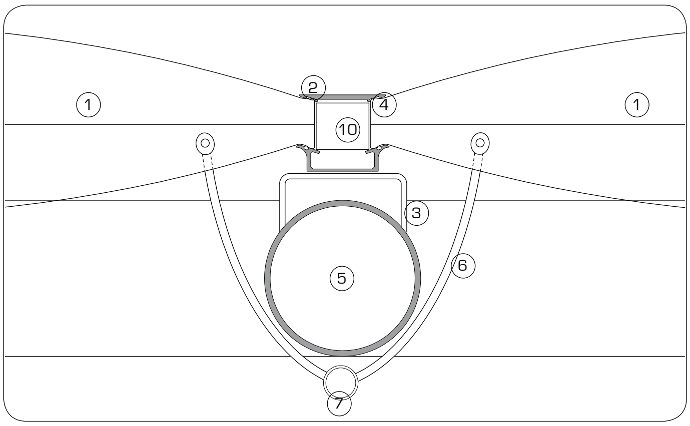




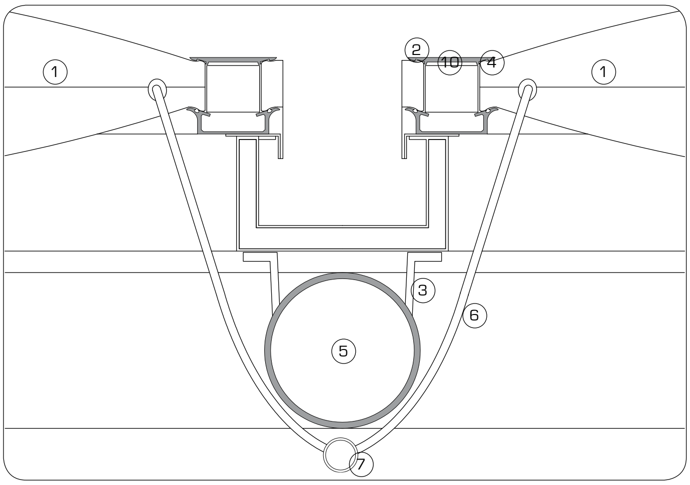
Details
1. ETFE Cushion
2. Extruded aluminium clamping plate
3. Extruded aluminium retaining profile
4. Plastic edge bead to ETFE membrane
5. Supporting structure
6. Plastic air supply tube
7. Main air supply tube
8. Insulated metal lined gutter
9. Metal flashing
10. Thermal insulation
11. Roof construction

3D overview of ETFE roof system

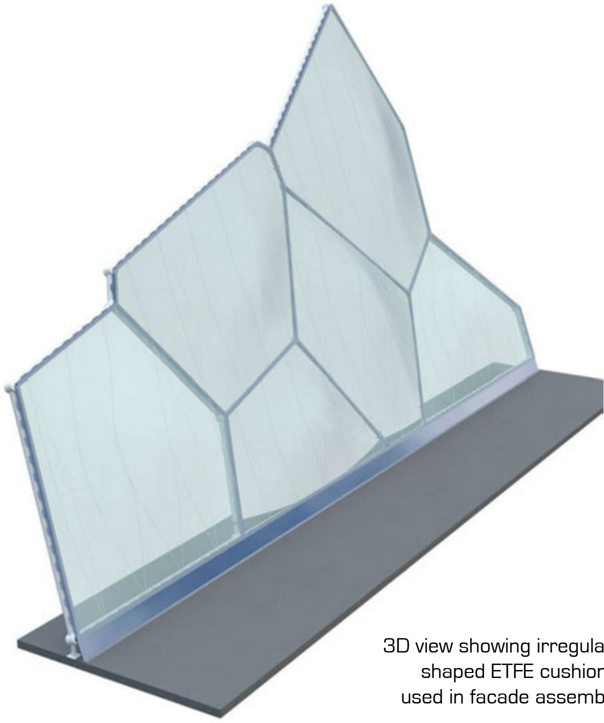
3D detail of cushion to cushion air supply



Vertical section 1:10. ETFE clamping detail



Vertical section 1:10. ETFE clamping detail with insulated gutter



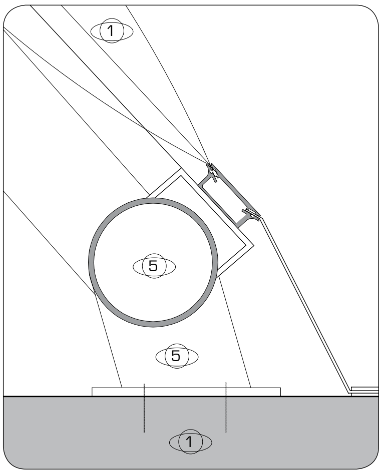
3D view showing irregular-shaped ETFE cushions used in facade assembly

3D detail of junction between ETFE facade and ground

avoid the passage of dust), as used in mechanical ventilation systems within buildings. The humidity level of the air is usually controlled to avoid the possibility of condensation forming within the cushions. Once the ETFE cushions have been inflated, air is supplied to the cushions for only around 5–10 minutes per hour to compensate for loss of air pressure caused by leaks from cushions or from air supply pipes.

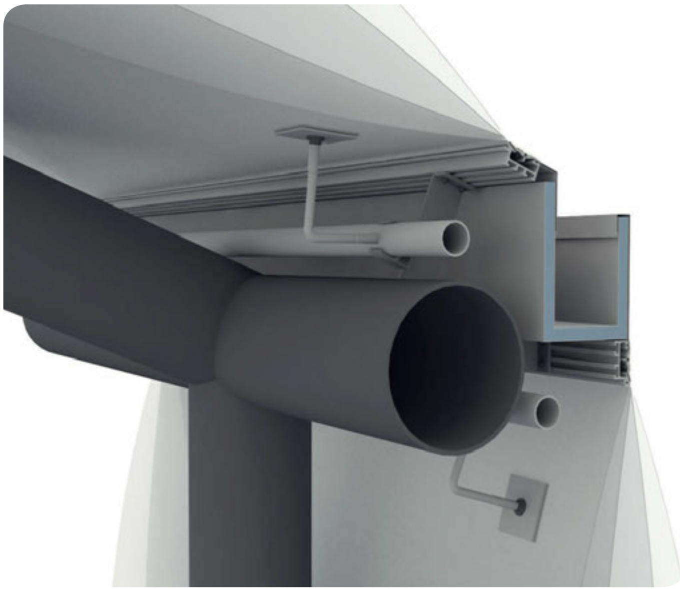
If air pressure within the cushion is lost as a result of damage to one of the outer membranes or from loss of air pressure in the supply pipe, the cushion deflates to its flattened shape. As wind pressures are applied to the external face of the cushion, the outer skin will deflect either inwards or outwards as a result of the positive or negative pressures. This does not usually cause damage to the cushions before the air supply is restored. Some manufacturers' systems have one-way valves to prevent loss of air pressure from the cushions back to the supply pipes.

ETFE cushions are usually fabricated in the workshop but can be assembled on site to suit project conditions. The material is manufactured in rolls of considerable length but of a width of around 1.5 metres. For this reason, ETFE cushions are often made with spans in widths of around 3.0 metres to 4.0 metres between clamped frames, in lengths up to between 15 - 30



Vertical section 1:10. Junction at base

Details
1. ETFE cushion
2. Extruded aluminium clamping plate
3. Extruded aluminium retaining profile
4. Plastic edge bead to ETFE membrane
5. Supporting structure
6. Plastic air supply tube
7. Main air supply tube
8. Insulated metal lined gutter
9. Metal flashing
10. Thermal insulation
11. Concrete slab

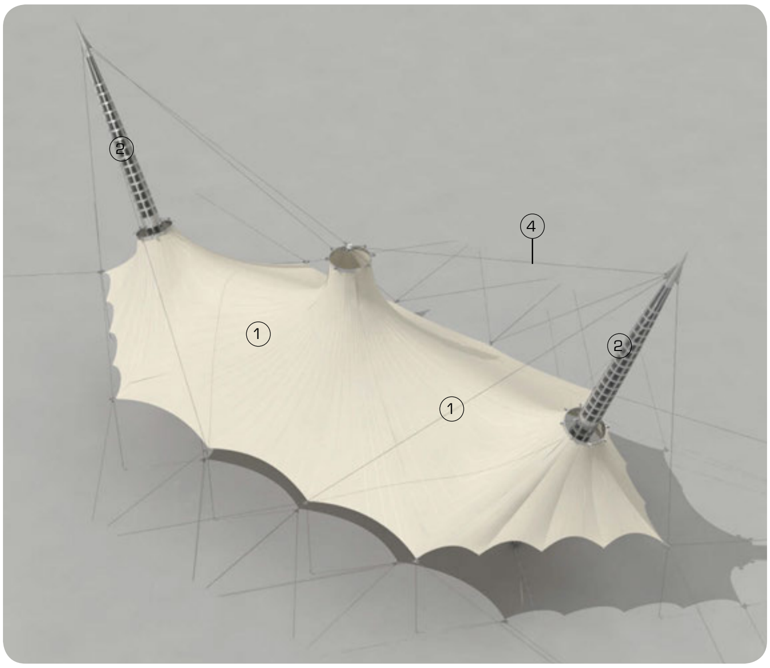


3D detail view showing underside of ETFE roof panel at roof-wall junction with location of air-supply pipes and gutter

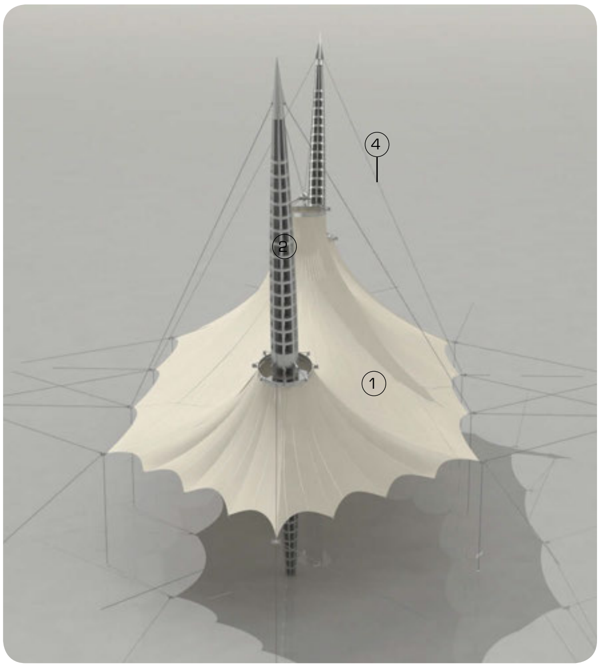
metres, but lengths of up to 60 metres have been used. Larger cushions are made by welding sheet together in the workshop to form wider sheets for cushions that vary from the rectangular form created from a standard width of ETFE sheet. Cushions of up to around 7.0 x 7.0 metres have been made in a variety of shapes from circles to hexagons using a hot welded process undertaken in the workshop. Larger cushions sometimes use a net of connected cables to provide additional restraint.

The cushions have an edge bead, typically in plastic, which is used to retain the panel in its supporting frame. The cushion is set into a clamping frame, usually made from extruded aluminium, that holds the panel in place by clipping it into an aluminium profile, then holding it in place with an aluminium pressure plate that clamps the edges. The complete assembly usually performs in a similar way to the framing used for glazed roofs, with a drained and ventilated inner chamber that serves as a second line of defence against rainwater penetration. Any rainwater that passes through the outer clamping plate is drained away in grooves formed adjacent to the edges of the ETFE cushions, the water being drained back to the outside of the roof. The clamping assembly is typically around 100mm wide, which is wider than that used for glazed roofs, but less framing is required than that used on glazed roofs .

3D sectional views showing ETFE roof and wall panel construction with steel tube support structure

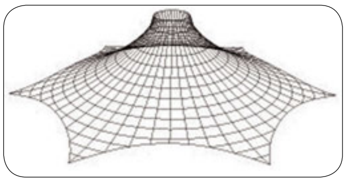


3D overview of cone shape roof with tension cable support.

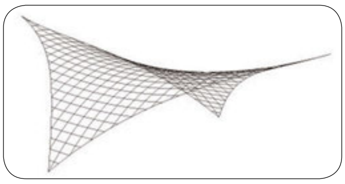


3D overview of cone shape roof with tension cable support.

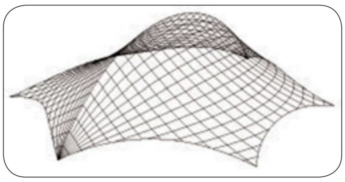
Tensile roof shape types:



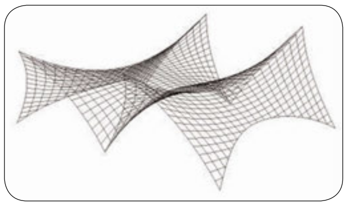
1. Cone



2. Saddle



3. Arch



4. Wave

System design

The advantages of single membrane fabric roofs are their smooth curves, typically with different, in opposite directions, and thin, sharp edges that provide translucent roofs allowing diffused daylight to pass through them. They use their curvature as a method of tensioning the membrane against a supporting structure, which is typically a mixture of mild steel tubes and stainless steel cables.

In a fabric roof the membrane is structurally modelled so that the resultant form developed between architect and structural engineer distributes the tensile forces within the membrane without over-tensioning some parts and under-tensioning other parts of the membrane, with the resulting design resisting all load combinations in their different directions. This work is usually developed in the form of a computer model, either by specialist structural consultants or by manufacturers as part of the design development process. The minimal surface form must also be suitable for draining away rainwater, which forms another aspect of design development together with the treatment of interfaces with adjacent areas of roof and external wall. The resulting form is designed to keep all parts of the fabric membrane in tension, not just from the supporting structure but from imposed loads; mainly wind loads. Wind pressures are resisted by re-distributing the forces within the fabric membrane. Any areas of the fabric roof that go into compression as a result of slackness in the membrane reveal themselves as creases in the material.

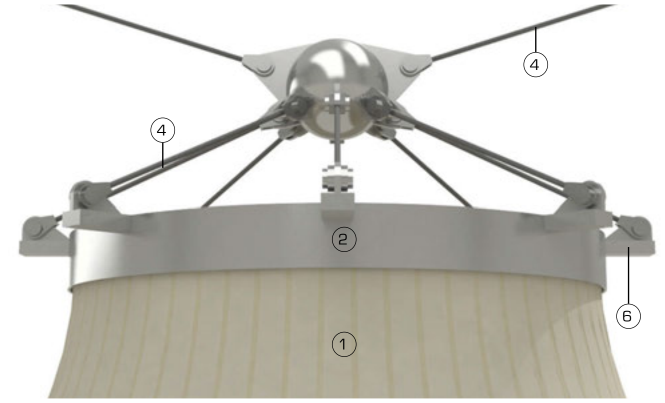
Both the cone-shaped example in this section and the barrel-shaped example in the following section make use of an internal steel structure that supports part of the membrane, to tension it in some areas with roof edges where the material is held and tensioned, either at points or with continuous clamped fixings similar to those described in the previous section on ETFE cushions. Generally speaking, the high points of the supporting structure take up the downloads from the membrane and imposed loads (mainly wind loads) and the lower points at the edges take up the effect of wind uplift. In shallow sloped roof membranes, more of the structural loads are taken by the edges or points at the base, often resulting in large columns or posts being required at these points. The distribution of loads within the fabric roof design is revealed in the supporting structure, which can be as visually lightweight and elegant as the fabric membrane itself, or can become visually heavy which can detract from the intended lightweight effect of the membrane. Where roofs transfer forces to an adjoining structure, rather than contain the loads within their own supporting frame, the visual effect on the adjoining structure is balanced with the requirements of the membrane roof and its own frame. As imposed loads such as snow or sand can cause permanent stretching of the fabric membrane, the form of the roof and its associated slopes are made sufficiently steep to avoid creating areas or pockets on the fabric roof where they can collect.

System details

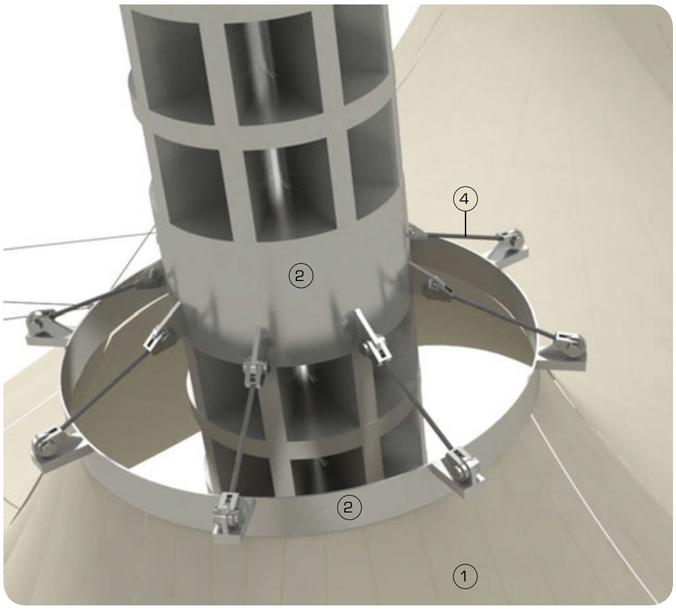
The two most common fabrics used are PVC-coated polyester fabric and PTFE-coated glass fibre fabric. Both are woven cloth

Details

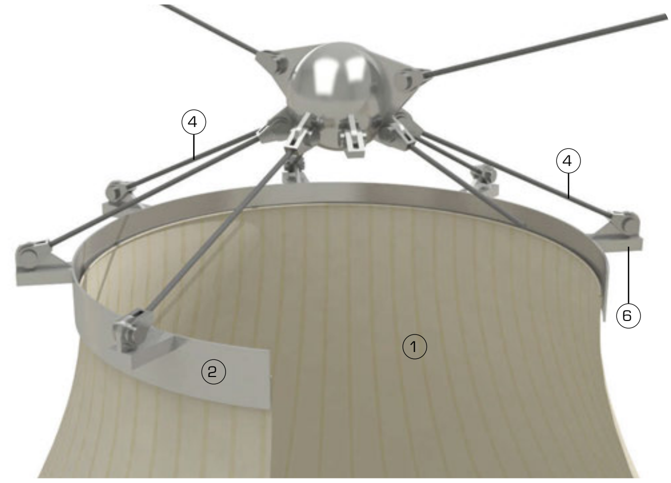
1. Fabric membrane panel
2. Supporting mild steel structure
3. Extruded aluminium clamp
4. Stainless steel cable
5. Membrane hood
6. Plastic edge bead to membrane panel



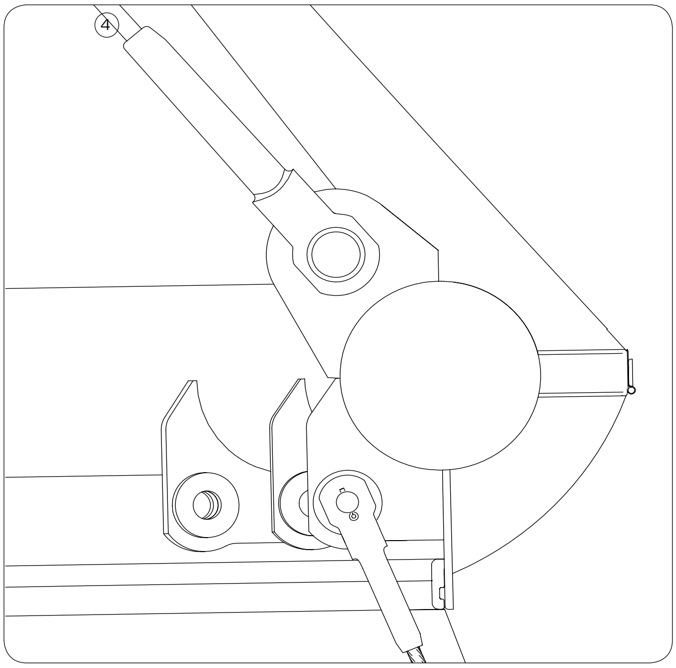
3D detail of edge ring supported by tension cables



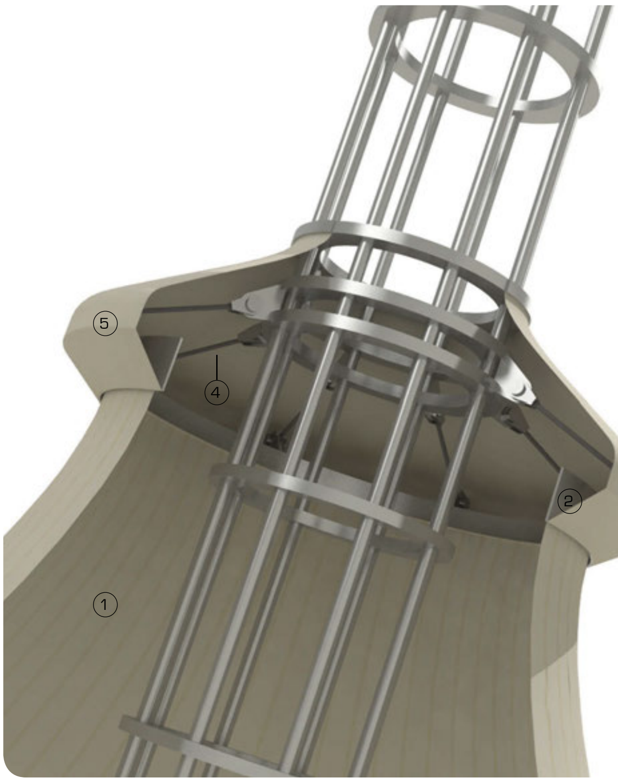
3D detail of alternative pinnacle condition with membrane hood



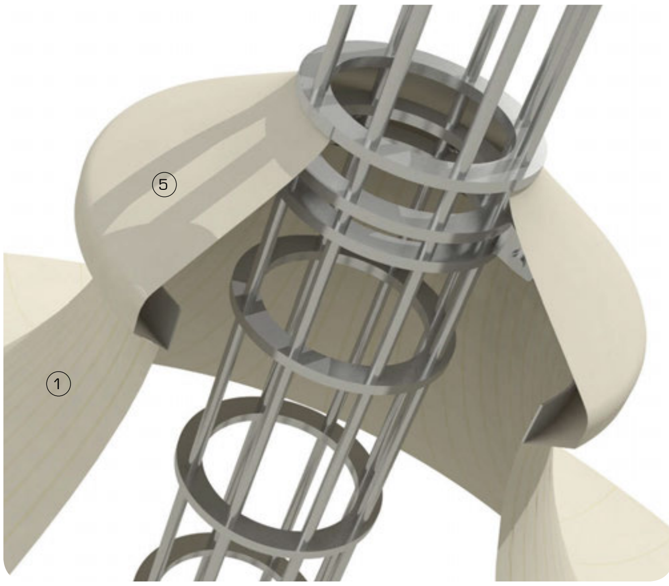
3D detail of edge ring supported by tension cables



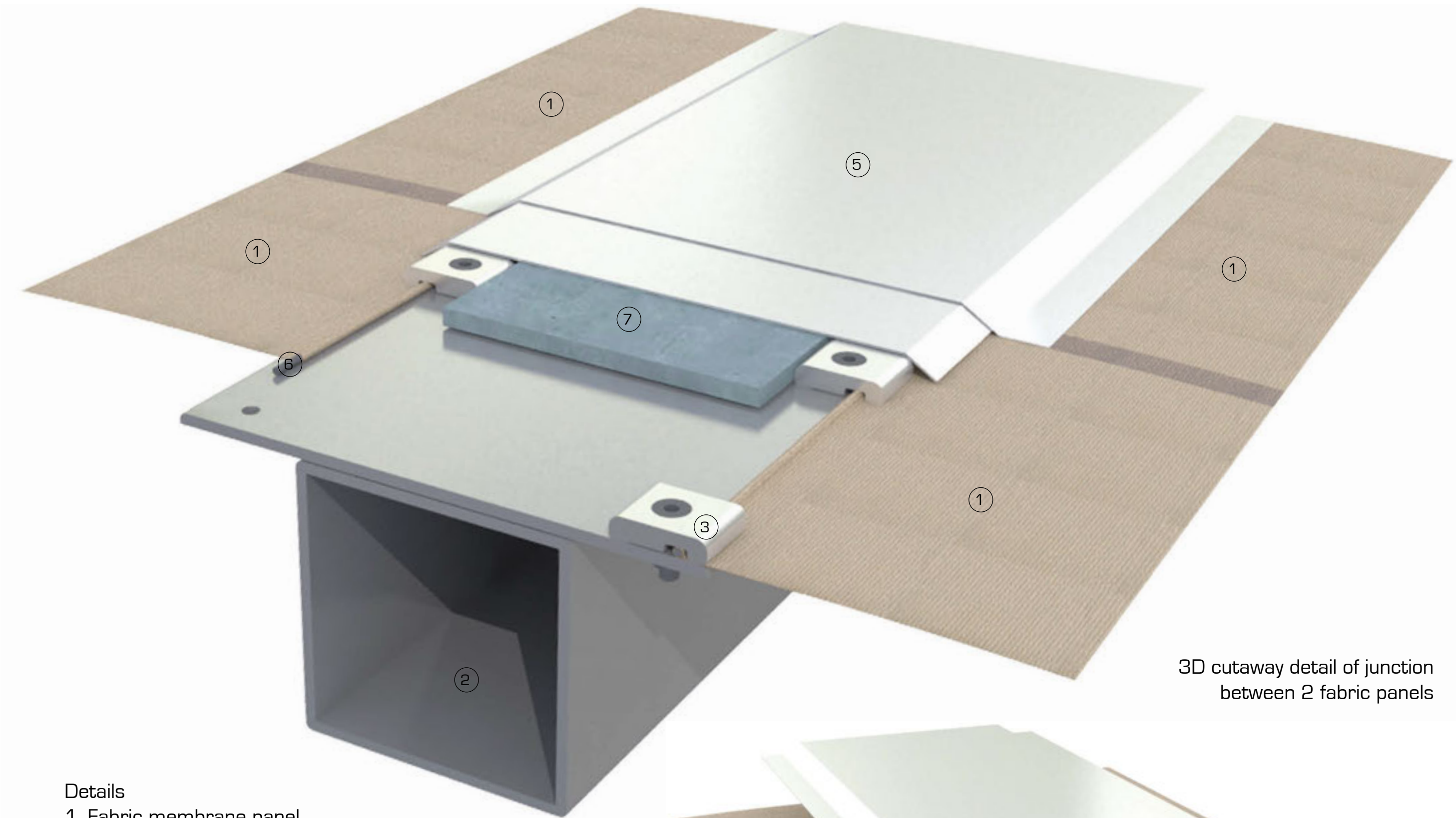
Vertical section 1:5 Clamping ring with membrane skirt



3D detail of cone top with protruding structural support



3D detail of cone top with protruding structural support

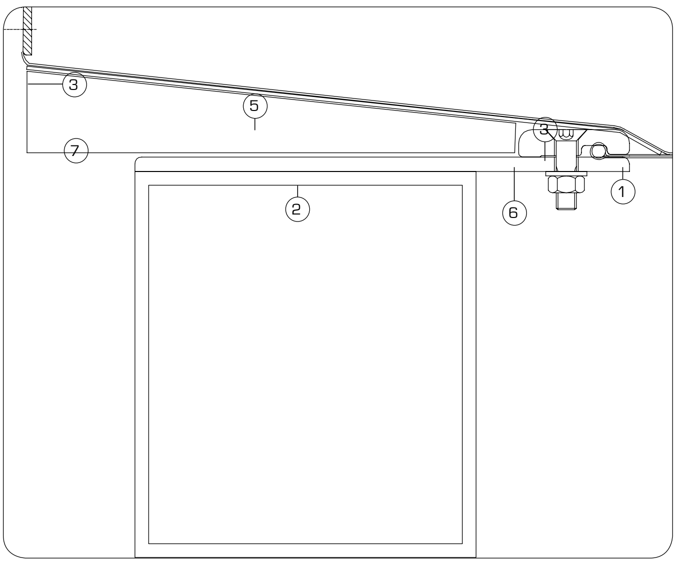


3D cutaway detail of junction
between 2 fabric panels

Details
1. Fabric membrane panel
2. Supporting mild steel structure
3. Extruded aluminium clamp
4. Stainless steel cable
5. Membrane hood
6. Plastic edge bead to membrane panel
7. Thermal Insulation

3D exploded detail of junction
between 2 fabric panels

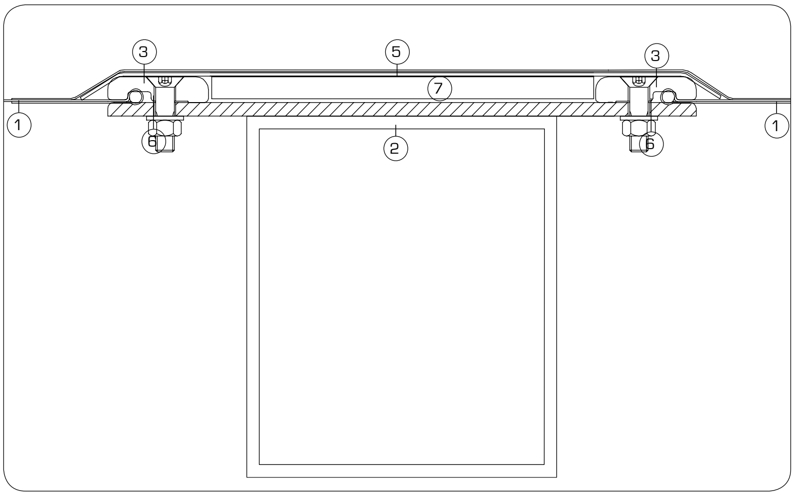
3-D detail of junction between 2 fabric panels



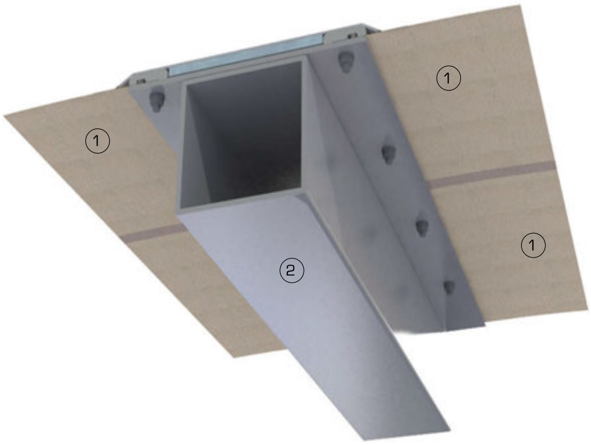
Vertical section 1:5 Edge of roof at abutment

materials which are protected by coatings, usually applied on both sides. Other open-weave materials are used as solar shading only, and are manufactured without protective coatings. These are made from polymer threads, sometimes with a protective coating applied to the manufactured thread itself, to increase the life expectancy of the material. In all these woven materials the strength of the fabric can be different in the two directions in which the 'cloth' is woven. When selecting a material, the strength of the' warp' threads running the length of the material is compared to the 'weft' threads running the width. In most commonly used roof membranes, the tensile strengths of the warp and weft directions are similar, but these need to be checked when the material type is chosen.

Most fabric roof materials imitate the appearance of natural canvas, but this material is used only where its appearance and individual texture is considered to be the most important feature. Natural canvas is less stable than synthetic fabrics when used in tension structures, and is difficult to clean. A modified acrylic canvas material, with a similar texture to natural canvas, is sometimes used for its greater dimensional stability. Neither material is suitable for long span fabric roofs.



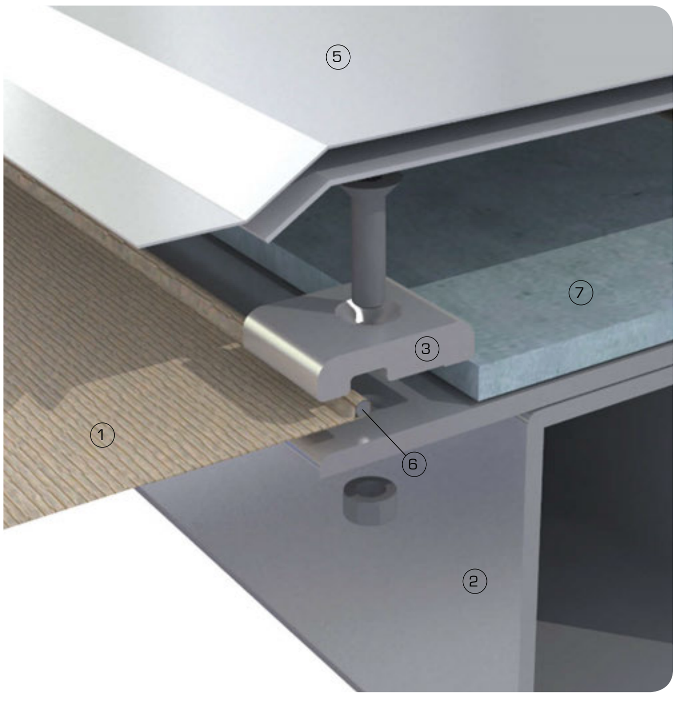
Vertical section 1:5 Junction between panels



3D detail of junction between 2 fabric panels

Fabric roofs are highly susceptible to damage from sharp objects. Small cuts in the membrane can be repaired with patches made from the same material which are glued into position. Larger tears are repaired with hot air welders, usually undertaken by the specialist contractor who installed the fabric roof. Large repairs are visible, and panels are replaced where visibility is the most important consideration. Since large tears can affect the overall structural performance of the membrane, the complete membrane is sometimes removed for another panel to be stitched or welded, and re-coated in the factory.

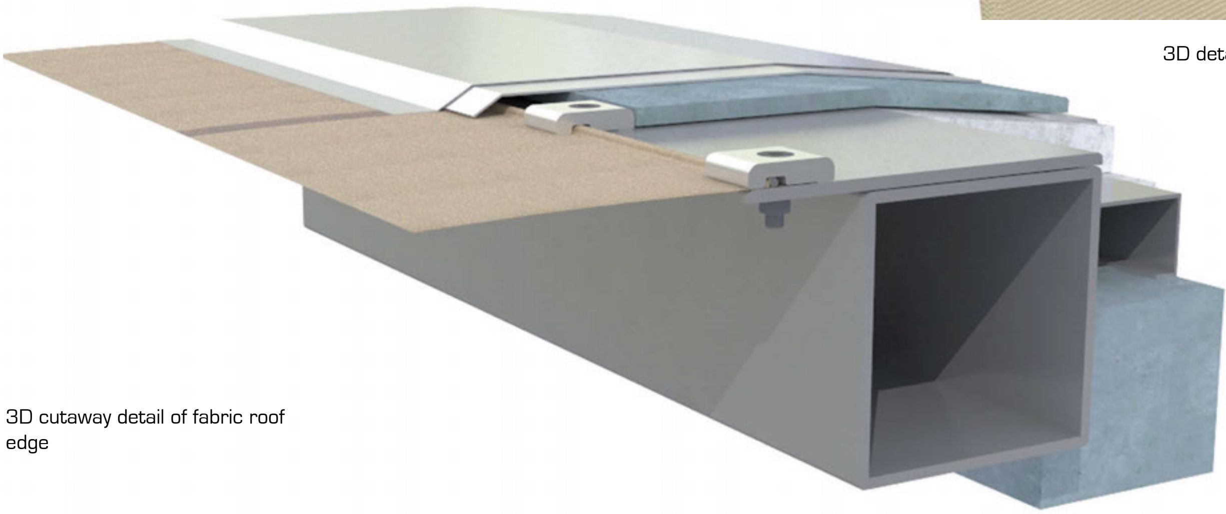
The outer surfaces of fabric roofs are cleaned with soft brushes that wash the membrane surface, the work being done typically from either a mobile platform or by rope access cleaners (abseilers) who are attached in harnesses and suspended from cables attached to a steel bracket anchor point on the top of the membrane roof. The anchor point forms part of the steel or timber supporting structure to the membrane roof. Cleaning is also an important consideration in areas of high humidity where there is a higher risk of mould forming on the surface of the fabric which can cause permanent staining. Regular cleaning prevents mould growth. PVC/polyester is more susceptible to mould growth than PTFE/glass fibre fabrics, essentially because the latter has lower surface friction.



3D exploded detail of clamp and membrane skirt

Details
1. Fabric membrane panel
2. Supporting mild steel structure
3. Extruded aluminium clamp
4. Stainless steel cable
5. Membrane hood
6. Plastic edge bead to membrane panel
7. Thermal Insulation
8. Perimeter wall build up
9. Fixing clip
10. Aluminium clamp assembly

3D detail of edge clamp

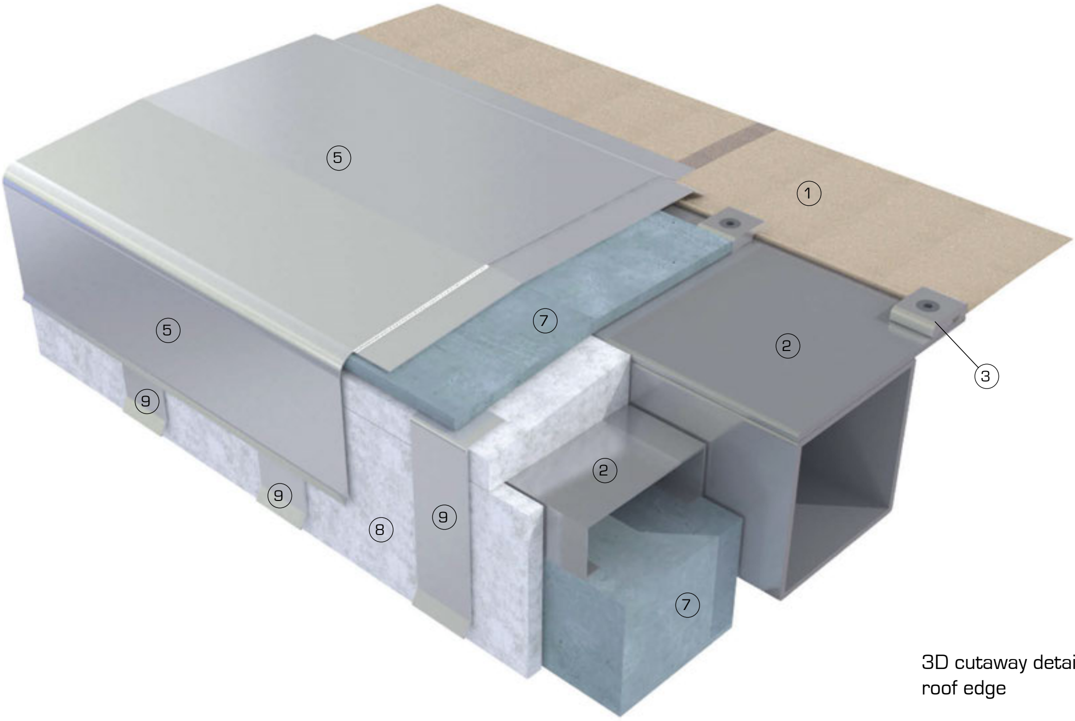


3D cutaway detail of fabric roof edge

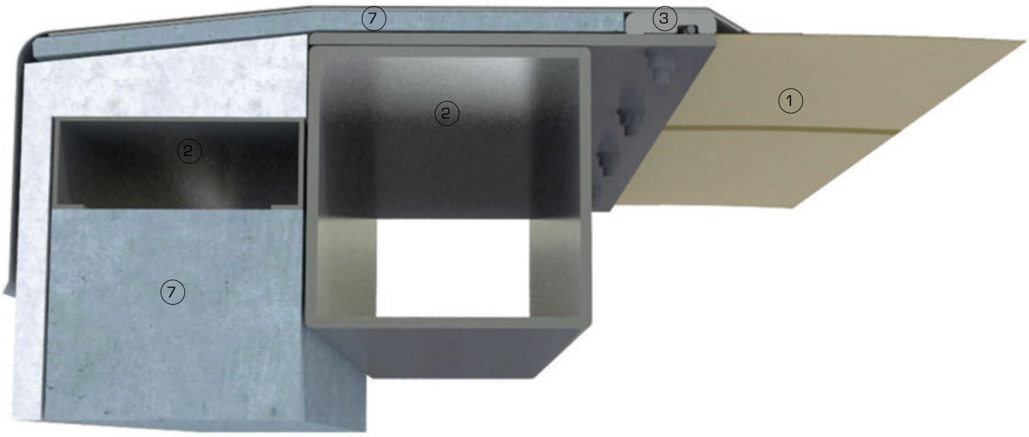
System design
Roof membranes are made from individual panels of fabric which are cut from sheet material, the curved forms of membranes being formed from flat sheet material. The conical-shaped example shown here is made from panels with edges that curve inward, while the barrel-shaped roof shown in the next section is made from panels with edges that curve outward. PVC coated polyester fabric is made in widths from 2000 - 3000mm, in thicknesses up to 1.2mm, while PTFE coated glass fibre fabric is made in widths up to around 5000mm in thicknesses up to 1.0mm. Large panels are usually cut by CNC cutting machines, with small pieces cut by hand, but even small pieces are now being made increasingly by a cutting machine. Fabric panels are usually made slightly undersized to allow for the stretching of the material when it is under tension as a roof membrane. Fabric panels are joined together with lapped seams which are either sewn, welded, bonded or joined in a combination of stitching and welding, with all processes being carried out in the workshop. The width of the lap, which is visible from below the roof as well as from outside the building, is determined by the structural forces on the membrane with higher loads requiring wider seams.

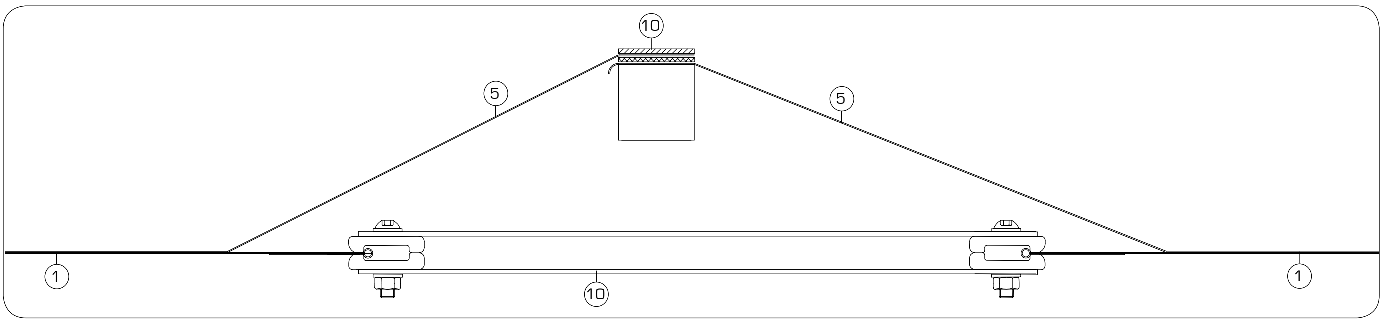
Edges of membranes are usually either gently curved or straight. Curved edges are formed with a cable held in a continuous pocket at the edges of the membrane. An alternative detail used in PTFE/glass fibre canopies is to have an exposed cable connected to the clamped edges of the membrane with a series of stainless steel link plates. Straight edges are usually formed with an edge bead made from a flexible PVC or EPDM rod in a small pocket. This reinforced edge is then held captive within an aluminium clamping plate assembly similar to that used for ETFE cushions, or alternatively in a luff groove extrusion.

System details
Cable restrained curved edges to fabric roofs usually follow a circular or catenary shape. A sleeve is formed by folding the membrane back over itself and stitching or welding it to form a continuous pocket in which a stainless steel cable is inserted. A 25mm diameter stainless steel cable is typical, depending on the structural forces. A strip of membrane material or plastic is set between the cable and the membrane to allow the two to move independently without abrasion occurring. A reinforced plastic strip is sometimes added into the pocket but this is not visible from either above or below the roof. Straight clamped edges use clamping plates, around 100mm wide set back to back and bolted together, which comprise two flat, grooved plates rather than the clamping plate and supporting extrusion used at joints between panels. Where two cables meet at membrane corners or points, they are usually fixed to a single mild steel plate. The cable is fixed into a stainless steel cable fixing which is secured with a pin connection back to a supporting steel plate. The corner of the membrane is cut to form a curved end. Additional straps are sometimes added to ensure that the membrane does not slide away from the corner.

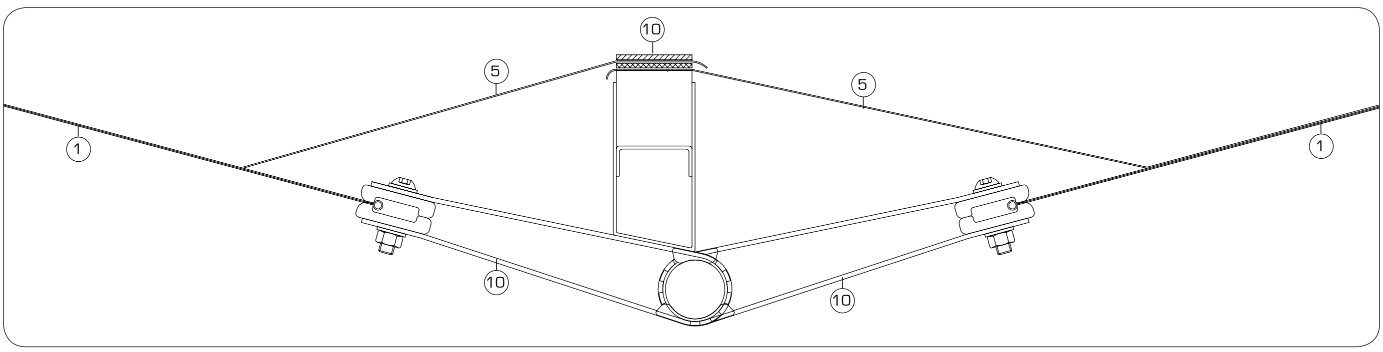


3D cutaway details of fabric roof edge





Vertical section 1:10. Junction of adjacent fabric membrane meeting at same angle

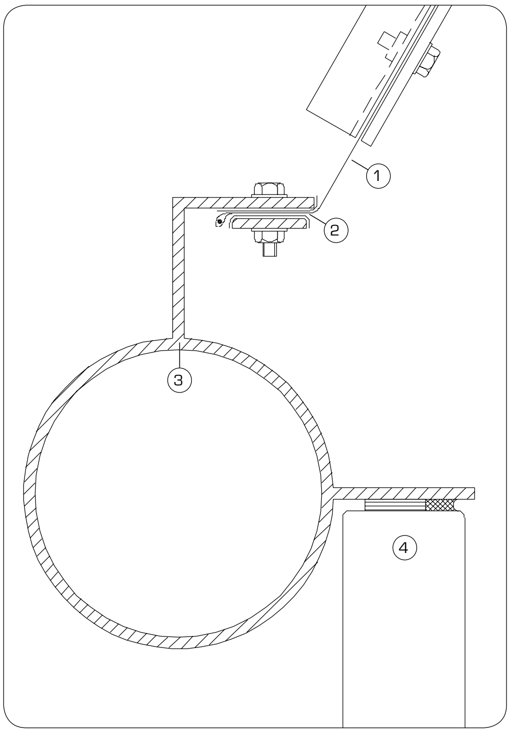


Vertical section 1:10. Junction of adjacent fabric membrane meeting at same angle

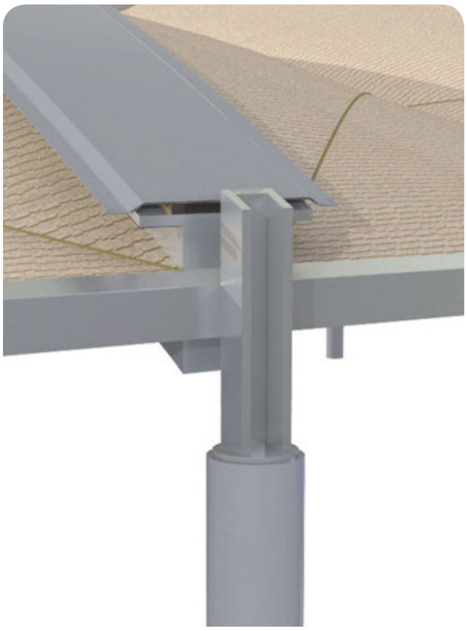
Fabric systems 3: single membrane: barrel-shaped roof

3D fragment view showing barrel roof configuration

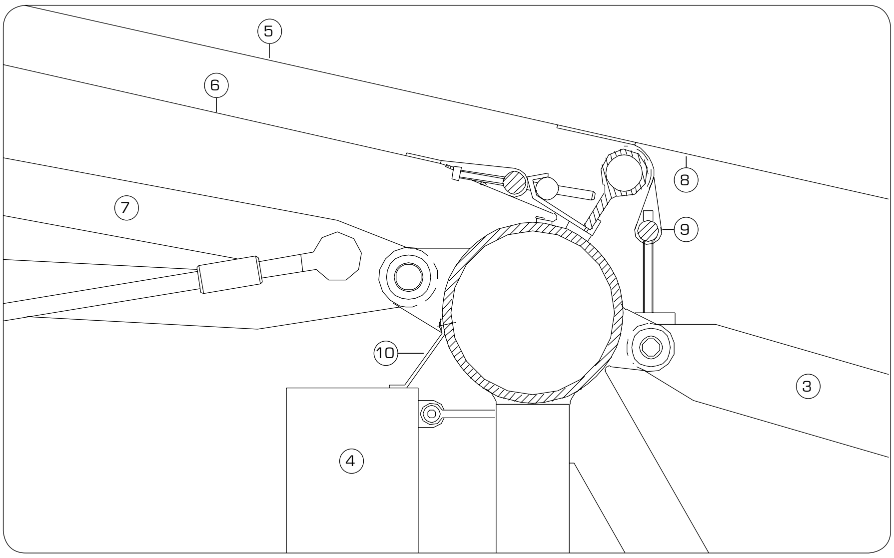
3D fragment view showing barrel roof configuration



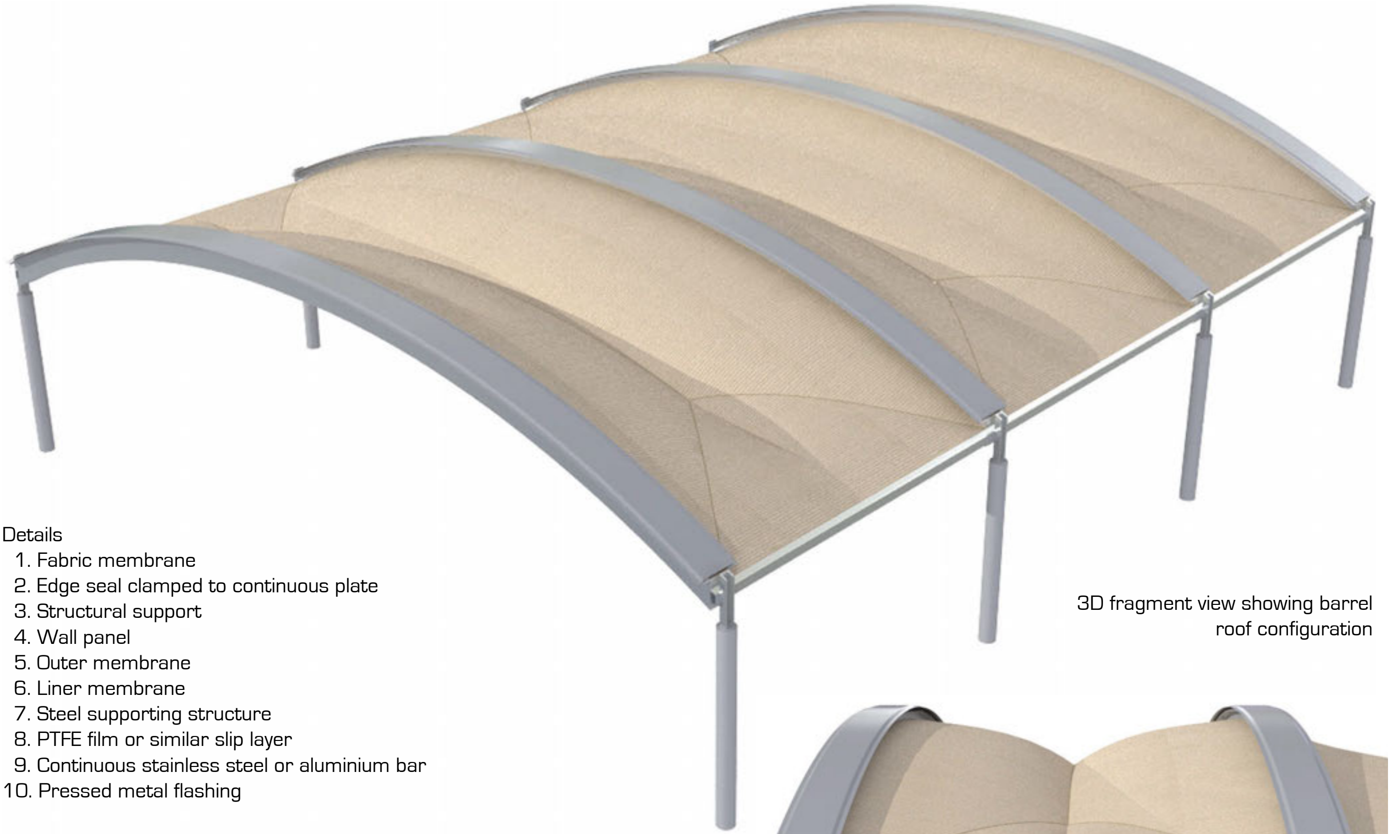
Vertical section 1:10. Single skin system with steel edge support



3D detail view showing membrane barrel roof connection to steel support structure



Vertical section 1:10. Double skin system with steel edge support



Details
1. Fabric membrane
2. Edge seal clamped to continuous plate
3. Structural support
4. Wall panel
5. Outer membrane
6. Liner membrane
7. Steel supporting structure
8. PTFE film or similar slip layer
9. Continuous stainless steel or aluminium bar
10. Pressed metal flashing

3D fragment view showing barrel roof configuration

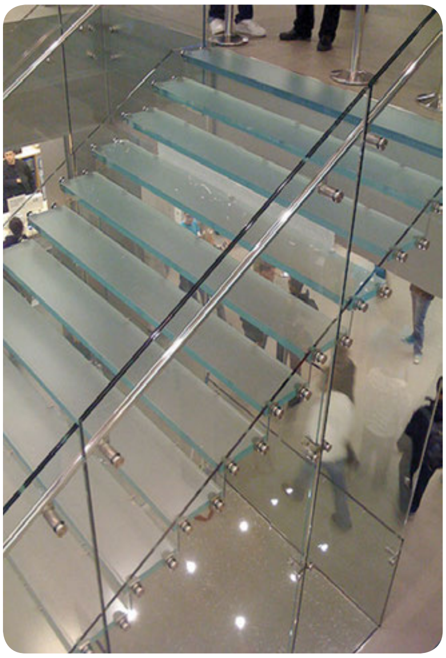
3D fragment underside view showing barrel roof configuration

Suspension points at the top of a cone-shaped fabric roof are usually formed either by a metal ring, which is fixed back to a central mast by cables or cantilevered brackets or, alternatively, by a 'palm tree' arrangement of projecting curved metal brackets which serve to tension the continuous membrane against its supporting mast set within the building.

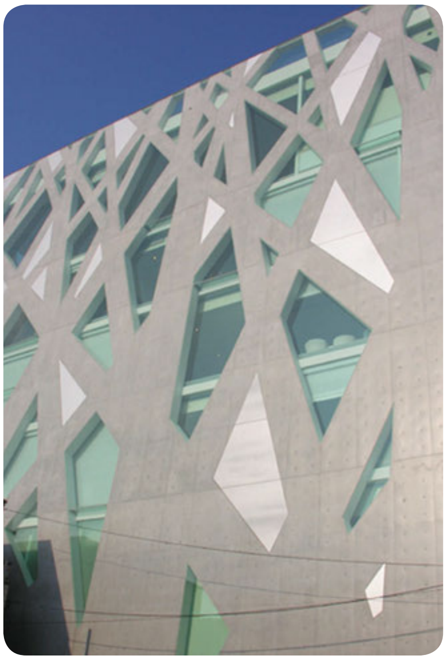
The first option with a metal ring requires an additional membrane cover piece, while the second 'palm tree' option forms a continuous membrane with a smooth curved top, without any breaks in the continuity of the membrane. In the 'ring' solution, the membrane is clamped between an inner ring and an outer ring fixed together with bolts. A second clamp is used to fix the cone-shaped membrane that covers the top of the ring. The top of the conical-shaped cover is either pulled over the top of the central mast or clamped around it. The ring is either freely suspended from cables, or is firmly fixed to the mast with cantilevered brackets to which the ring is secured. In the 'palm tree' supported solution, cantilevered brackets with a curved shape are set out radially in order to create a smooth curved form on which the membrane is set. The brackets are usually aligned with joints between membrane panels.

In an external fold in a roof membrane, the material is draped over the supporting structure, fixed with fabric strips that are sewn or welded to the underside of the membrane and clamped to the supporting structure. An additional membrane cover strip is fixed to the top of the joint to conceal the stitching if required. An alternative method is to form a joint between two membranes at the external fold, clamping them with a pressure plate to an aluminium extrusion which is supported by the primary structure, such as a mild steel tube, curved to form the shape taken up by the membrane. Internal folds are formed in the same way as ridges, with the membrane folded outwards rather than across the ridge and downwards. In some cases the membrane may pass under the cable. These junctions are formed by clamping the ends of adjacent membranes that form the valley. The edge of each membrane is clamped with an edge bead, while the clamp itself is fixed to a central cable. The gap between the membranes is closed by two membrane strips which are sewn or welded to the base of the strip and are clamped down to a thin pressure plate between the membranes. The clamp that closes the two membrane strips is supported off the metal straps beneath. By raising the closing strips above the height of the joint, two adjacent gutters are formed, with the clamping strip securing the closing flaps above the level of the water being drained.

4 STRUCTURE



Glass stair. Apple store, Regents Street, London, U.K. Architect: Bohlin Cywinski Jackson



Reinforced concrete structure. Tod's Building, Tokyo, Japan. Architect: Toyo Ito

ETFE Roof structure. Eden Project, Cornwall, U.K. Architect: Grimshaw Architects

Curved concrete frame. Science Park, Valencia, Spain. Architect: Calatrava

Curved concrete frame. Science Park, Valencia, Spain. Architect: Calatrava

Structural stability

This chapter sets out the most commonly used material systems for structures together with the relationship between structure and enclosure. Typical details are shown for each material system and their interface with walls and roofs. Structural 'types' in this chapter are described as systems based on the use of a primary material used to make a complete building structure. Each example can be used as a single structural system for a complete building or, more commonly, be combined in a mixed construction. Building structures are put into categories depending on whether they are either 'braced' or 'unbraced' in their construction. Braced types use devices such as internal walls or service shafts, or alternatively use cross bracing to stabilise the structure. This vertical bracing is usually provided in two vertical planes at right angles to one another in order to stabilise the structure both along its length and across its width. Horizontal bracing is provided by the floor structures which act as horizontal girders. The roof, if sufficiently rigid in the horizontal direction as in a reinforced concrete slab, can also be considered to be horizontal bracing. Unbraced structures, in contrast, are allowed to sway as a result of their being unbraced in one direction. Their stability is provided by rigid connections that provide stiffness within the structural elements, such as in portal frames. Like braced structures, bracing in the horizontal direction is provided by floors and, in the case of single storey structures, by bracing in the plane of the roof. The most common elements used to make building structures are braced frames, portal frames, loadbearing boxes, trusses, arches and shells, and space grids. Reinforced concrete and masonry structures, despite their essentially monolithic nature, are considered to be braced structures as some walls provide specific bracing elements.

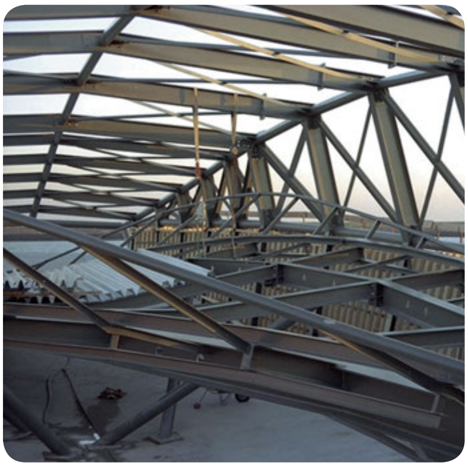
Structural movement

The term 'structural movement' covers a wide range of effects of deformation and movement in building structures. Dead and imposed loads, together with wind and snow loads and forces specific to use or location such as dynamic and seismic loads, can bring about movements seen as bending and shear deformations which are a normal part of the building in use. An essential aspect of structural movement in the overall design of buildings is that its effects need to be taken into account in the external envelope and its interfaces, primarily at roof level. Temperature changes, and differences in temperature between different parts of a structure, can cause expansion and contraction of structural members, with possibly some local bending of those members. The detailing of both the components and any associated weatherproofing or internal

Loadbearing glass box. Broadfield Glass Museum, West Midlands, U.K. Architect: Design Antenna

Glass footbridge. Rotterdam, Holland. Architect: Dirk Jan Postel

Timber truss roof structure. Resource Centre, Cumbria, U.K. Architect: Sutherland Hussey

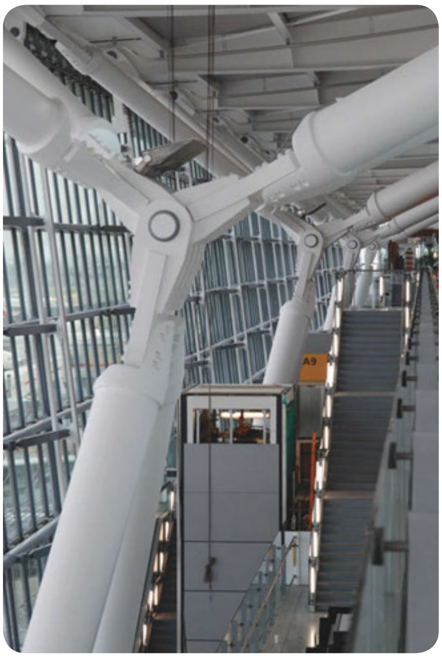


Braced steel frame. Saltwater Pavilion, Neeltje Jans, Holland. Architect: Oosterhuis Associates

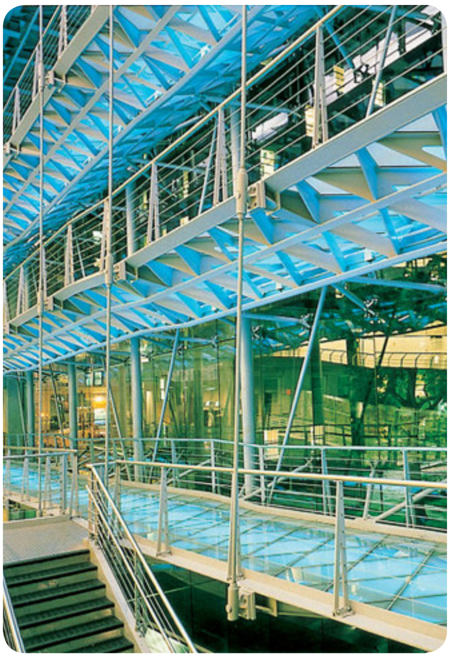
Concrete frame. Siobhan Davies Dance Studios, London, U.K. Architect: Sarah Wigglesworth

Steel frame structure. Fawood School, London. U.K. Architect: Alsop Architects

Reinforced concrete structure. CAC Museum, Cincinatti, U.S.A. Architect: Zaha Hadid Architects



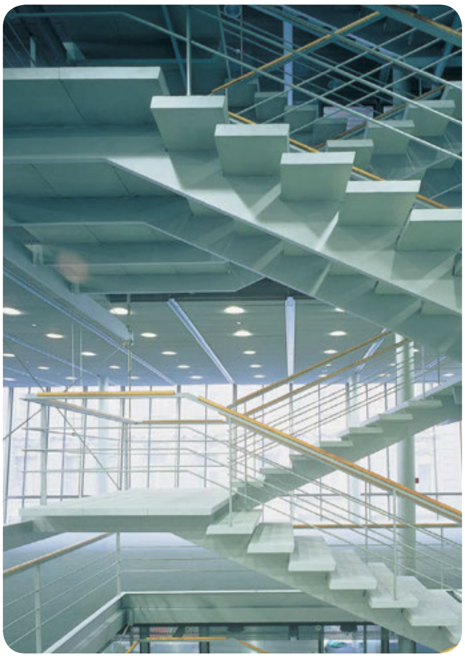
Branced steel roof structure. Heathrow Terminal 5, London, U.K. Architect: Rogers Stirk Harbour



Braced steel frame. Educatorium, Utrecht University, Holland. Architect: OMA

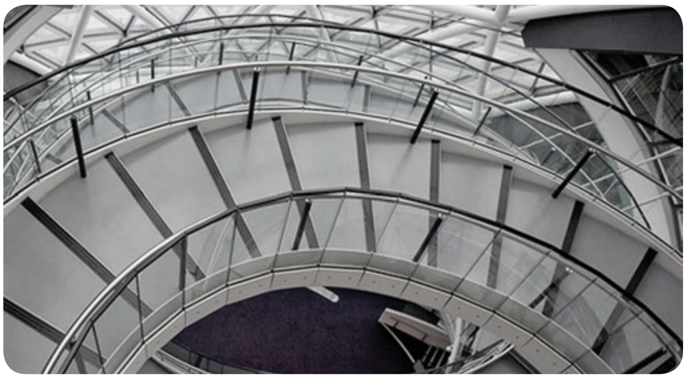
Loadbearing masonry. Brindleyplace, Birmingham, U.K. Architect: Porphyrios Associates.

Loadbearing glass box. House extension, London, U.K. Architect: Paul Archer Design



Steel staircase. Museum of Contemporary Art, Los Angeles, U.S.A. Architect: Arata Isozaki and Associates

Concrete staircase. Hyogo Museum of Art, Japan. Architect: Tadao Ando



Steel stair. City Hall, London, U.K. Architect: Foster and Partners

finishes must accommodate this movement without causing damage to these finishes. Moisture penetration can cause expansion and contraction in concrete, masonry and timber structures. Frost action, caused by the freeze/thaw cycle of moisture within structural materials, can eventually cause damage if the detailing is not sufficiently robust.

Trends in the use of building structures

Much effort in the design of building structures is focused on economy combined with safety, in terms of both the quantity of material used and the amount of fabrication needed to assemble the structure. The appropriate use of structure can often be seen in the 'fine tuning' of the balance of material used and fabrication undertaken. This approach is being increasingly paralleled in architectural design in the external envelope and internal fittings where there is a growing tendency to use the least number of components, while tempering this approach with the needs of their fabrication. This has led to an important trend in structures of their increased visibility and as self-finished components within buildings. This brings the aims of structural design and architectural design much closer together where the relationship between structure, enclosure and internal finishes are co-ordinated at an early stage of the design, continuing through the following detailed design and construction phases.
In steel structures, frames have become a full part of the language of architectural design. Assemblies in steel, ranging from small lattice trusses to cable-stayed structures that resemble 'kits of parts', have led to their widespread use as highly visible structures, set either outside or inside the building enclosure. The necessity of joining steel sections with either welds or bolts has led to a visual richness in both the design of structural members and the joints between them. This has been helped enormously by the development of intumescent paints, which protect the structure during a fire by expanding to form a heat-insulating layer that protects the integrity of the structure for a limited period, usually one hour. These finishes, once only roughly textured or trowel applied, can now achieve a smooth finish previously associated only with the regular paint finishes used in unprotected structures such as single-storey roof structures. Issues of thermal bridging in steel structures and the penetration of the waterproofing layer with steel components are now easier to overcome with thermal breaks, within joints and across weatherproofing membranes such as with the use of a set of bolted connections that are difficult to achieve in either concrete or timber.

Concrete structures are now being exposed as self-finishes within buildings, both on the external walls and in the soffit (underside) of structural slabs, with a quality of finish traditionally associated with only plastered walls and ceilings. Exposed

Clad steel frame. Jewish Museum, Berlin, Germany. Architect: Daniel Libeskind.

Loadbearing concrete. Lyon-Satolas Station, Lyon, France. Architect: Santiago Calatrava

Braced steel framed construction. Wood Street, London, U.K. Architect: Richard Rogers

Organic concrete forms. Phaeno Centre, Wolfsburg, Germany. Architect: Zaha Hadid

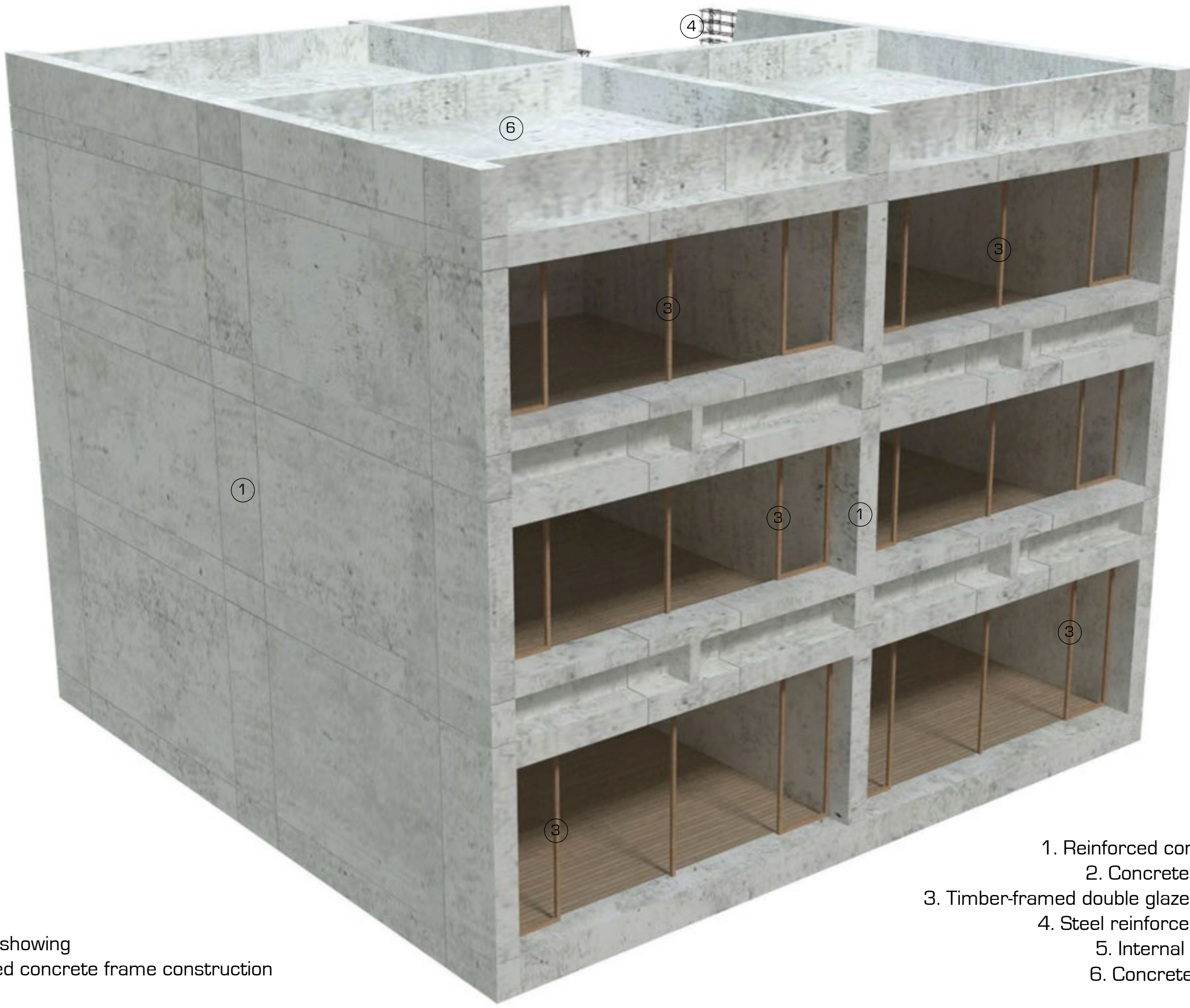
Braced steel frame. Pompidou Centre, Paris, France. Architect: Richard Rogers

finishes in concrete are now less common due to their poor weathering, from a visual point of view, but are enjoying a revival in predominantly dry climates where thermal insulation is set within the depth of the wall. The renewed interest in precast concrete structural systems, other than those used for parking garages, is set to continue with ever-greater expression of jointing forming part of the visible language of detailing.

Timber structures are becoming ever more complex both in terms of construction techniques and geometries used in their design. The development of pinned jointing systems as well as the interest generated in the material by its low levels of embodied energy have resulted in the revival of exposed timber structures. The new generation of pinned joints helps to overcome the traditional problem of creating reliable and elegant joints that perform well in tension, particularly in large-scale glue-laminated structures.

The use of CAD/CAM techniques, or computer aided design/computer aided manufacturing, for both timber and steel structures as well as the use of these materials for concrete formwork, is set to transform the geometries of structures built from all these materials. The use of CAD/CAM permits much greater accuracy and closer tolerances in assembly with joints that are increasingly visually elegant. CAD/CAM is set to push further the drive towards prefabrication. Timber and concrete, traditionally considered to be materials that are worked on site, are now more frequently fabricated at the factory, for example in the pre-cutting of timber components and in the precasting of concrete components instead of their casting in situ. The building site will inevitably become a place where assemblies are fixed together rather than being the temporary workshop to which we are accustomed.

Thermal bridging, and the related effects of condensation, associated with the integration of building structure with walls and roofs, continues to be a significant issue in building design in almost all climates. This has led to the increased use of vapour barriers and the careful placing of thermal insulation, which need to be co-ordinated with the structural design in order to avoid interstitial condensation. The thermal mass of exposed concrete structures is being used for the night-time cooling of buildings in conjunction with ventilated facades. The increased prefabrication of both structures and facades has led to a greater awareness of issues of co-ordination at an early stage of the project to ensure that highly visible finished components, which in earlier buildings would have been covered over by successive building trades, can be successfully exposed as high quality finished components.



Details
1. Reinforced concrete wall
2. Concrete floor deck
3. Timber-framed double glazed windows
4. Steel reinforcement bars
5. Internal floor finish
6. Concrete roof deck

3D view showing
reinforced concrete frame construction

The use of precast and in-situ cast (cast in place) concrete in frames provides a homogeneous structure where joints are made as rigid connections. These frames require additional stiffness from bracing that can be provided typically by either concrete shear walls or steel cross bracing. Alternatively, lateral stability can be introduced into concrete frames by stiffening other elements such as cores, shafts or stair enclosures. The inherent fire resistance of concrete provides structures that require no further fire protection measures. With in situ cast construction, the ability to re-use formwork is important in keeping its use economic. Each 'lift' of concrete, typically a floor with its supporting walls and columns, takes longer to construct than an equivalent steelwork structure, since the concrete takes time to reach an adequate strength to allow another floor to be built on top. Although the construction of an in-situ cast reinforced concrete frame is considered slower than erecting a steel frame, the construction times can be matched if the concrete work is well organised. Frames in concrete combine easily with ground structures such as retaining walls and foundations because they are of the same material and can be continuous.

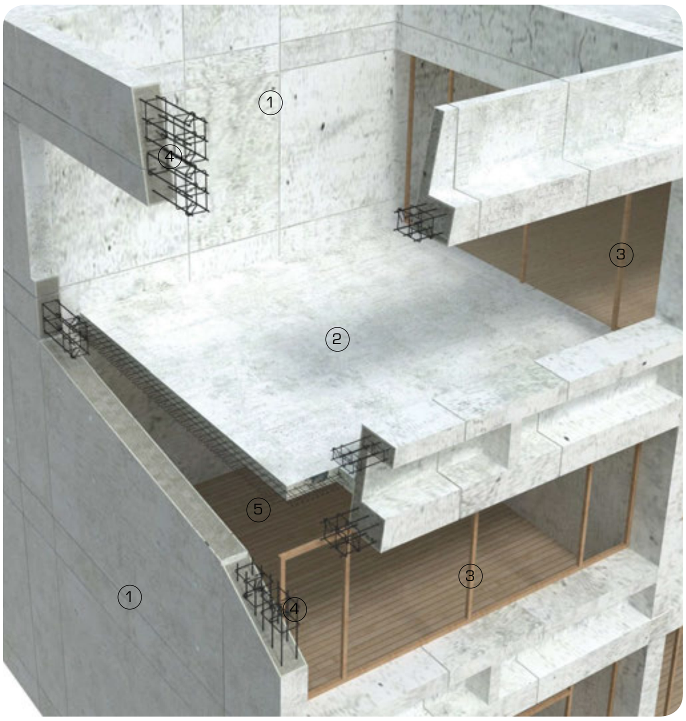
Joints and Connections

Stiffness at the junctions of the frame is important both to provide sufficient rigidity in the frame itself and to make its deflections compatible with the cladding and internal elements such as staircases. This can be achieved either within the joints forming the frame, by including extra reinforcement, or by using additional stiffening walls such as those used to enclose elevator (lift) shafts and service cores. Typically, deflections in concrete beams or slabs are designed to be compatible with the external cladding, partitions and fittings within the building.

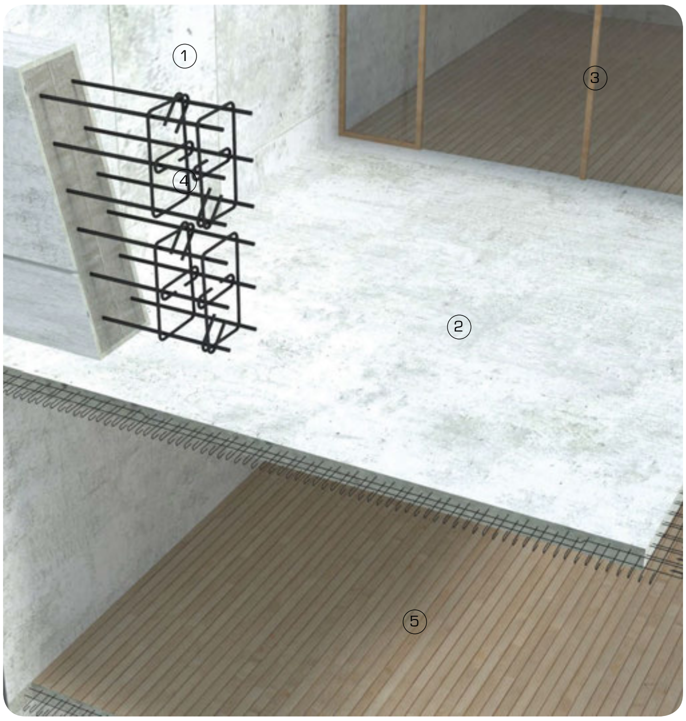
Movement joints are introduced to allow for thermal movement. These junctions are effectively breaks in the structure, resulting in the overall structural frame comprising a set of smaller linked frames, each an independent stable structure. Movement joints are usually taken through the external walls and roof, requiring envelope details that allow for structural movement while remaining weatherproof.

Interface with external envelope

Concrete frames can be either exposed outside the weather line of the cladding, that is, the non-loadbearing walls, or be completely enclosed by the external envelope. When exposed externally, the penetration of the frame through the walls and roof requires careful detailing to overcome weatherproofing and thermal bridging around penetrations of structural members through the cladding. Grooves are often cast around penetrating beams to allow flashing pieces to be inserted to assist in forming a weather seal. Cladding is fixed either by a continuous stainless steel channel that is cast into the edge of the concrete slab, or by expansion bolts secured into the slab when the cladding is fixed. The bolts may also secure stainless steel angles, brackets or continuous rails depending on the nature of the lightweight cladding. Reinforced concrete panels can be secured with additional metal pins cast into the top surface of the concrete slab.

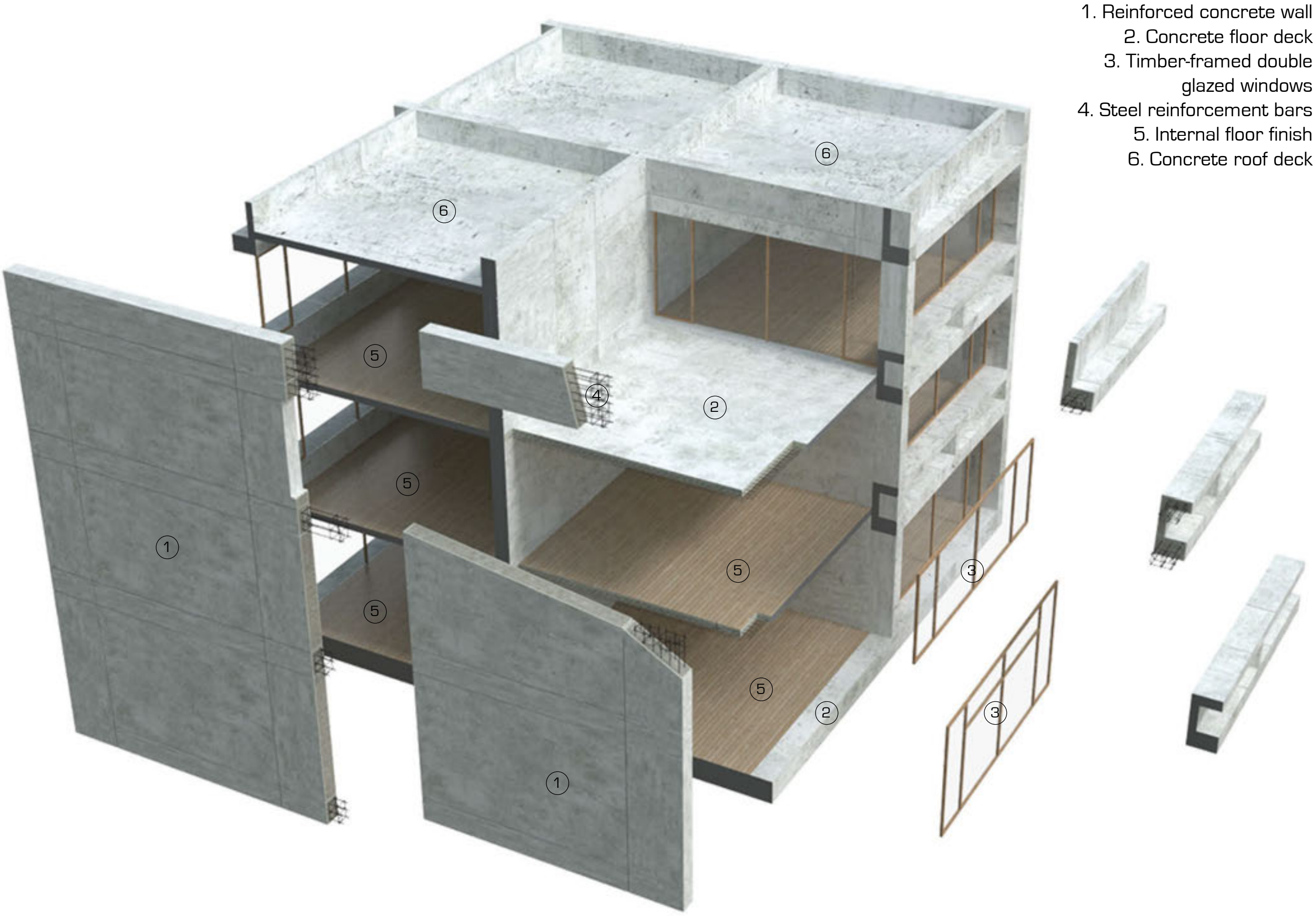


3D cutaway view showing concrete frame and steel reinforcements bars



3D cutaway view showing concrete frame and steel reinforcements bars

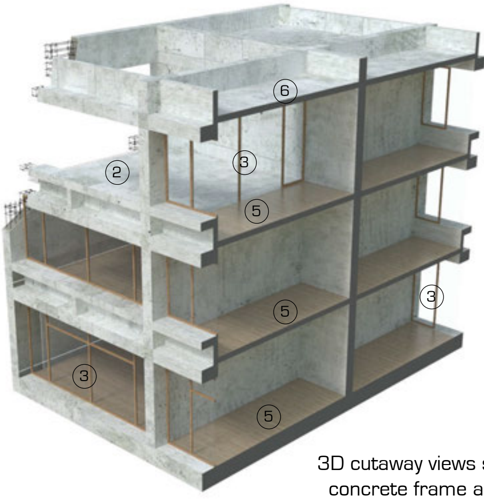
Details
1. Reinforced concrete wall
2. Concrete floor deck
3. Timber-framed double glazed windows
4. Steel reinforcement bars
5. Internal floor finish
6. Concrete roof deck

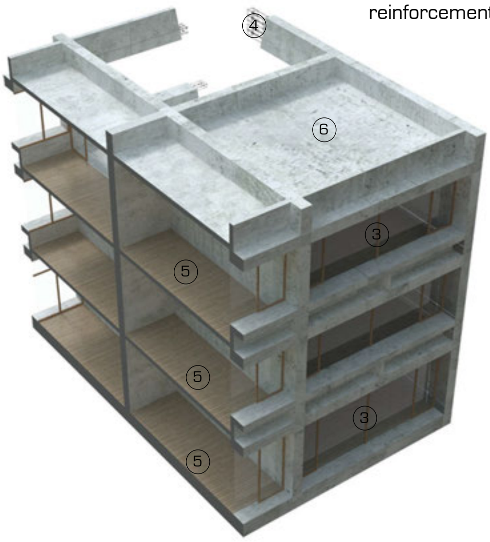


3D exploded view of concrete frame and panel system

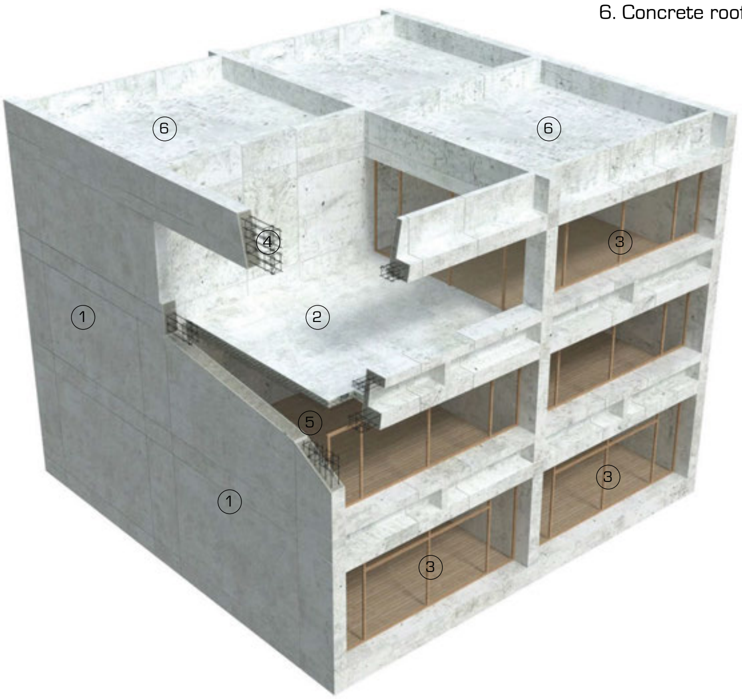
3D cutaway view showing concrete frame and steel reinforcements bars

Details
1. Reinforced concrete wall
2. Concrete floor deck
3. Timber-framed double glazed windows
4. Steel reinforcement bars
5. Internal floor finish
6. Concrete roof deck

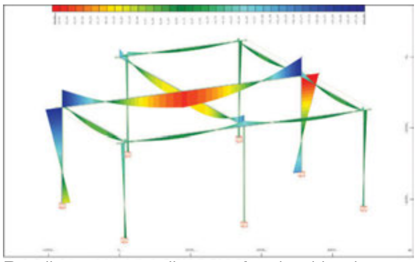




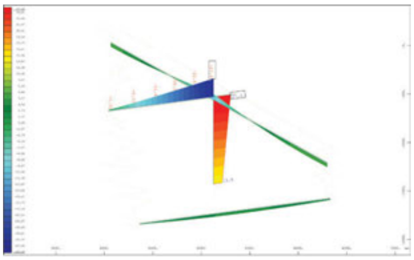
3D cutaway views showing concrete frame and steel reinforcements bars



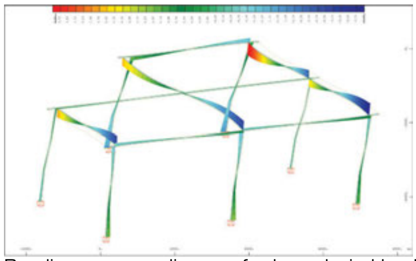
3D cutaway view showing concrete frame and steel reinforcements bars



Bending moment diagram for dead loads.

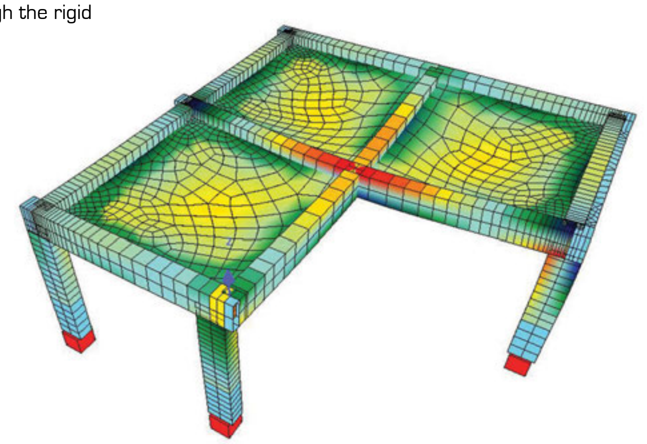


Bending moment is transmitted from the beam to the column through the rigid connections of the frame.

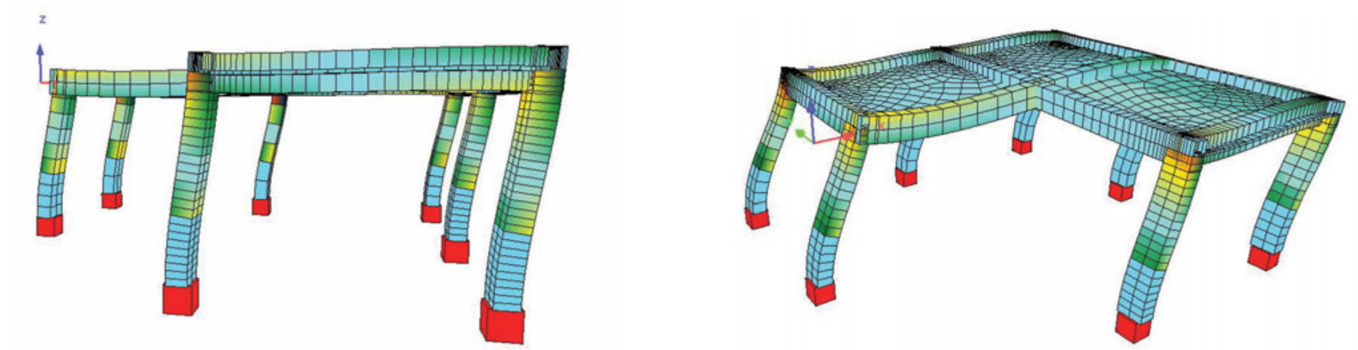


Bending moment diagram for lateral wind load.

Structural model of concrete frame structure: typical floor system



Stresses in the structure under dead loads: the secondary concrete slabs deflect in their plane, transferring the load to the intersecting primary frames (the structural movements shown are magnified).

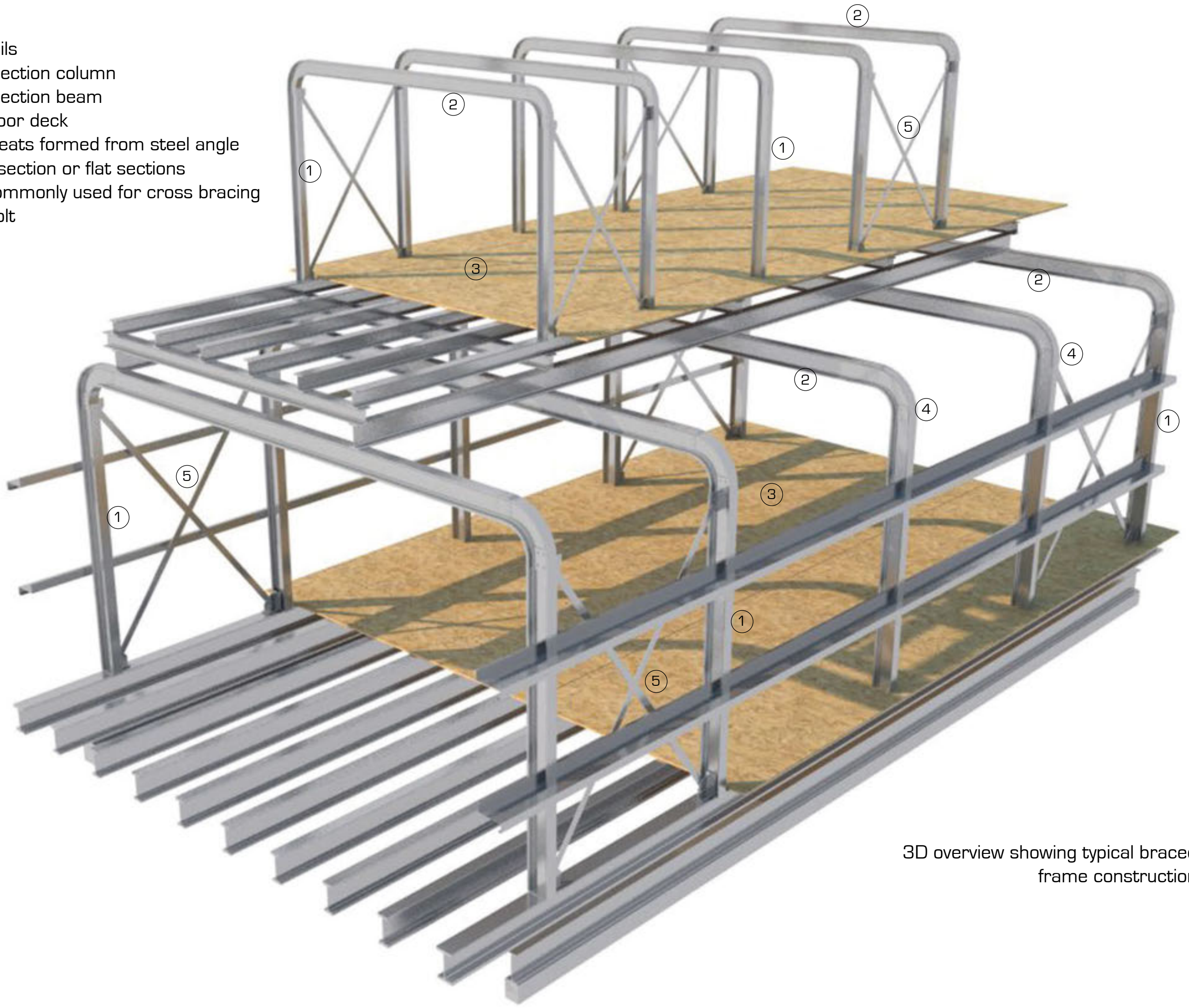


Considerable bending strength in the columns is required against lateral wind loading (the structural movements shown are magnified)

Reinforced concrete frames provide an integration of wall, roof, floors and columns into a single form of construction. Supporting walls and floors can be integrated into shell forms as seen in the Science Park in Valencia by Santiago Calatrava. Concerns about the weathering capability of concrete have led to the material being covered by an additional weathering material, which can be thin metal panels or even an applied coating. Recent improvements in surface finishes, with honing and polishing used in precast concrete, have allowed a slow re-introduction of concrete as an expressed finish. An essential issue has been the thermal bridging associated with concrete structures, which has led to thermal insulation being set externally with an additional weathering material on the outside. The positioning of the insulation externally allows the environmental strategy within the building to benefit from the thermal mass of concrete. In recent years, with the enhanced weathering characteristics of precast concrete, the thermal insulation is set into the thickness of the wall, resulting in the construction being of diaphragm type rather than a single wall with a non-loadbearing skin set either internally or externally. In the diaphragm wall, the two halves of the wall are linked by either stainless steel ties or by reinforcing bars.

Regardless of whether concrete is formed in-situ or is precast, the material is cast in formwork. In-site formwork is typically made from plywood sheets but any material can be used. The material used for formwork leaves a strong impression on the concrete finish, often with a high degree of visible detail. This allows the concrete frame to have a wide range of finishes from timber boards, leaving a high degree of visible texture on the surface, to very smooth concrete where plastic laminate coated plywood is used. Digital fabrication has had a modest influence over concrete construction, with the introduction of CNC cut polystyrene forms that are set into the formwork to produce complex shapes in either precast or in-situ cast concrete. The ability of concrete to take up complex shapes using economic formwork has led to a gradual move to more sculpted forms in concrete frames, as seen in the work of Zaha Hadid and Santiago Calatrava. The visual continuity of openings in walls, roofs and floors within buildings gives a spatial continuity and fluidity which can be achieved without the need for elaborate decoration; the frame provides an elegant expression of form without the need for secondary finishes. The development of the reinforced concrete frame of columns and beams has seen considerable elaboration in the work of Calatrava, following visual principles of animal skeletons as well as drawing visual inspiration from equivalent steel structures. Reinforced concrete frames have shown the ability to move from being simple, rectilinear flat forms to being visually rich structures of complex geometry of either curves or folds.

Details
1. I-section column
2. I-section beam
3. Floor deck
4. Cleats formed from steel angle
5. T-section or flat sections commonly used for cross bracing
6. Bolt



3D overview showing typical braced frame construction

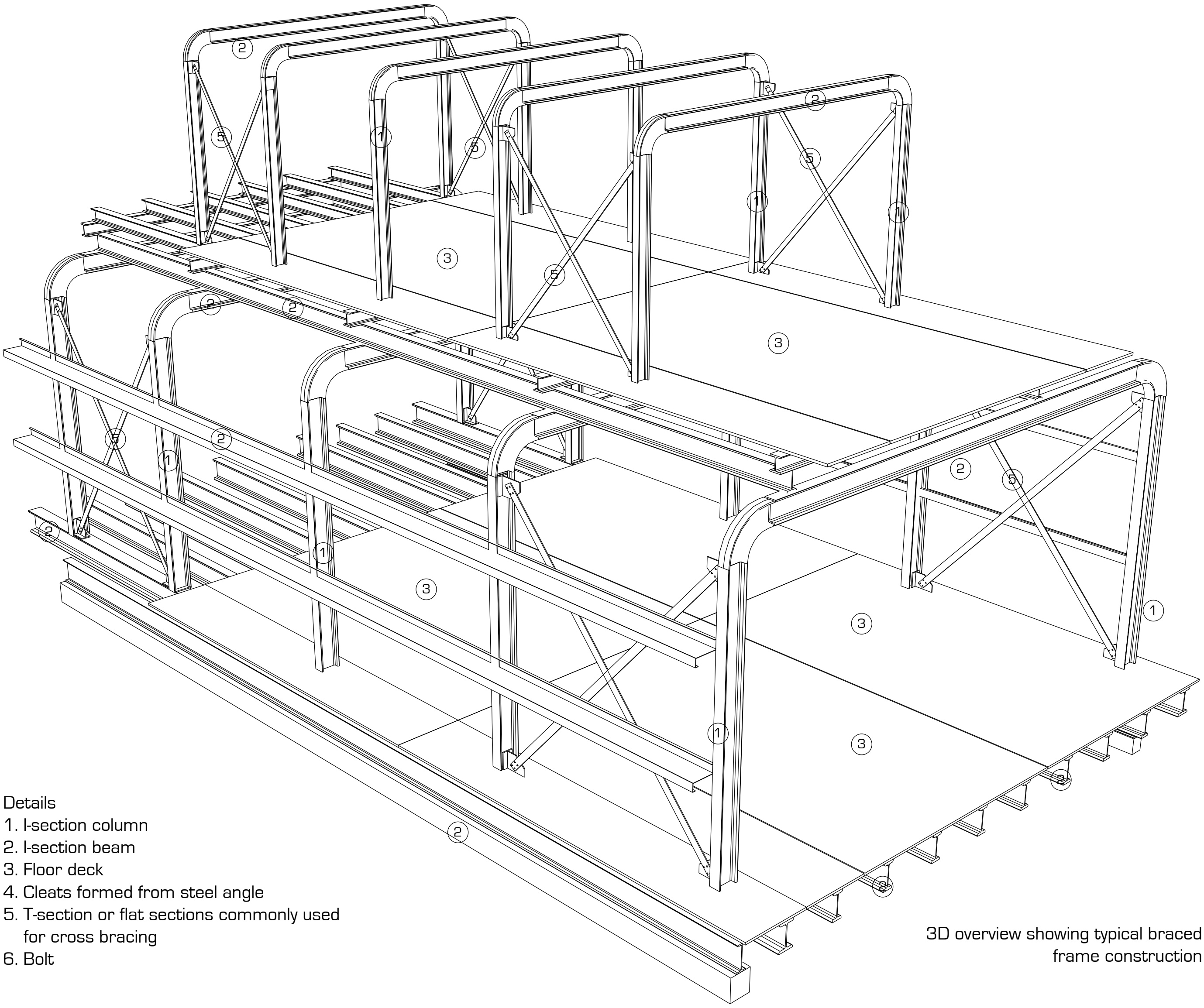
Steel frames are made from columns and beams that are fabricated in factories and workshops and assembled together on site. Unlike reinforced concrete frames, steel frames can be readily assembled with either rigid moment connections or with pin connections. Lateral stability is provided typically with either the cross bracing of some bays, or with staircase enclosures, cores or shafts.

Steel frames are usually shot blasted, cleaned and primed prior to erection. Frames that are not to be left exposed visually require no further painting. However, most steel structures require fire protection, which is provided typically with either concrete encasement, an intumescent paint or by enclosing the frame with fire resistant board. Steel frames not requiring fire protection, such as those used for roof structures only, are painted to avoid corrosion during construction and after the frames are assembled. Members which are to remain visible when assembled, such as in visible roof structures, are often delivered to site as pre-painted components that can be assembled on site and lifted into place by crane, avoiding the need for substantial scaffolding. Care is taken not to damage the surface finish, as touching up of galvanizing and paintwork on site is slow, laborious and more difficult than in the factory.

Joints and Connections
Joints in steel frames are bolted or welded. Bolted connections are the most commonly used, with either cleats or plates used as connectors. The advantages of a fast speed of construction on site associated with steel frames is often continued into the configuration of the floor slab, which often uses trapezoidal shaped floor deck instead of full concrete slabs. The profiled metal deck is used as both permanent formwork as well as having a structural role in composite action. Concrete is poured on top of the metal deck, which typically has shear studs or connectors to form a bond between the two materials. The profiled metal deck is set either on top of the steel beams of the structural frame, or is set on a continuous steel plate welded to the bottom flange of the steel beam. The advantage of the former method is its simplicity of construction, while the advantage of the latter is in reducing the overall depth of the structural floor zone, which can in turn reduce the overall height of the building with attendant savings in the cost of the external walls. In addition, the use of a composite concrete and steel deck provides essential properties of fire protection and acoustic separation. Movement joints are introduced to allow for thermal movement in the steelwork, which can be greater than that of concrete. These joints are breaks in the structure where each part of the structural frame must be independently stable of its neighbour. The corresponding movement joint on the external wall and roof is detailed so as to provide a continuity of waterproofing while creating a break in the structural support of the external wall across the joint. Movement joints in the external wall are typically up to around 20mm wide, so do not have a significant visual presence on the facade, but are usually designed to make them an intentional part of the language of construction.

3D detail view showing steel connection plate detail

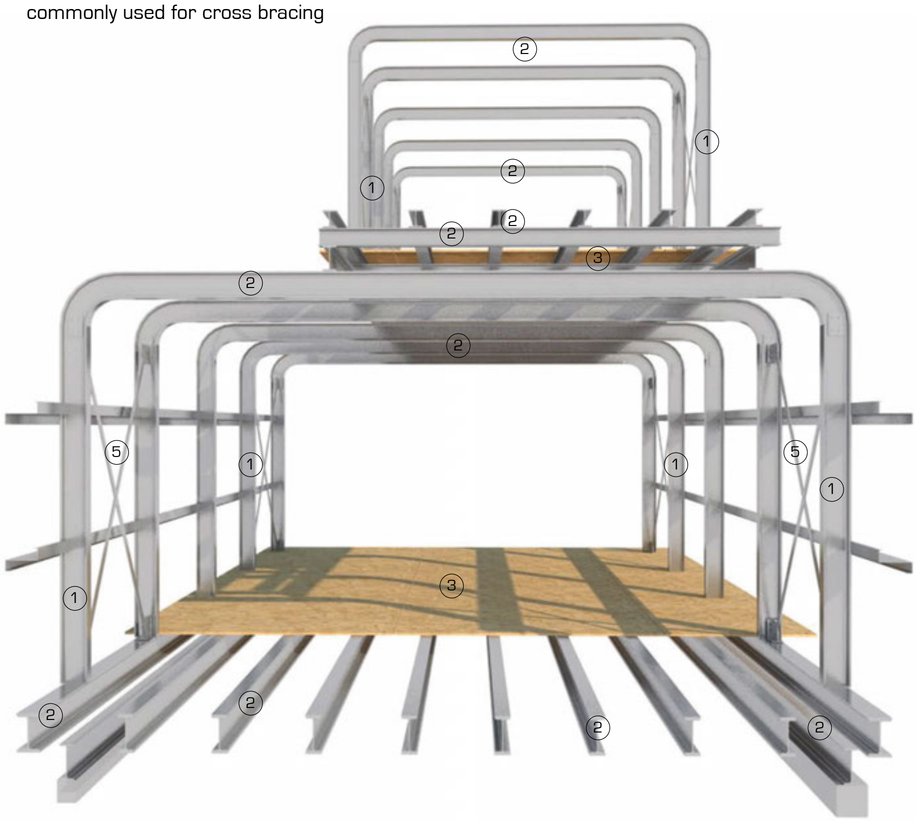
3D detail view showing steel connection plate detail



Details
1. I-section column
2. I-section beam
3. Floor deck
4. Cleats formed from steel angle
5. T-section or flat sections commonly used for cross bracing
6. Bolt

3D overview showing typical braced frame construction

Details
1. I-section column
2. I-section beam
3. Floor deck
4. Cleats formed from steel angle
5. T-section or flat sections commonly used for cross bracing



3D overview showing typical braced frame construction

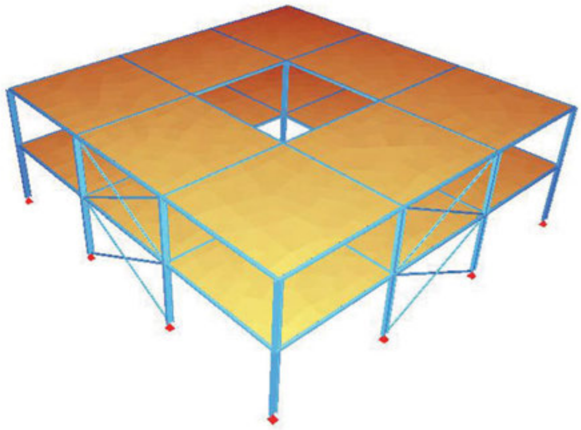
3D detail view showing curved steel I-beam connection

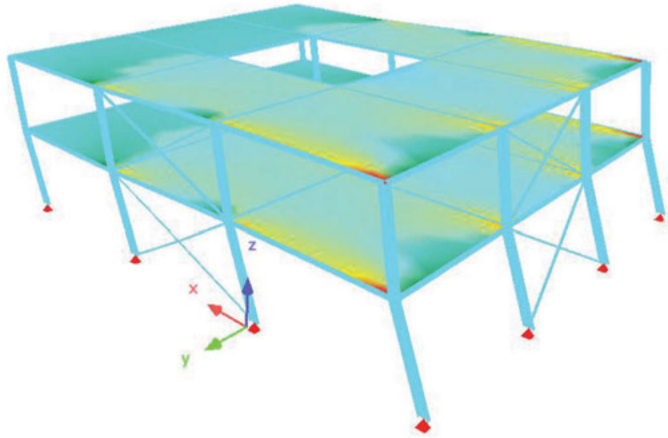
Smaller scale steel frames for one or two storey buildings have the advantage of being possible to fabricate in the workshop as a 'kit of parts' for complex forms. Profiles can be cut, curved, welded and bolted in factory conditions for individual projects where the steel frame is visible from either inside or outside the building. This method allows welded joints which can be ground smooth and painted before being delivered to site in sections, where they can be bolted in place, achieving a level of workmanship that would be more difficult under site conditions. For short spanning, lightweight steel frames, cold formed sections can also be used. They have the advantage of being lighter to handle, forming frames which are more like a steel equivalent of the timber platform than a regular steel frame, with members at closer centres. The ability to mix hot rolled steels, capable of long spans, with cold formed or 'pressed' sections provides a mixture of material systems in a single material, using a common method of fixing with screws and bolts. Small frames can benefit from the wide range of structural steel sections available, from I-sections to T-sections, box sections, tubes and flats, as well as specially fabricated sections of irregular shape. The introduction of irregular shapes has been possible as a result of the development of digital cutting tools.

Interface with external envelope

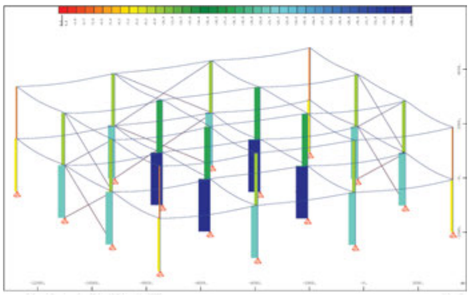
In common with reinforced concrete frames, steel frames can be either exposed outside the external skin or set inside the building; but when set externally, the frame is typically thermally insulated to reduce thermal movement of the frame. However the connection of the externally-set columns and beams to the floor slab through the external wall can be challenging. The need to create a weathertight seal around this junction requires special attention as the seal is usually formed within a spandrel panel. More commonly, external walls are set on the outside of steel frames as cladding fixed to the edge of the concrete floor slab, sometimes with an additional backing wall set onto the edge of the floor slab. Sometimes facades are supported by brackets fixed to the outer face of the steel beam at the edge of the frame, but this can be difficult to achieve in practice due to the co-ordination needed between steelwork and facade away from site, which can be challenging from the point of view of sequence of procurement and construction.

Roofs in different material systems are set onto steel frames either directly, as in the case of a profiled metal deck, or with support brackets fixed to the steel framing members in the case of a glazed roof. The use of brackets that lift the roof system clear of the steel supporting members give a sense of visual separation, which can assist visually in the relationship between frame and covering.

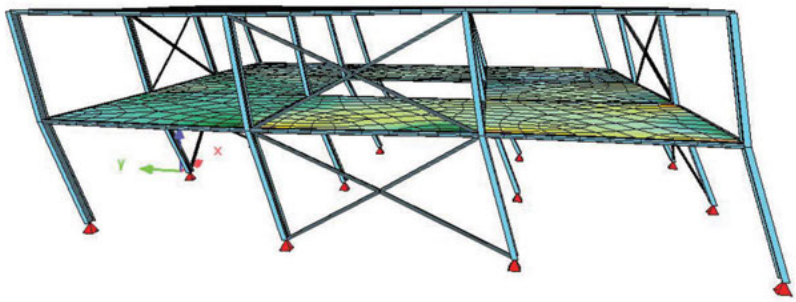




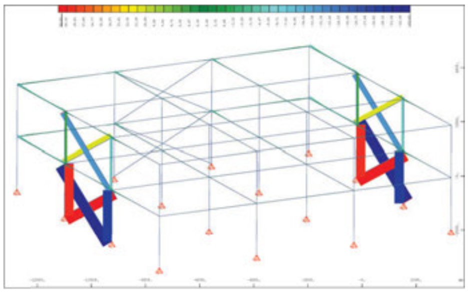
Structural model of a steel frame structure: concrete floor slabs provide horizontal stiffness.



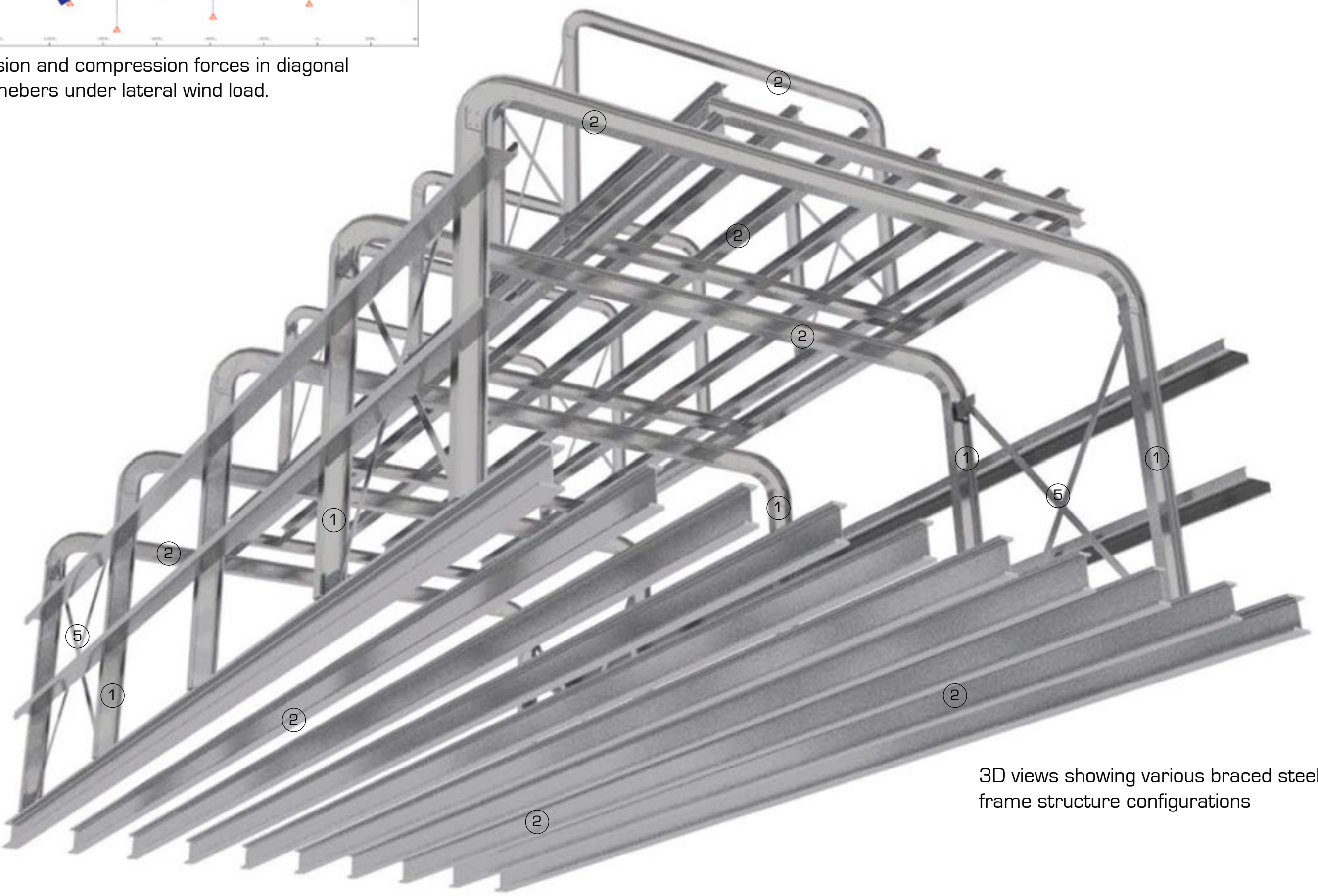
Column compression forces under dead loads.



Diagonal bracing is necessary in steel frames for lateral wind and seismic loads (the movements shown are magnified)



Tension and compression forces in diagonal memebers under lateral wind load.



3D views showing various braced steel frame structure configurations

3D views showing typical timber joinery and connection details

3D cutaway view showing typical timber balloon frame on a masonry base

The platform frame

The platform frame consists of softwood timber studs, typically 100mm x 50mm, spanning vertically from floor to floor between horizontally-set timber sections, called plates. The studs are set at close centres, typically 400mm as described in the section called 'Cladding to the platform frame' in the Walls chapter. Floor joists are aligned with the studs to transfer the loads efficiently from floor to wall. Timbers are butt jointed and nailed, following the tradition of using simple techniques and relatively few tools to make a complete structural frame from cut timber sections that can be lifted by hand. The stability of the frame is provided by plywood sheets, which also form a substrate for a breather membrane and external finishes. Prior to the use of plywood, timber boards were the main form of sheathing for the frame. Floor spans are typically at up to around 3500mm to suit the ready availability of cut sections, but plywood-based floor joists can achieve longer spans depending on the design. Openings in walls, floors and roofs are easily formed and steel or engineered wood beams can be incorporated to increase floor spans. The walls to the platform frame are discussed in the Walls chapter, and timber floors are discussed later in this section.

Long-span timber frames

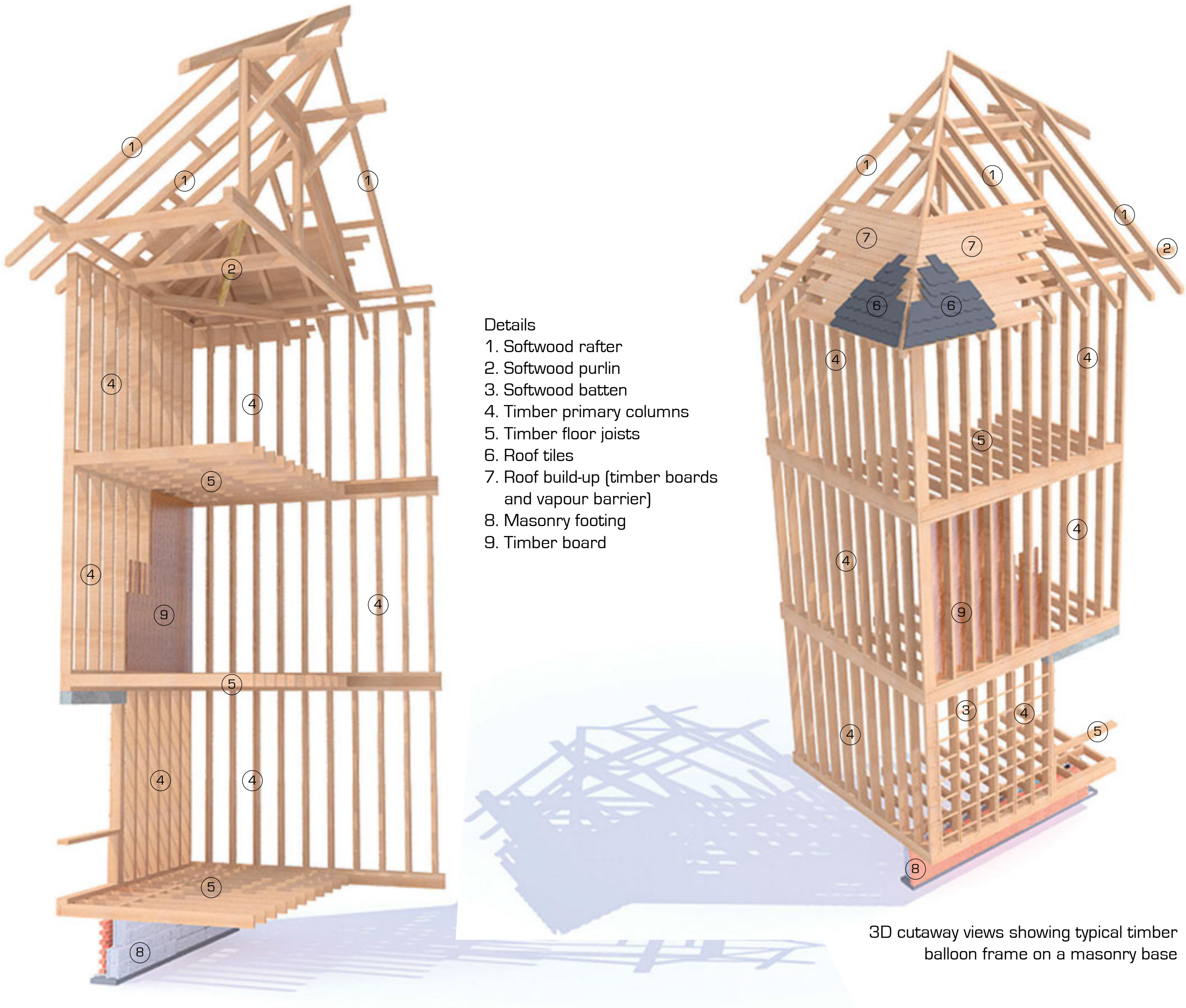
Larger frames can be made from either laminated timber or large cut sections which are connected pairs, spaced apart, to make larger components. These frames consist of columns and beams at 5-6 metre centres with infill panels between them to make walls. Floors are usually set on top of the beams. The large scale nature of the frame makes it necessary to introduce cross bracing or timber framed wall panels to provide lateral stability. These large scale frames are increasingly being formed in cross laminated timber, which have the ability to also be used as floor decks that have higher acoustic performance than timber joists and floor boards. Although sand pugging and layers of ceiling board can be added to the timber joist floor, their disadvantage has been to add mass without increasing the strength of the floor construction.

Hardwood timber frame

There has been a revival in recent years in the UK for the use of timber frames that use large size sections of hardwood such as oak, Douglas fir and larch to make frames that use traditional methods of frame construction rather than those of the platform frame. This method uses timber sections from around 300 x 300mm down to small scale 100mm x 50mm sections; in a hierarchy of primary, secondary and tertiary members, allowing most of the timber construction to be revealed rather than being concealed behind plywood sheathing and internal lining more typically associated with timber construction. Spans are modest, typically achieving those of platform frames.

Joints and Connections

Where platform frames use primarily nails to fix the frame together, hardwood frames use knee bracing and wooden pegs



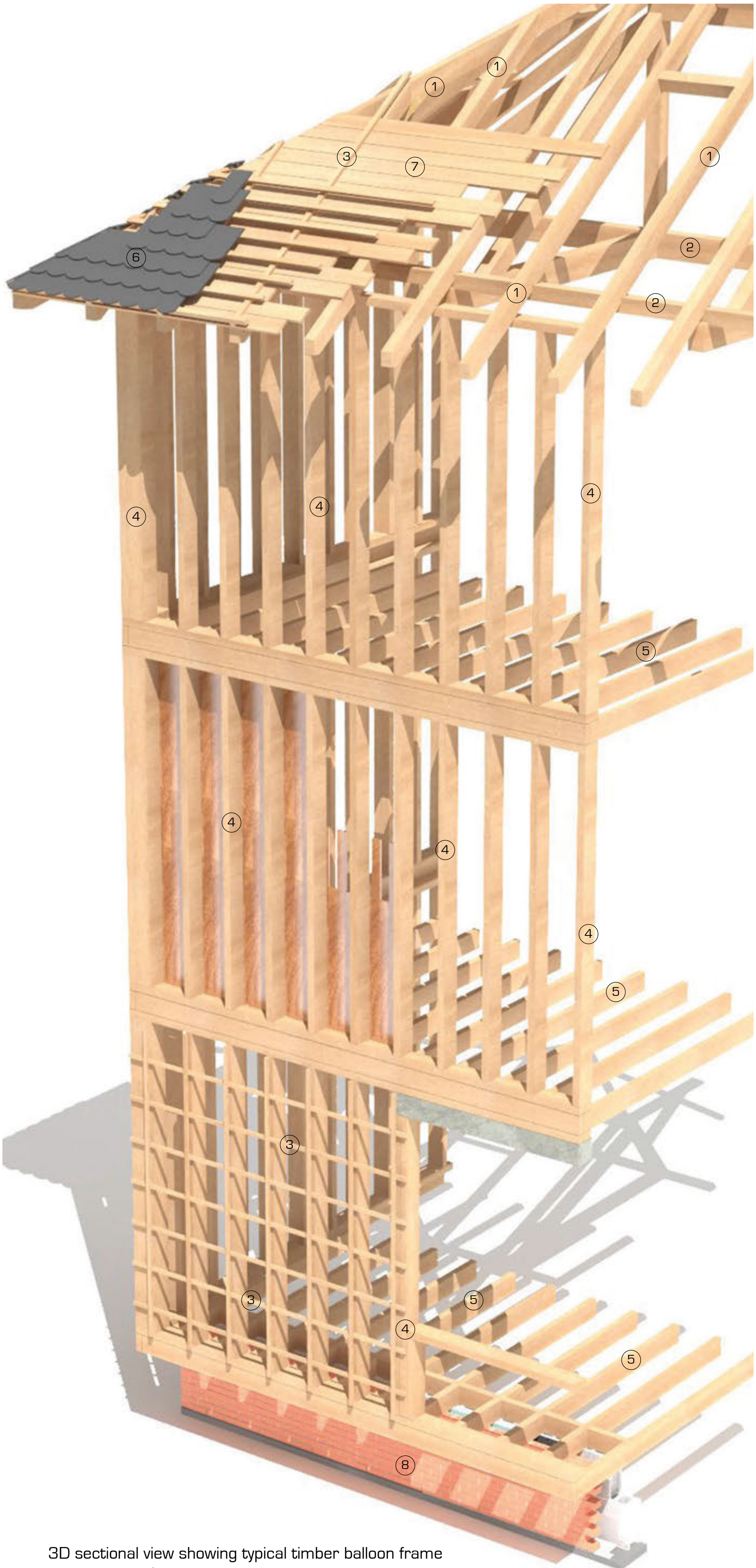
3D cutaway views showing typical timber balloon frame on a masonry base

at joints as an alternative to visible metal connectors. The use of larger size sections allows them to be cut to curves from single pieces of timber, or even to use traditional joints between large scale sections which interlock as a result of their shape rather than rely on straight metal connectors

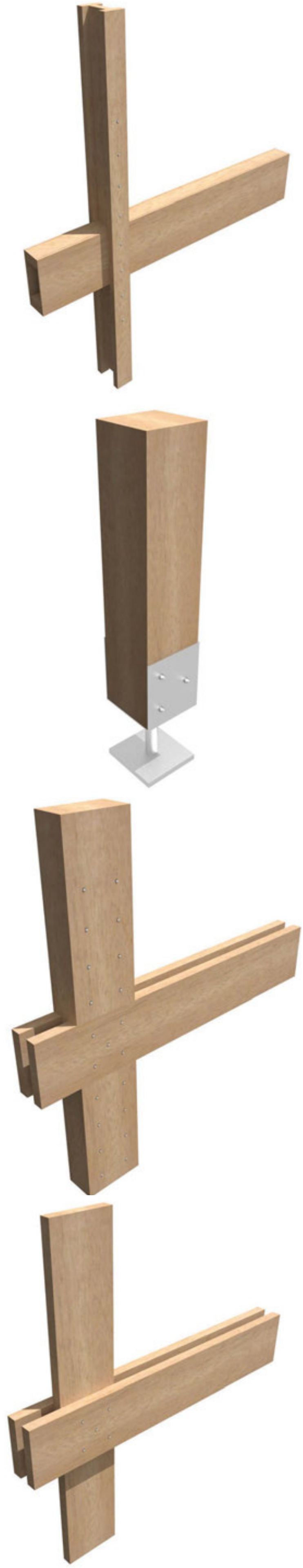
Long span timber frames, connected in with timber blocks and bolted together, often form simple bolted connections with timber columns by setting the beams on the outside of the column, or vice versa to suit the structural design of the frame. However, this technique is being superseded by tight-fit connections that use CAD/CAM techniques to direct computer-operated machinery that can plane, rout or drill structural timbers. This new technique can provide economic connections that transfer loads more efficiently than do traditional techniques. Solid timber circular columns are increasingly being used to reduce the amount of fabrication required and provide a substantial and smooth appearance. Timbers are fixed together using a set of tight-fit steel pins that are inserted into the connecting members. This type of connection is used at tension joints, which are hard to achieve except by either bolting or by using split ring connectors.

Interface with external envelope

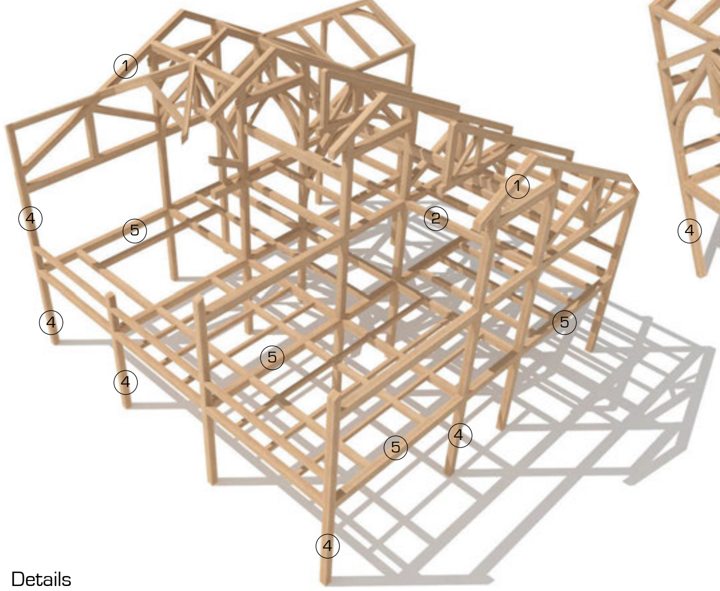
The use of the platform frame suits continuously supported, or short-spanning, cladding materials such as timber boarding and metal sheet. In the case of hardwood timber frames and long-span frames, the framing forms a primary part of the external walls, providing an opportunity to use infilling panels such as double glazed units or low energy materials such as straw bale and hemp, described in the Environment chapter. Roofs to hardwood frames follow traditional principles of keeping the structure dry within the building, with the roof covering the complete structure, but allowing the frame to be fully visible within the building. A traditional issue of infill panels has been to assure a weathertight joint between a timber frame which undergoes structural movement, and an infill that is also subject to its own movements. The use of breather membranes and rainscreen construction has greatly improved this traditional technique to meet modern requirements. The timber frame can also be fully protected externally, typically with a breather membrane and rainscreen cladding to control moisture movement in the frame as well as providing ventilation to the construction where it meets the external wall. As with other forms of timber construction, timber frames are set onto masonry or concrete bases to keep them dry and ventilated, typically set a minimum of 150mm above external ground level, but subject to specific design requirements. The base wall follows the principles of that form of construction, typically a cavity wall in the case of brickwork or a waterproofed concrete wall with an additional outer skin to protect and conceal the membrane.

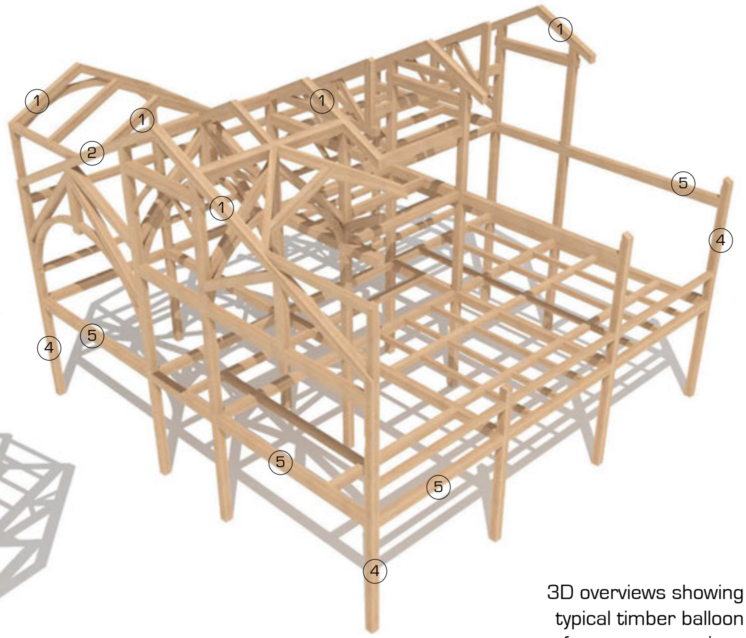


3D sectional view showing typical timber balloon frame on a masonry base



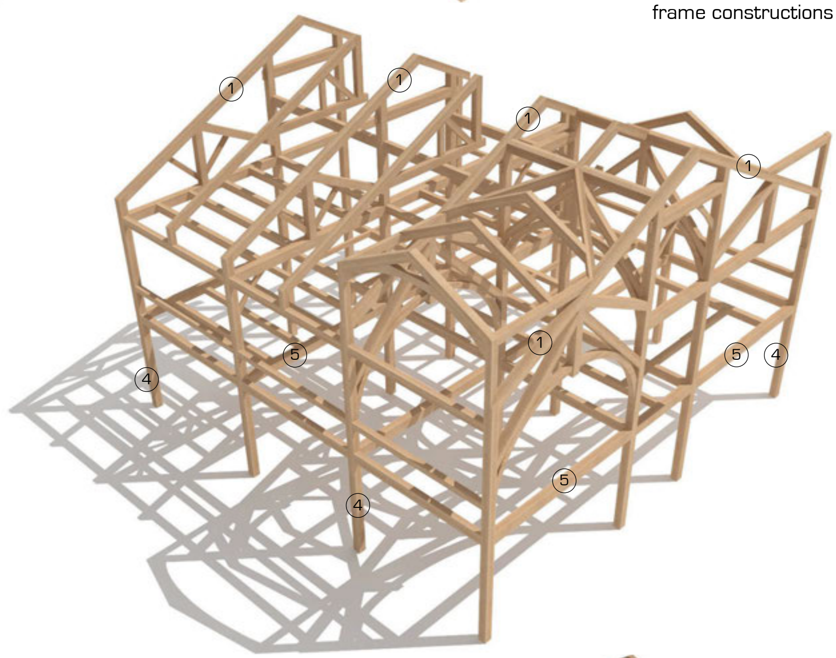
3D views showing typical timber joinery and connection details

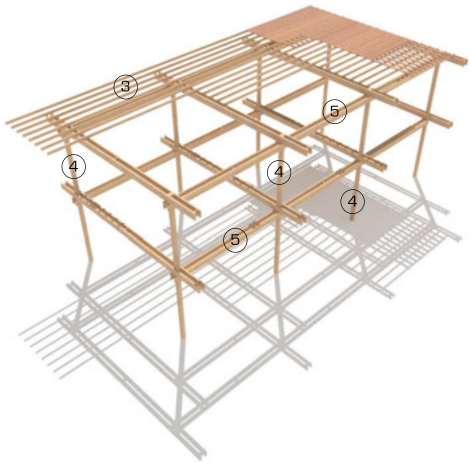


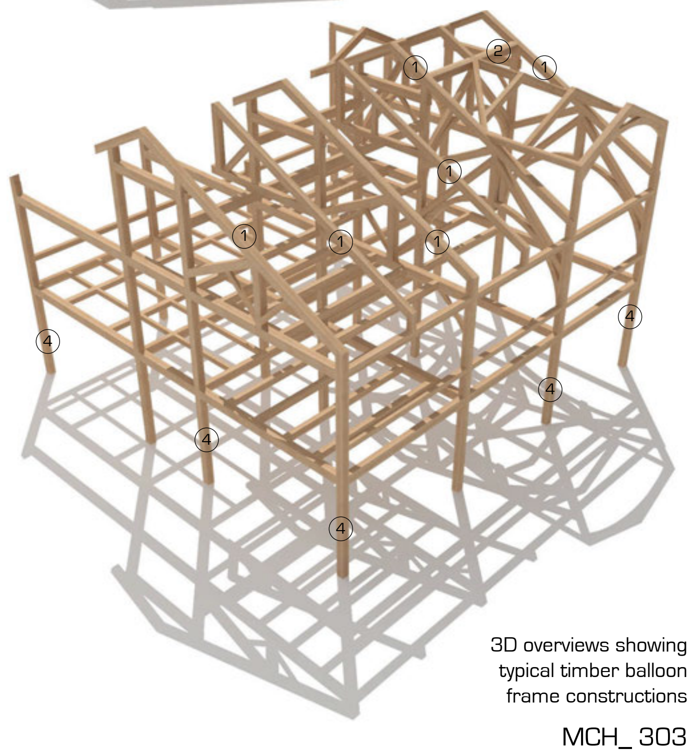


3D overviews showing
typical timber balloon
frame constructions

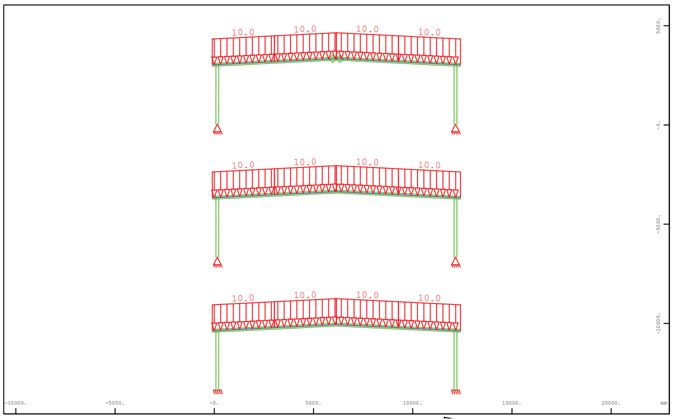
Details
1. Softwood rafter
2. Softwood purlin
3. Softwood batten
4. Timber primary columns
5. Timber floor joists
6. Roof tiles
7. Roof build-up (timber boards and vapour barrier)
8. Masonry footing
9. Timber board

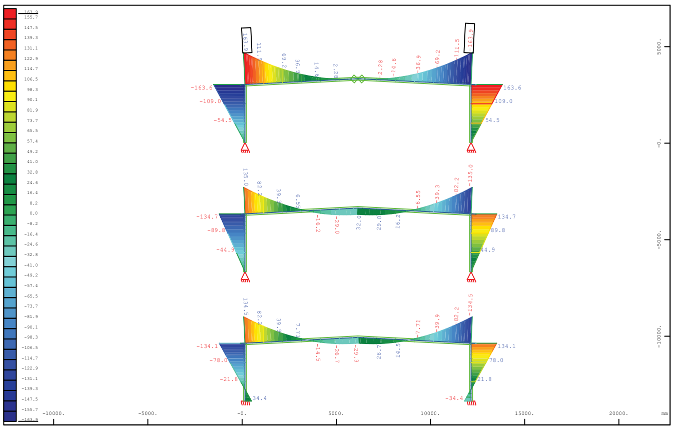




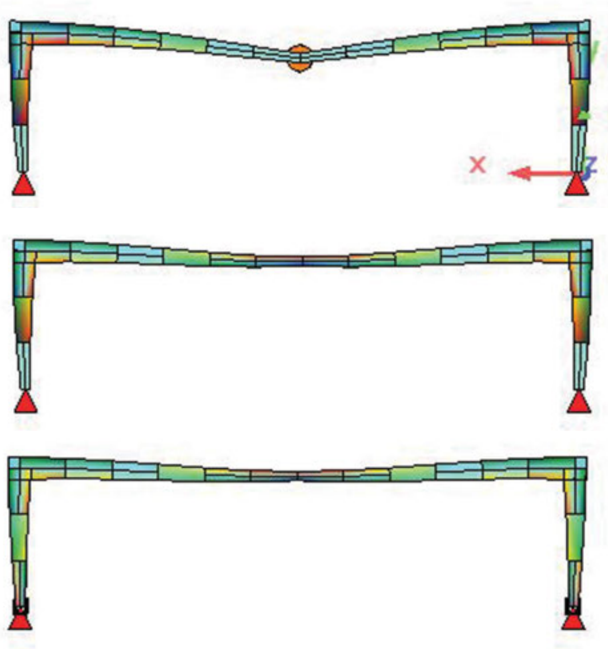


3D overviews showing
typical timber balloon
frame constructions

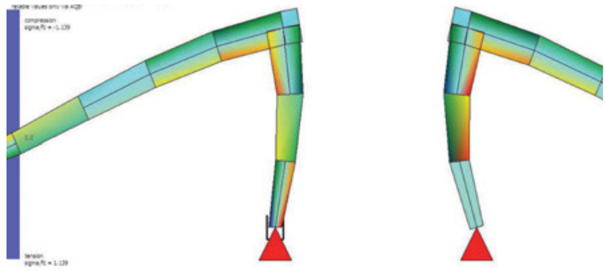




Under the same dead loads applied, the rigid frame shows the lowest bending moment values.



Structural model of typical timber portal frames



Different structural behaviour of pinned and clamped columns.

An essential characteristic of the portal frame is that it supports loads by bending at its primary joints rather than using the pin joints of other frame types. However, in practice portal frames are made in sections which are pin jointed; typically at the top, in the centre and at their base. The frame is made stable in the plane of the frame as a result of the rigid moment connection between the column (or vertical member) and the rafter (or horizontal member). Structural members are formed typically either as solid beams or framed trusses, and resist bending at their knee joint to form the moment connection by the use of rigid connectors. These connectors might be glued joints in laminated timber, metal connectors in framed timber members or welds in steel sections. An advantage of this structural type is in its economic use of material, combined with a simple construction technique. A wide range of structural components can be used, from trusses and trussed columns to I-sections. Although associated primarily with single storey structures, the principle of the portal frame can be applied to multiple storey frames, though they are typically used to provide economic structures for long-span single storey buildings with the benefit of their comparatively low weight.

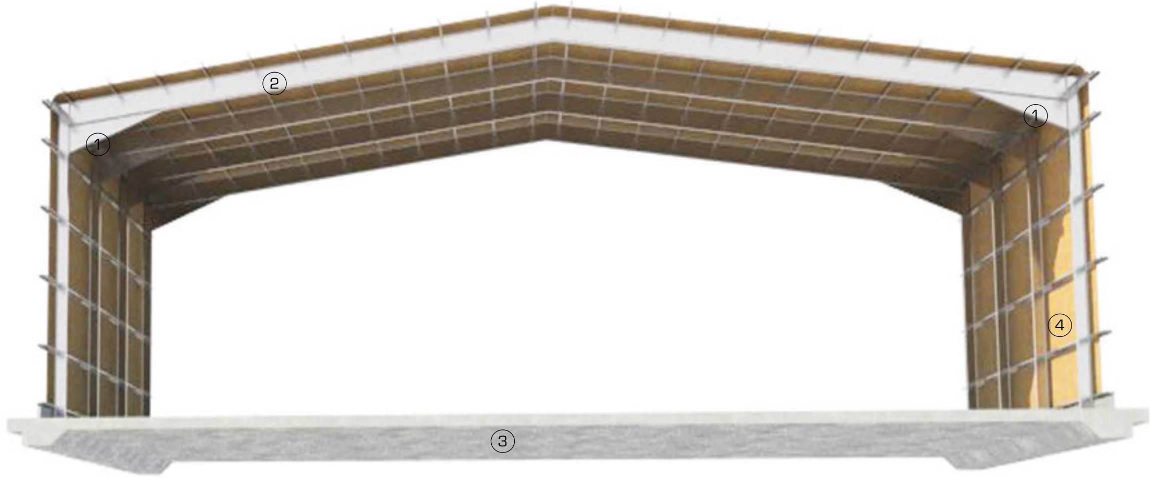
Portal frames are typically made from steel, laminated timber and reinforced concrete. As is the case with arches, there are three types: the rigid frame, the two-pin frame and the three-pin frame. In the rigid portal frame, the structure uses the least material, with the rigidity of the joints being taken down as far as the base of the frame. The pinned types act in a similar way to arches but the loads in each member are resisted in bending. Portal frames are linked together with purlins to form linear arrangements at around 3000mm to 6000mm centres. Since the purlins alone do not usually provide sufficient rigidity in the transverse direction, the frames are stiffened with additional lateral bracing in a few of the bays, usually near the ends of the structure, but this depends on the scale of the structure and the specific design.

Joints and connections

Moment connections are typically either welded or bolted with plates to form haunches. Some steel portal frames use specially fabricated connectors into which standard size box sections can be slotted and welded. Larger scale connectors use castings for both moment and pinned connections, giving a visual continuity to the design, though they are used primarily on larger scale projects where the benefits of making castings in high volume can be made economic. Pinned connections use types illustrated here. Smaller scale portal frames can be fixed together in a way that gives them the appearance of being single components, but which are bolted or glued together on site. This can give the portal frame a more sculptural appearance, with the structure resembling more boat construction than traditional building. The use of digital fabrication tools such as CNC routers brings the opportunity for portal frames to be made in different sizes in order to form a more complex space within the building. The purlin members that connect the portal frames together are then cut at different angles on their ends in order to follow a

3D view showing rigid reinforced steel portal frame

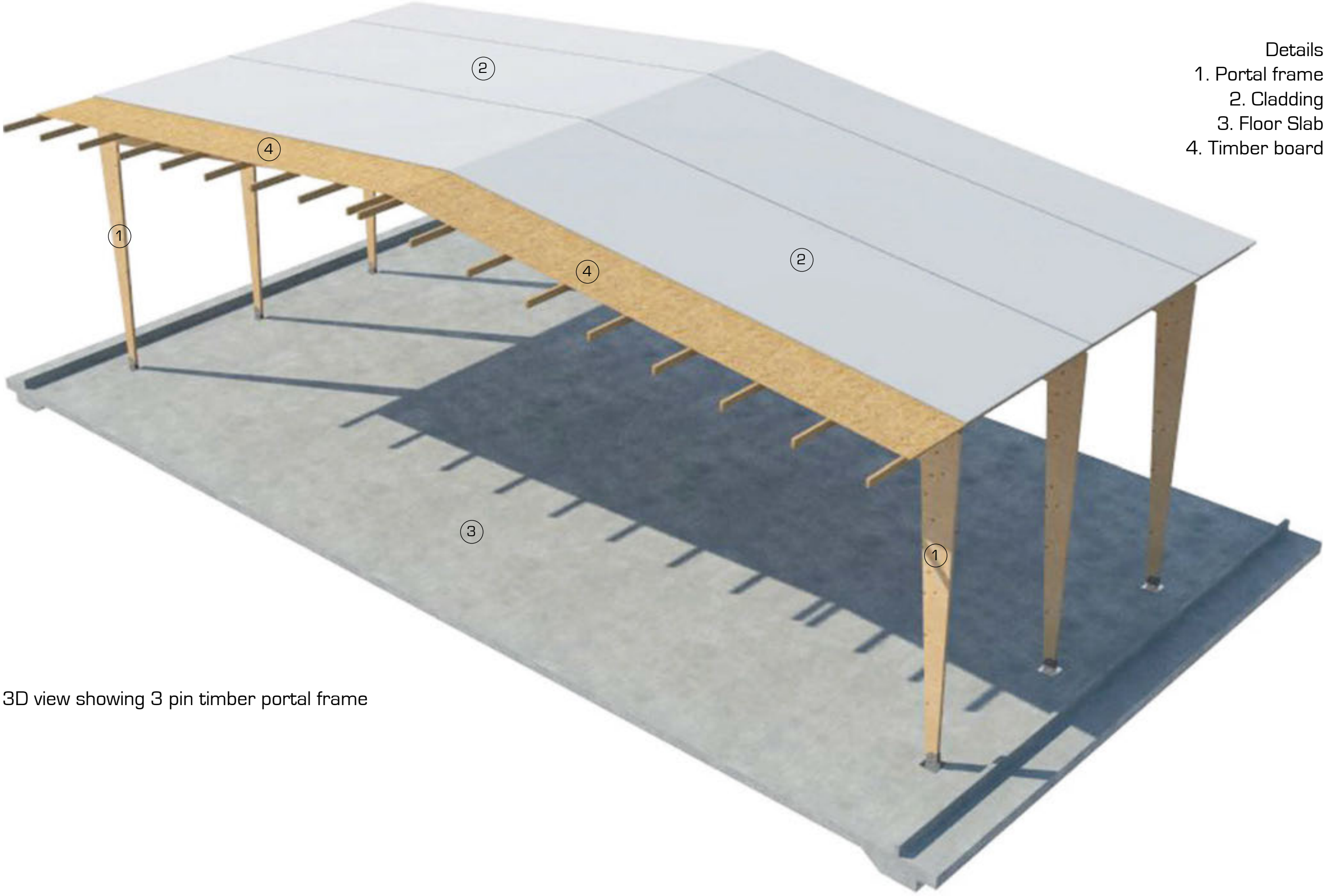
Details
1. Portal frame
2. Cladding
3. Floor slab
4. Timber board



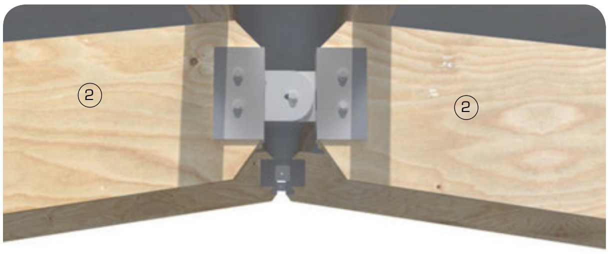
3D view showing rigid reinforced steel portal frame

3D view showing rigid reinforced steel portal frame

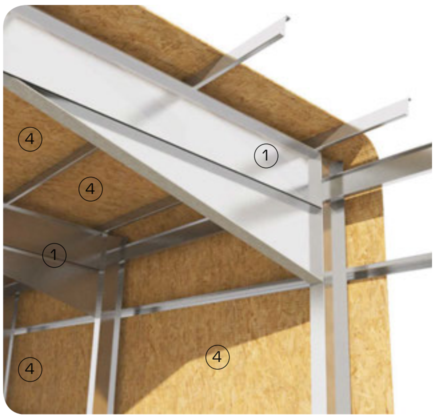
Details
1. Portal frame
2. Cladding
3. Floor Slab
4. Timber board



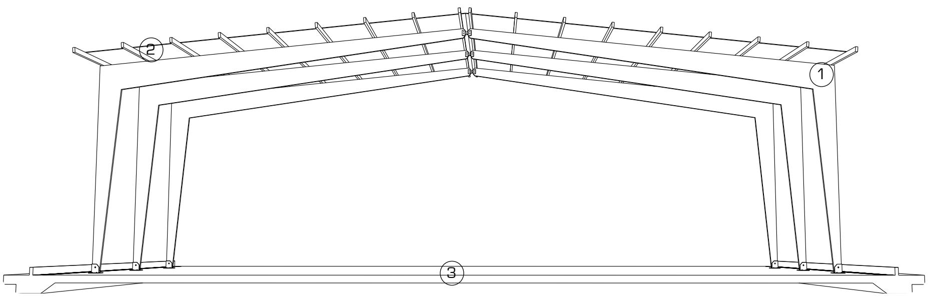
3D view showing 3 pin timber portal frame



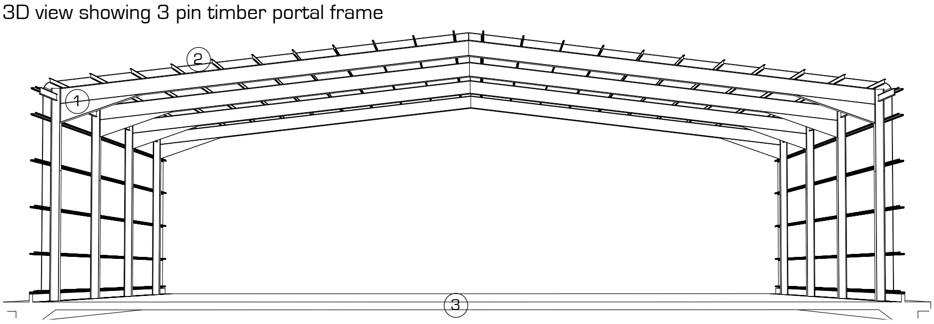
3D view showing pin detail within timber portal frame



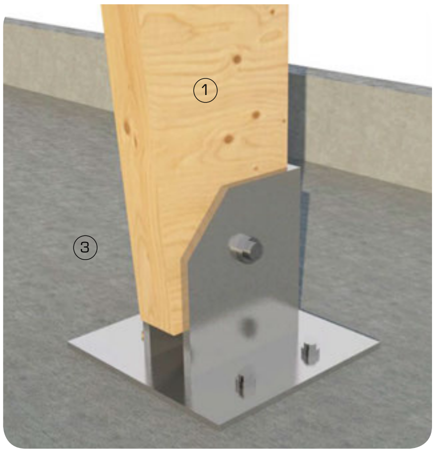
3D view showing corner detail through rigid steel portal frame



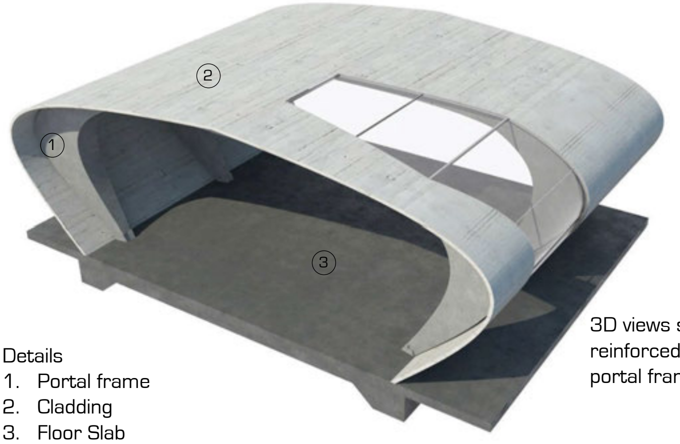
3D view showing 3 pin timber portal frame



3D view showing rigid reinforced steel portal frame

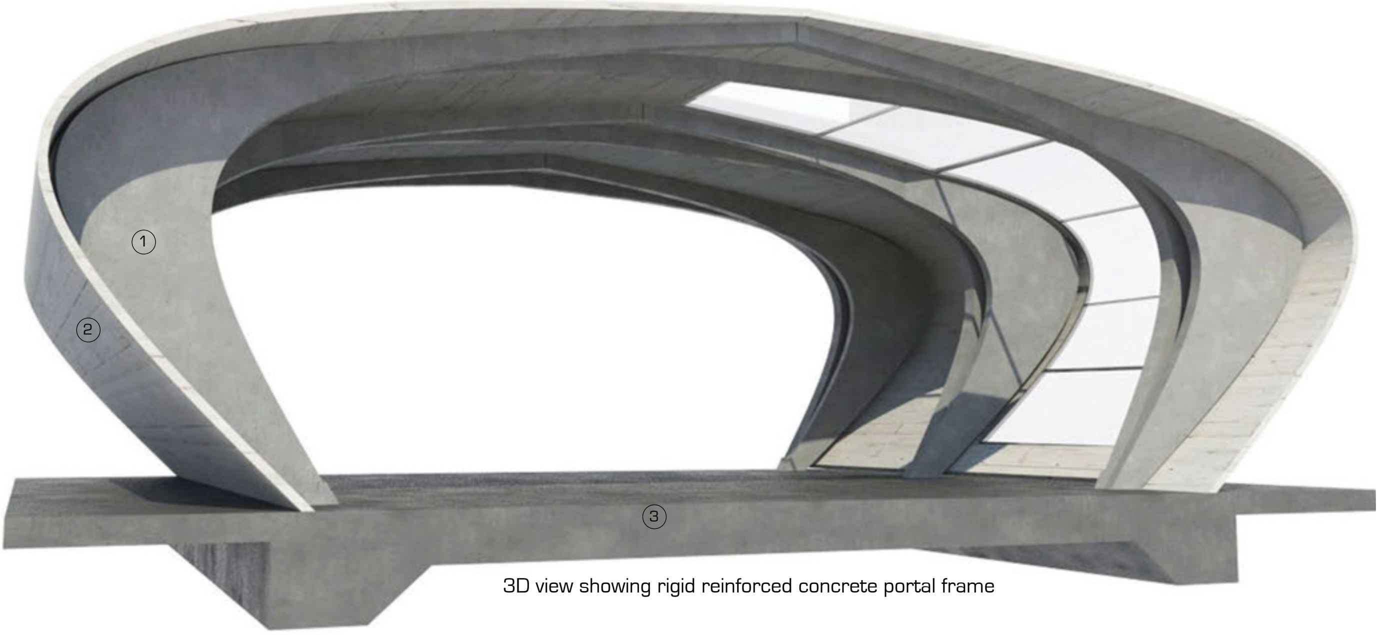


3D view showing base plate acting as pin joint for timber frame timber frame



Details
1. Portal frame
2. Cladding
3. Floor Slab

3D views showing rigid reinforced concrete portal frame

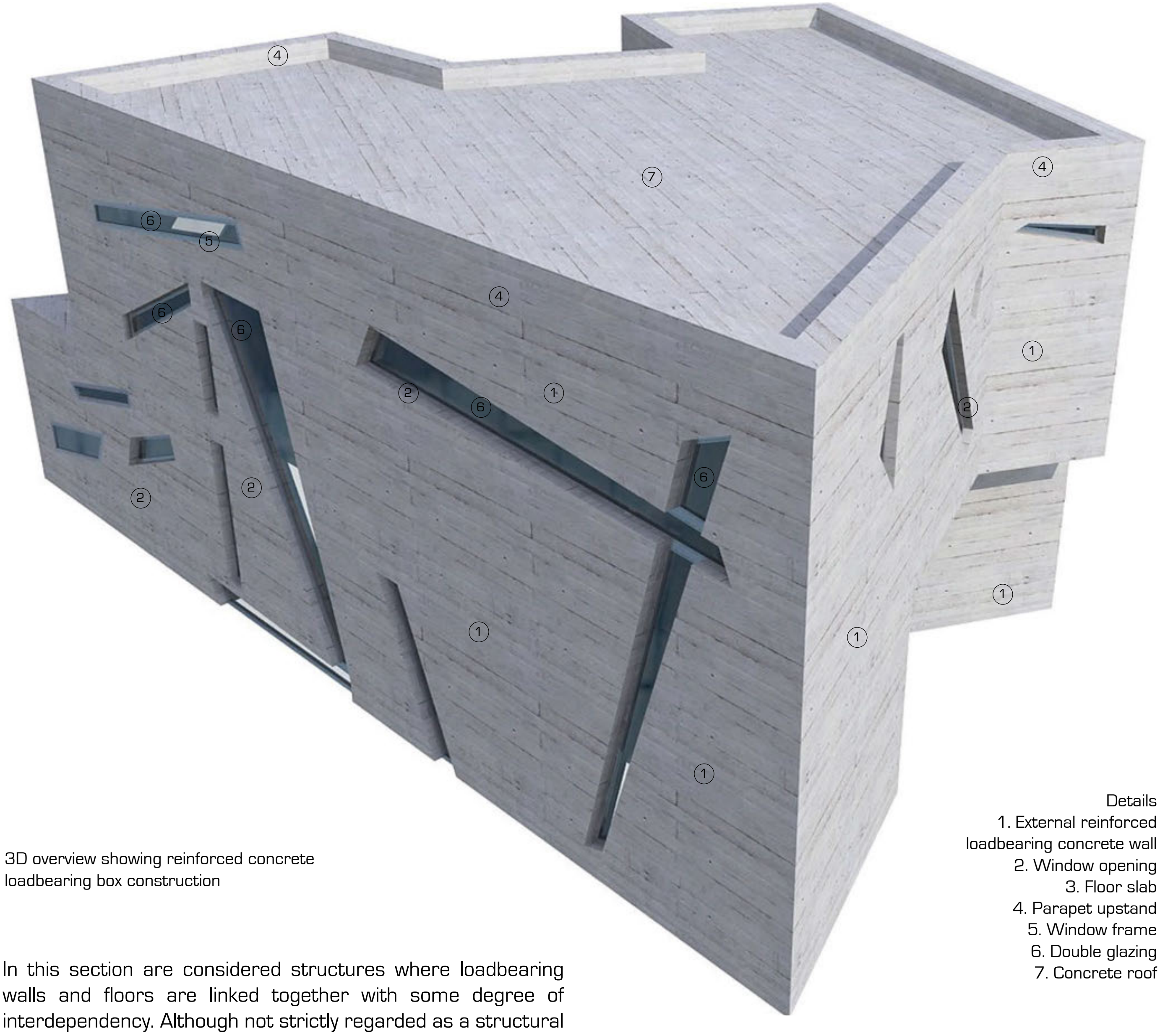


3D view showing rigid reinforced concrete portal frame

particular line across the structure, which may be visible from inside or set in a staggered arrangement to suit the external roof and wall finishes. Portal frames are being increasingly associated with non-rectilinear structures due to their ability to form complex shapes with visually elegant connections. Large scale portal frames can provide a visually elegant and more slender alternative to classic trusses, creating roof structures that more resemble shells than frames. A recent development is a hybrid of portal frame structures which is the use of a 'tree' like column arrangement of portal frame connections at the top of a structure that supports curved beams along its length.

Interface with external envelope

An advantage of portal frames is their ability to form a single surface for both walls and roof. In recent years, sheet metal roofs have been used with small scale portal frame structures, with their ability to render the shape created by the structure. In other examples the external skin is set between the portal frame members, revealing the shape of the frame and making the structure the visual expression of the design. The portal frames are weather protected and thermally insulated, often using the same metal sheet system, but with the opportunity for setting glazed units between the portal frames in line with the adjacent covering for wall and roof. Purlins are used to support the external cladding. Where profiled metal cladding is used they are called sheeting rails. In common with arches, cladding is fixed to these purlins rather than directly to the portals in order to keep the connection type simple. The stiffness of junctions between walls and roof makes the transition in the external envelope straightforward and economic. Larger scale portal frames require a gutter at the edge of the roof, which cannot always follow the geometry of the frame itself. A solution is to set the external envelope away from the portal frame, usually by setting the purlins on the outside edge of the portal frames, thus creating a gap between frame and envelope. This gap can then accommodate the shape of the gutter without interrupting the visual line of the roof / wall enclosure on the outside. The inside face of the external skin can also be lined to conceal the gutter if required. The base of portal frames typically has an upstand to provide weatherproofing at this point, dependent on the position of the portal frames, either at ground level or as part of a larger structure. The upstand provides a termination to the external envelope, forming a transition between wall and adjacent roof deck or ground conditions. The hybrid structures with their tree-like base use a range of curved and welded steel plate and cast connections to create complex forms that serve as moment connections that can contrast visually with adjacent pinned connections at roof level. Generally, the use of portal frame structures as single enclosures suggests a continuation of the interdependency of structure and envelope that are clearly visible in contemporary examples.



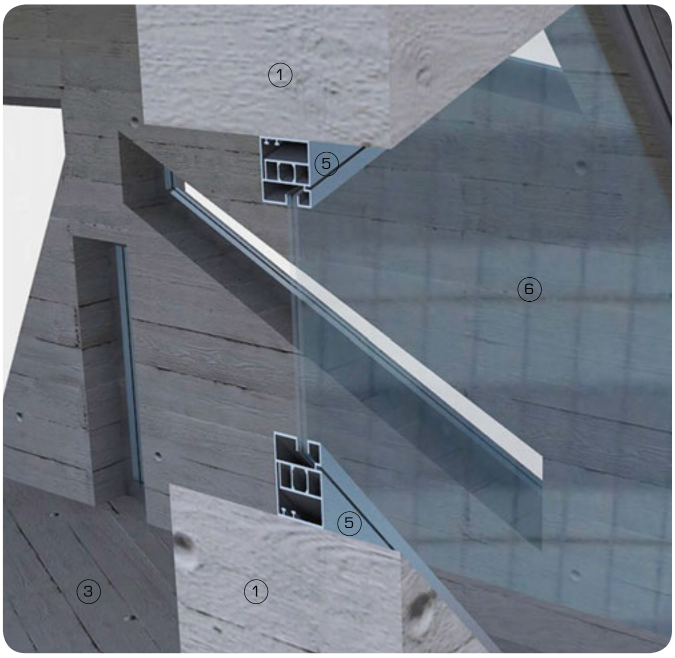
3D overview showing reinforced concrete loadbearing box construction

Details
1. External reinforced loadbearing concrete wall
2. Window opening
3. Floor slab
4. Parapet upstand
5. Window frame
6. Double glazing
7. Concrete roof

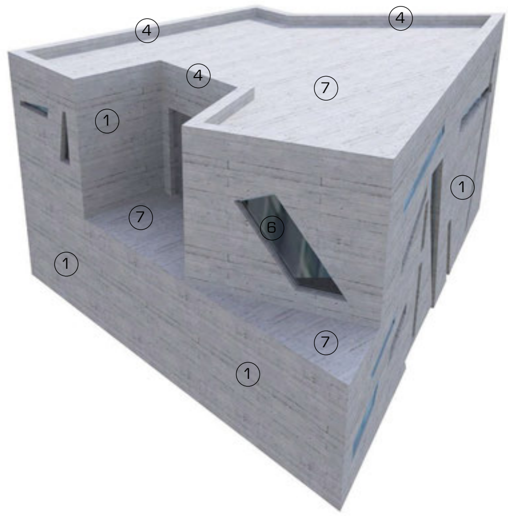
In this section are considered structures where loadbearing walls and floors are linked together with some degree of interdependency. Although not strictly regarded as a structural system, techniques of loadbearing concrete wall and floor construction are very common in Europe for large-scale housing projects. Many European houses are built with loadbearing masonry walls with either timber or concrete floors that provide stability to the external walls.

Concrete loadbearing boxes

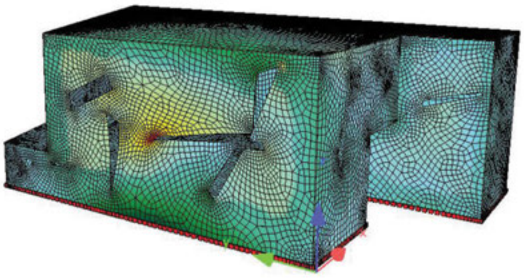
Loadbearing walls and floors made in reinforced concrete can be combined to make a complete monolithic structure. Both in-situ cast and precast concrete techniques can be used, though precast methods suit projects where a high degree of repetition occurs in panel types. Concrete loadbearing boxes have the advantage of high fire resistance combined with high sound insulation from both airborne and impact sound. Concrete can be used in conjunction with both steel and concrete structures. In situ cast techniques generate a monolithic connection between floor and walls. Precast components are stitched together to form a similar connection. Since concrete is not regarded as vapour-proof, the outside of the concrete is either rendered or covered with a cladding system, typically a rainscreen. Measures to ensure thermal insulation, together with finishes, are discussed in the in-situ cast walls section in chapter 2.



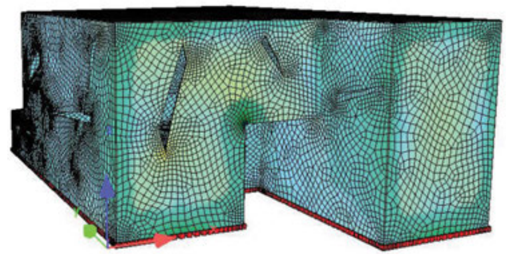
3D detail view showing window opening in reinforced concrete loadbearing box construction



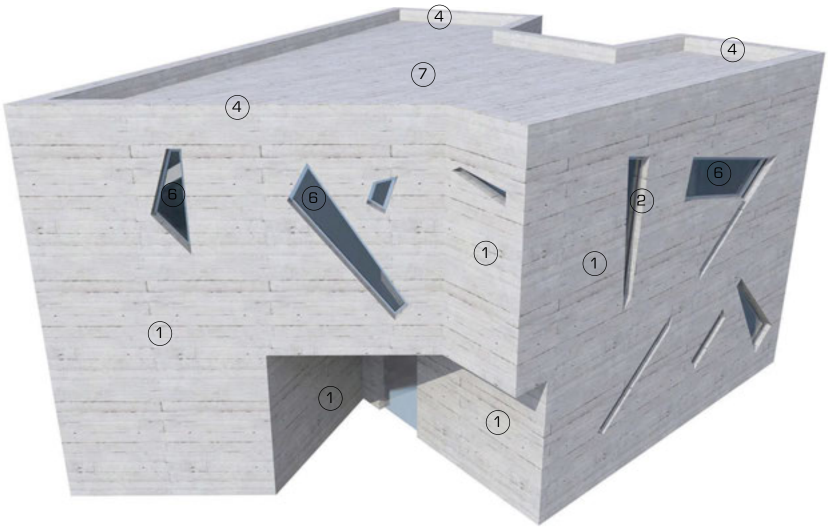
3D overview showing reinforced concrete loadbearing box construction



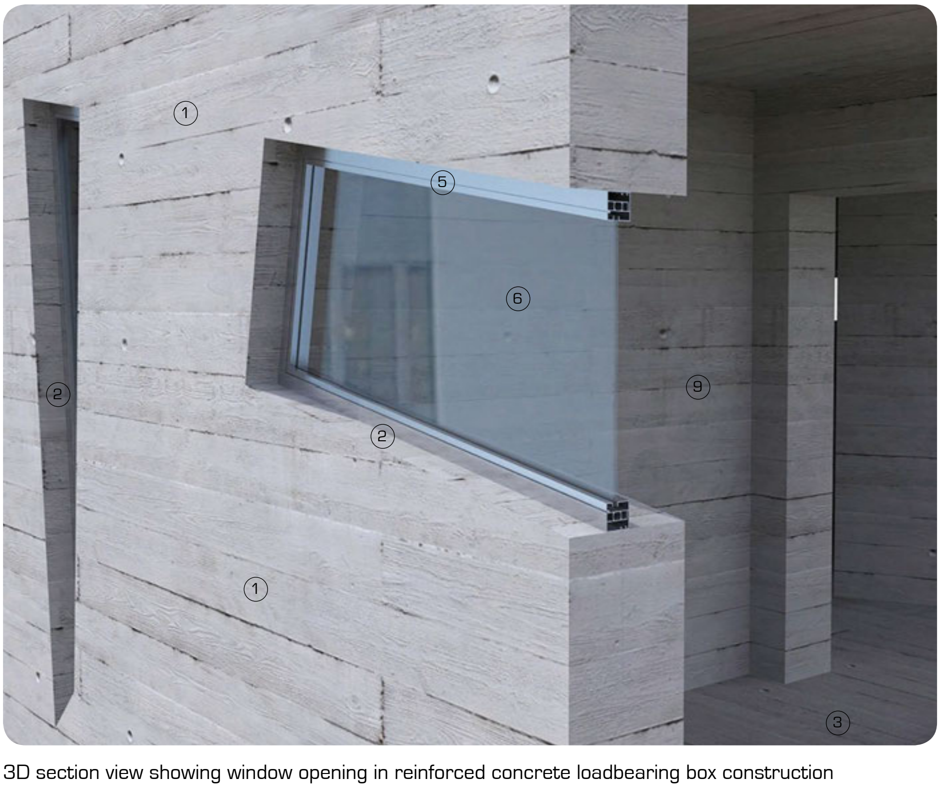
Structural FE model of a loadbearing reinforced concrete structure.



Stress distribution analysis for lateral wind loads (the movements shown are magnified)

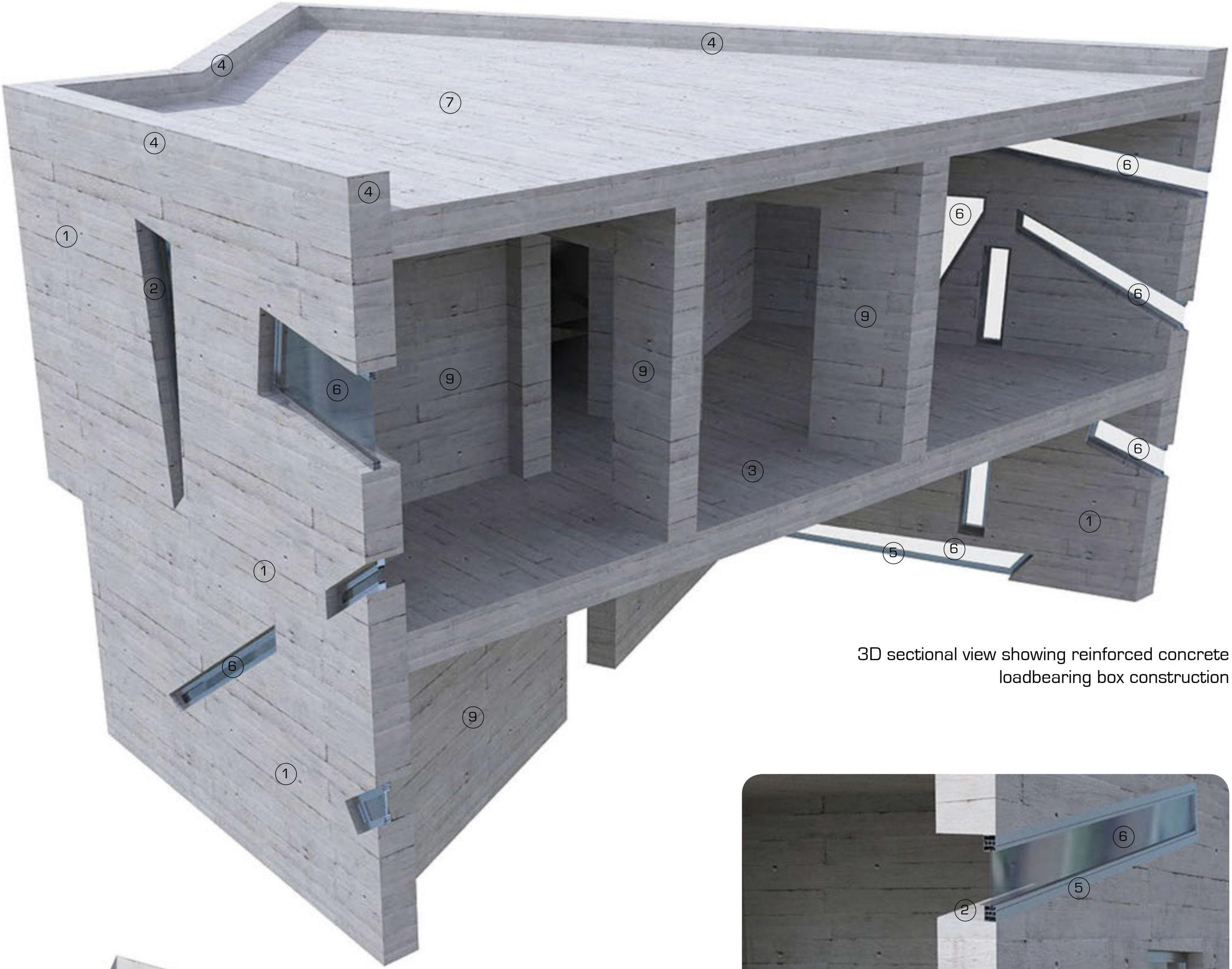


3D overview showing reinforced concrete loadbearing box construction



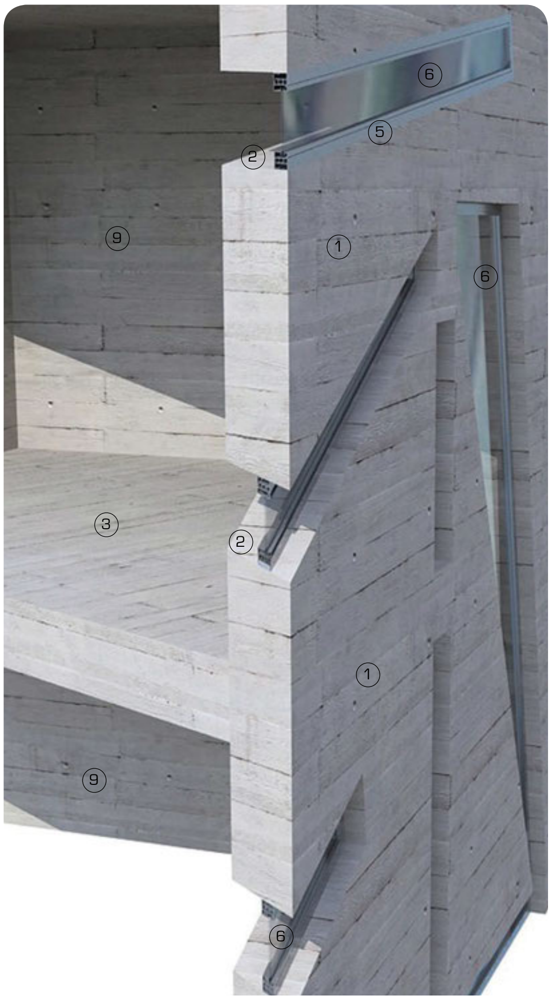
3D section view showing window opening in reinforced concrete loadbearing box construction

3D view showing window openings of varying recess depths in reinforced concrete loadbearing box construction

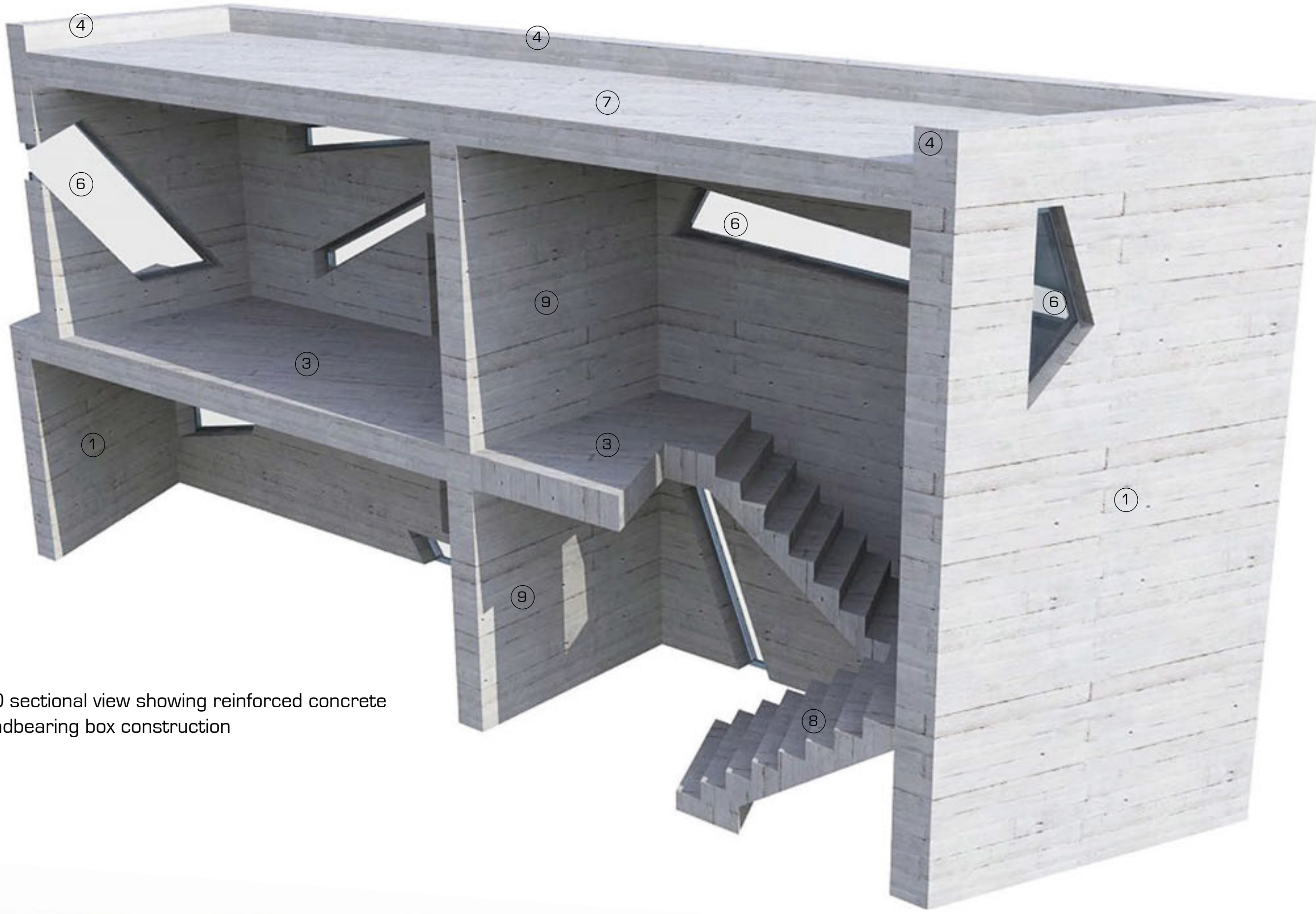


3D sectional view showing reinforced concrete loadbearing box construction

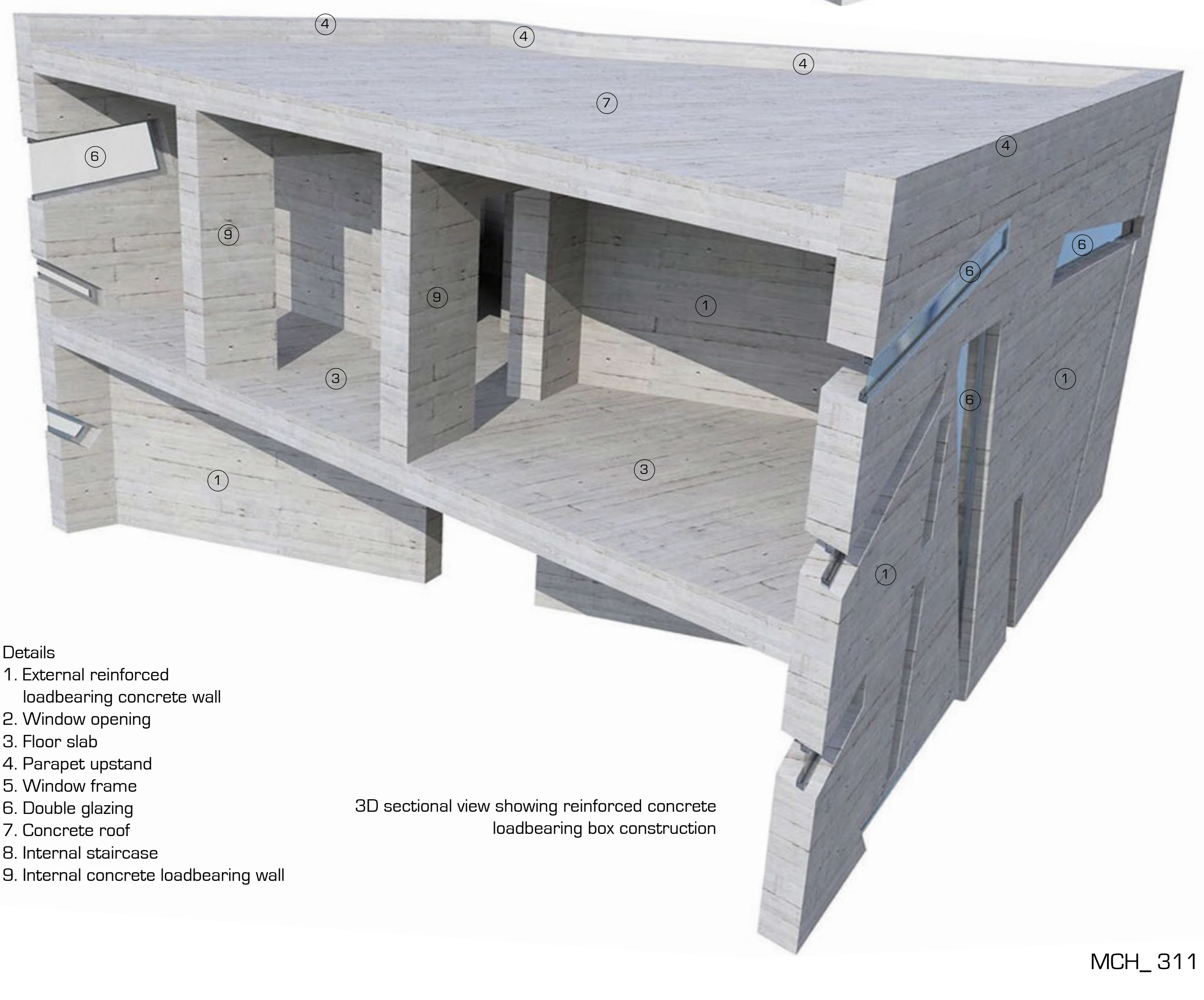
3D overview showing various openings in reinforced concrete loadbearing box construction



3D sectional view showing window openings varying recess depths in reinforced concrete loadbearing box construction

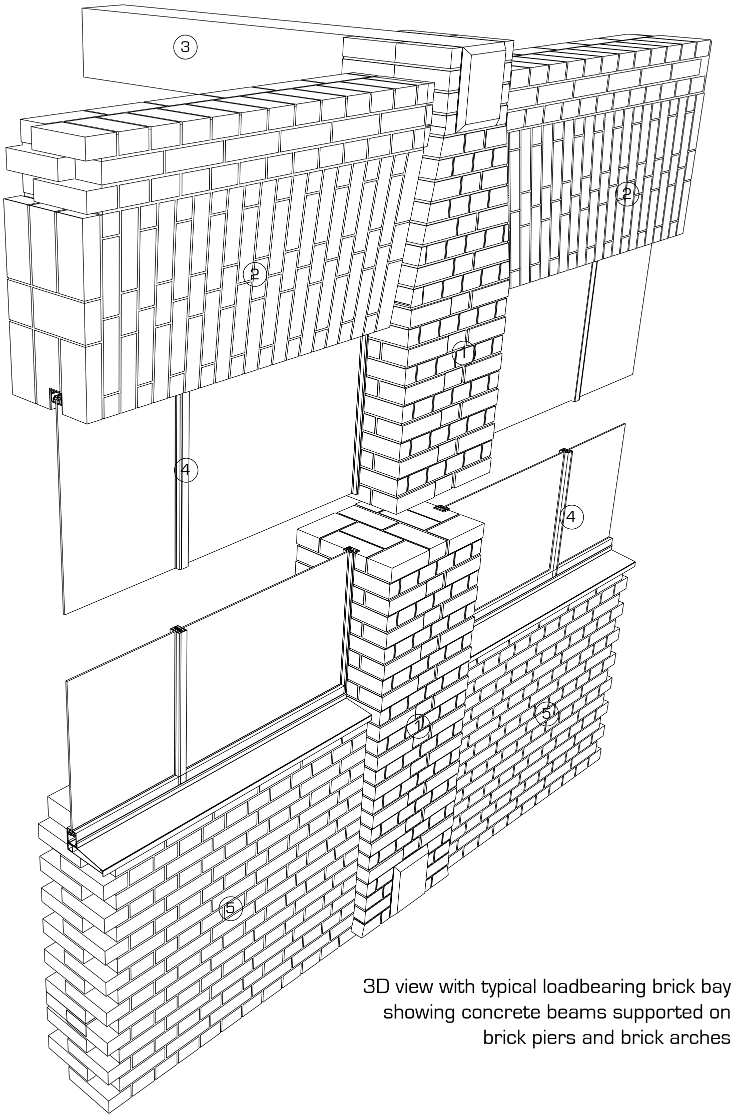


3D sectional view showing reinforced concrete
loadbearing box construction

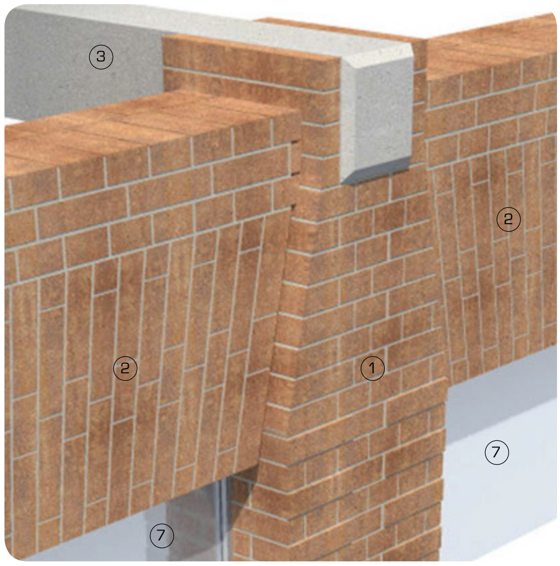


Details
1. External reinforced
   loadbearing concrete wall
2. Window opening
3. Floor slab
4. Parapet upstand
5. Window frame
6. Double glazing
7. Concrete roof
8. Internal staircase
9. Internal concrete loadbearing wall

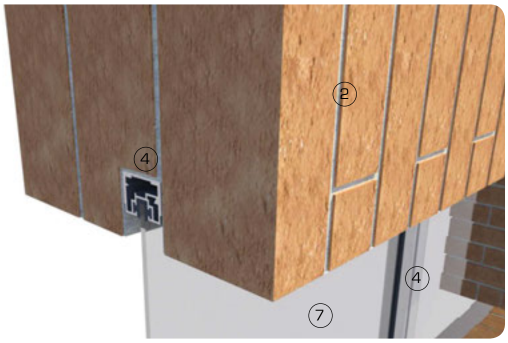
3D sectional view showing reinforced concrete
loadbearing box construction



3D view with typical loadbearing brick bay showing concrete beams supported on brick piers and brick arches



3D detail view showing typical loadbearing brick bay showing concrete beams supported on brick piers and brick arches



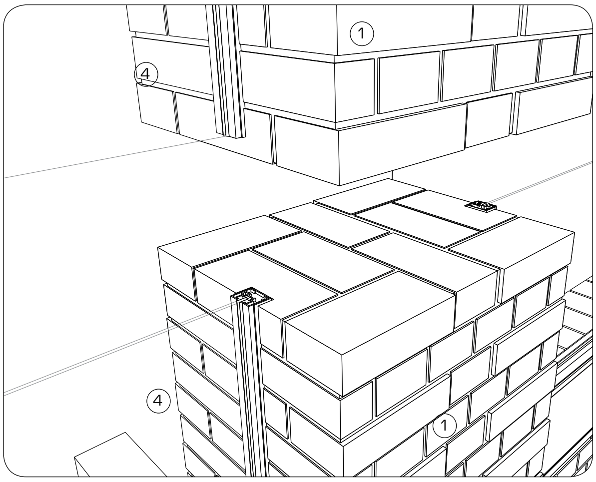
3D view showing window opening in typical loadbearing brick bay

Loadbearing brick structures are rarely used in buildings in industrialised countries since they are more expensive than cavity walls, use more material and are slower to build. Traditionally, they have also been less efficient at excluding rainwater than contemporary cavity walls, with the separation of internal and external skins that has made cavity wall construction a technically accomplished and less expensive alternative to solid, loadbearing construction. Over the past 100 years, the design of brickwork has generally aimed towards increasing its strength through the use of higher strength mortars, though this results in a more brittle structure with reduced flexibility that was provided by the lime-based mortars. This has led to the need for movement joints in the material, usually at around 6.5 metres centres, with the effect that loadbearing walls become a series of linked panels. The gradual re-introduction of lime putty mortars, with their lower strength but greater allowance for movement, is set to change the nature of loadbearing brickwork, and its use is discussed in the Walls chapter.

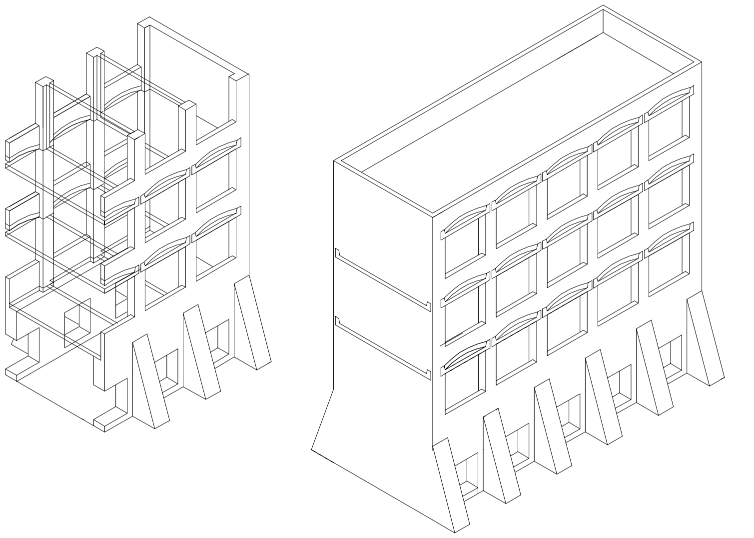
The use of brick in these structures is restricted to the walls, since traditional vaulted brick floors have been superseded by timber or concrete floor construction, which can more easily achieve longer spans. Loadbearing walls are usually much thicker than their cavity wall equivalents, making the structure much heavier in order to provide sufficient waterproofing, since the brick absorbs rainwater near the surface and later dries out. Traditionally, openings in walls have been made with arches of the same material as the surrounding wall and in flat, curved or pointed variations. Flat arches require considerable skill to construct, and are often reinforced with bed reinforcement in the form of steel rod or expanded mesh. In common with other types of masonry construction, brickwork cannot be loaded, and will fail in tension.

Loadbearing brickwork was used in the Indian Institute of Management at Ahmedabad, India (completed 1974) and part of the National Assembly at Dhaka, Bangladesh (completed 1983), both designed by Louis Kahn. The architect had previously used brick slips (thin brick tiles that imitate brickwork) to conceal openings formed in either steel or concrete. In these two projects structural brick arches are used. Because of their large size, spanning up to approximately three metres they were combined with reinforced concrete lintels as tied arches. The ends of the ties were specially formed to bond into the adjacent brickwork, thus avoiding the need for additional steel connectors.

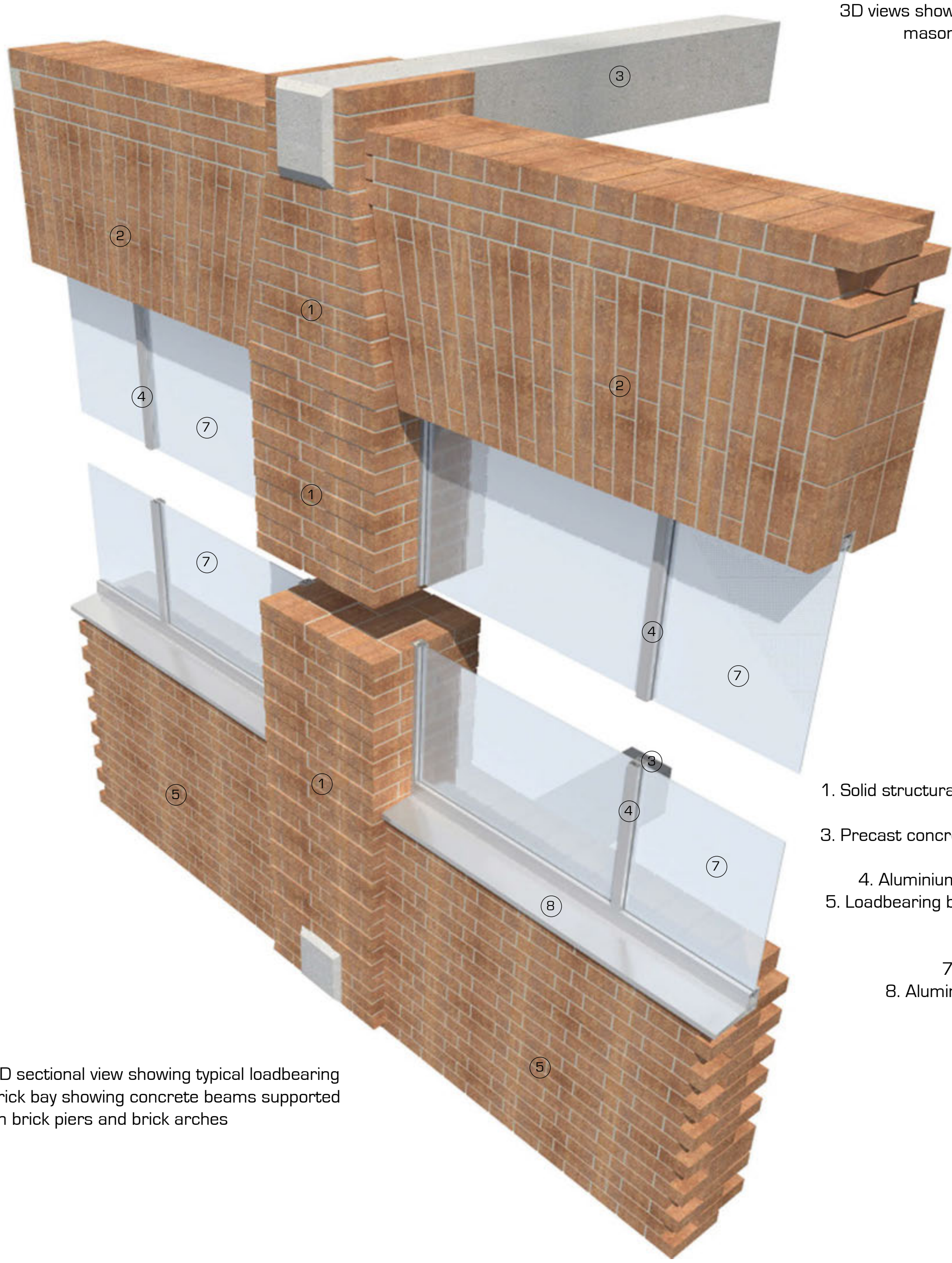
Recent built example
Glyndebourne Opera House in England has loadbearing brick walls, which consist of two skins 220mm thick with a 50mm cavity providing acoustic separation. The inner leaf supports the back of the balconies. The brickwork forms a loadbearing drum 33.7m in diameter, 17.7m high, truncated on one face where it intersects with the fly-tower. From this wall radiates a series of precast concrete panels that form the soffit to the



3D detail showing window opening in loadbearing masonry construction configuration

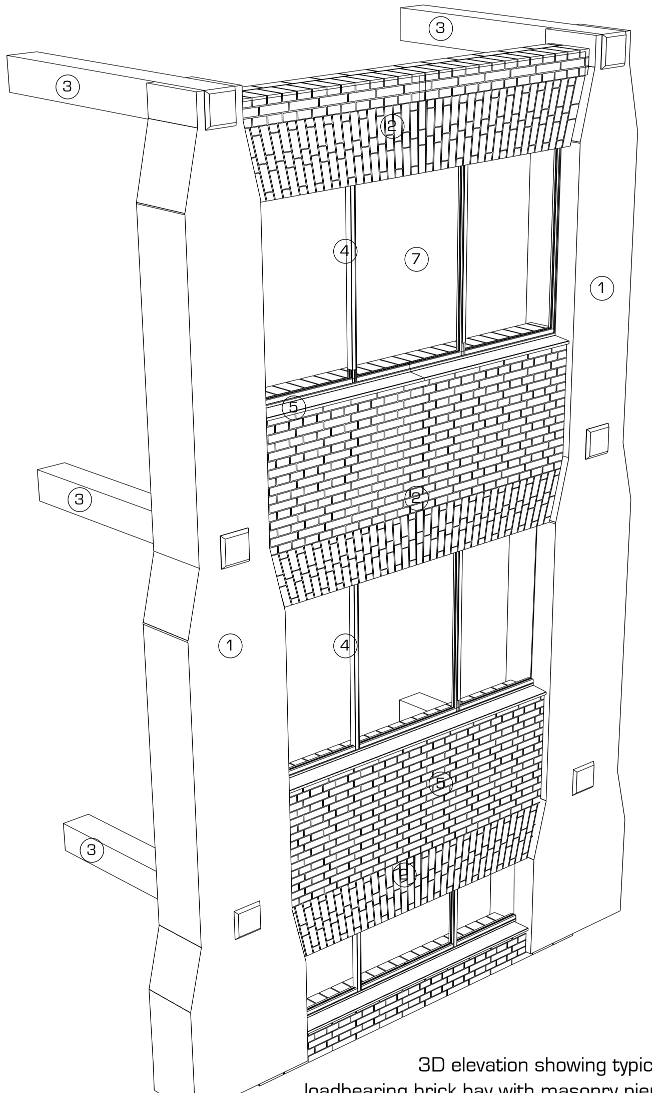


3D views showing loadbearing masonry construction configuration



Details
1. Solid structural brickwork pier
2. Brick arch
3. Precast concrete floor beams with padstone
4. Aluminium window frame
5. Loadbearing brickwork wall in English Bond
6. Floor slab
7. Double glazing
8. Aluminium window cill

3D sectional view showing typical loadbearing brick bay showing concrete beams supported on brick piers and brick arches



3D elevation showing typical loadbearing brick bay with masonry piers

3D elevation showing typical loadbearing brick wall configuration with masonry piers

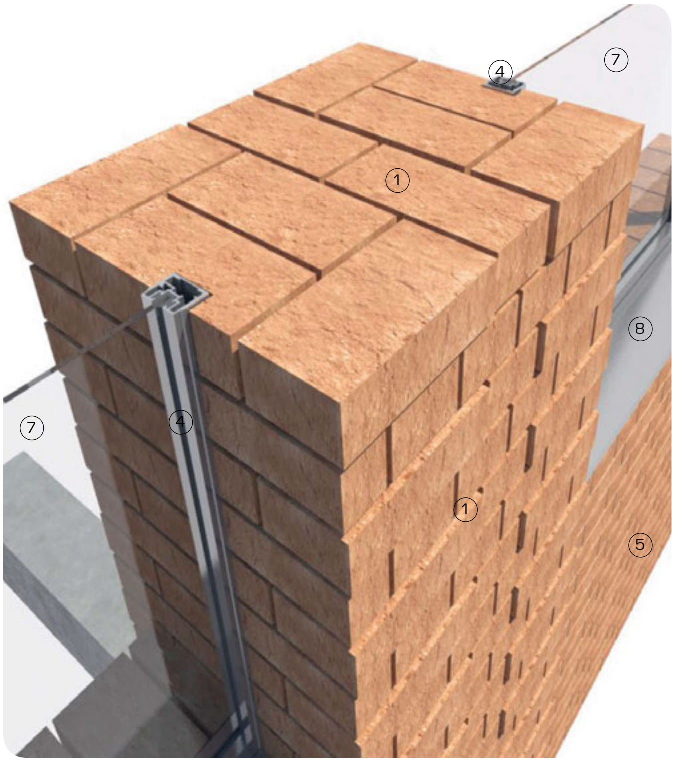
balconies and partially support the seating above. In-situ cast columns that are tied together with an in-situ cast topping and ring beam provide additional support. Where the structure runs alongside the side stages, the inner wall becomes an acoustic wall 220mm thick, but elsewhere it is less dense and where it is punctured by openings providing access to the auditorium, it becomes a series of piers. The walls supporting the balconies are 334mm thick continuous skin, supported by flat arches resting on gently tapering brick piers. The mix used for the lime putty mortar in the brickwork was a 1:2:9 (cement:lime putty:sand) ratio by volume. The cement gave early strength to the wall and slightly improved durability and weathering. The compressive strength of the bricks was 27.5N/mm2 and that of the lime putty mortar was 1.5N/mm2. This provided an overall compressive strength of 6.2N/mm2, which is less than half that of conventional brickwork at around 15N/mm2.

Current applications

The use of loadbearing brickwork in recent economic applications has been mostly in situations where thermal insulation is not required, such as in walls set externally to form a screen wall to external spaces or semi-external spaces. Alternatively, the loadbearing wall is used in a hybrid condition, where it supports itself in the manner of the outer leaf of a cavity wall, but is only connected at points to the floor slabs behind in order to reduce the thermal bridge through the material. Thermal insulation, when required, is set on the inside face of the wall, and is also set between slab and wall. These applications are set to revitalise the use of brickwork as they start to combine the authenticity of loadbearing walls with contemporary requirements for weatherproofing and thermal insulation. An advantage of loadbearing brickwork is its ability to vary in thickness to suit structural requirements without the need for the stainless steel fixings and supports associated with cavity brick walls, where any modelling of the surface of the wall is difficult to accommodate structurally due to the nature of its construction, which is to be non-loadbearing. Loadbearing brickwork is also able to use other materials in its construction, from cut stones forming pieces of loadbearing arches to precast concrete ties, lintels and cills as an integral part of the construction. The additional cost of this form of construction over that of cavity wall construction makes its application less widespread, but this may change with the possibility of prefabricating sections of the wall away from the site, and assembling the pieces on site in the manner of precast concrete construction, where speed of construction is a benefit. Some recent examples have set steel reinforcement into the depth of the wall so as to increase its strength, and resistance to wind load, without increasing its thickness beyond one and a half bricks thick, which is generally considered to be the minimum thickness of loadbearing walls which can exclude rainwater (though this is not always sufficient, of course). The use of steel reinforcement can help reduce the overall weight of the wall in order to remain within the loadbearing capacity of the wall.

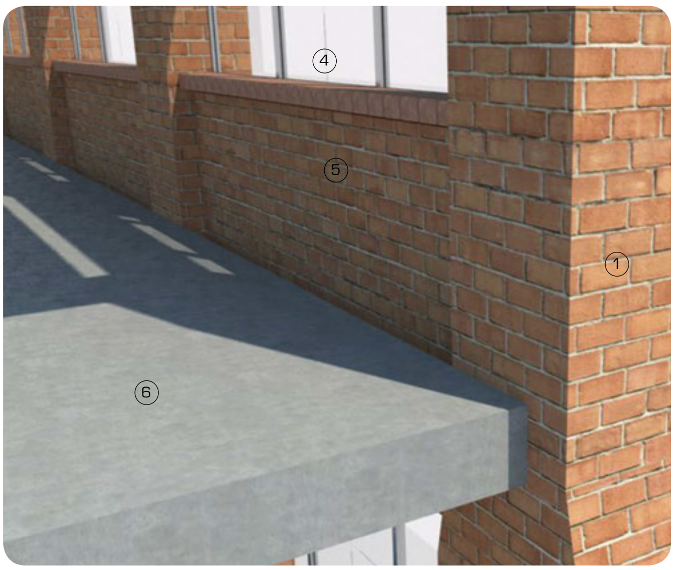
3D view showing window opening in typical loadbearing brick bay

Details
1. Solid structural brickwork pier
2. Brick arch
3. Precast concrete floor beams with padstone
4. Aluminium window frame
5. Loadbearing brickwork wall in English Bond
6. Floor slab
7. Double glazing
8. Aluminium window cill

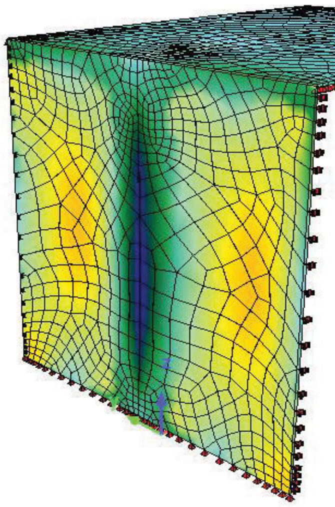


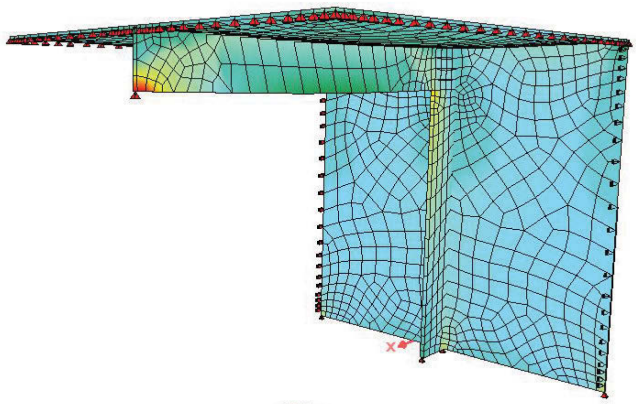
3D view showing window opening in typical loadbearing brick bay at brick pier

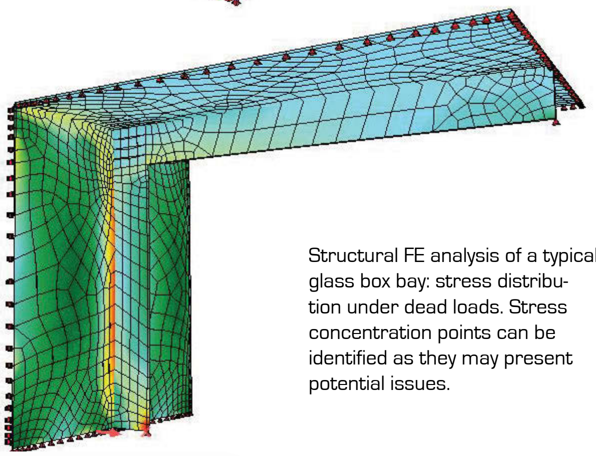
3D view showing typical loadbearing brick bay



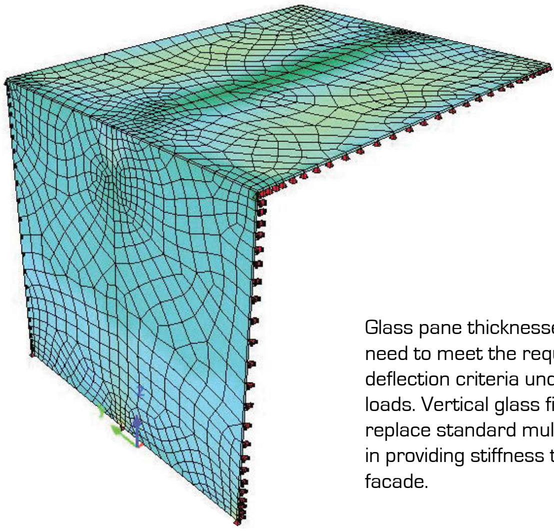
3D view showing floor slab junction in typical loadbearing brick wall configuration



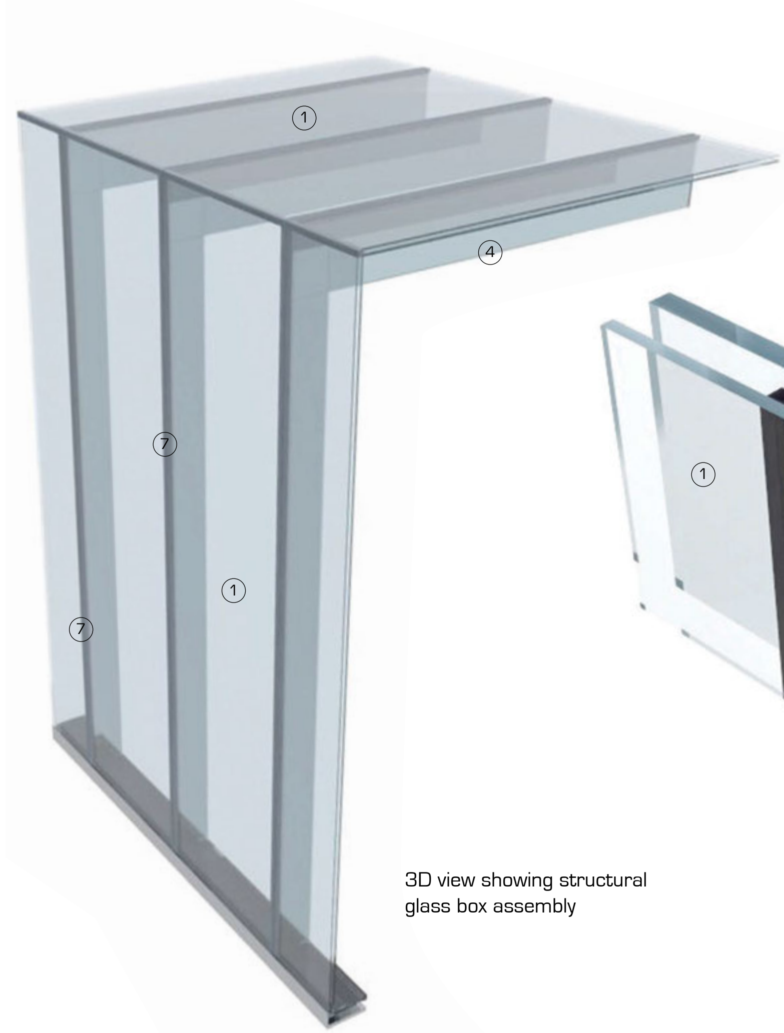




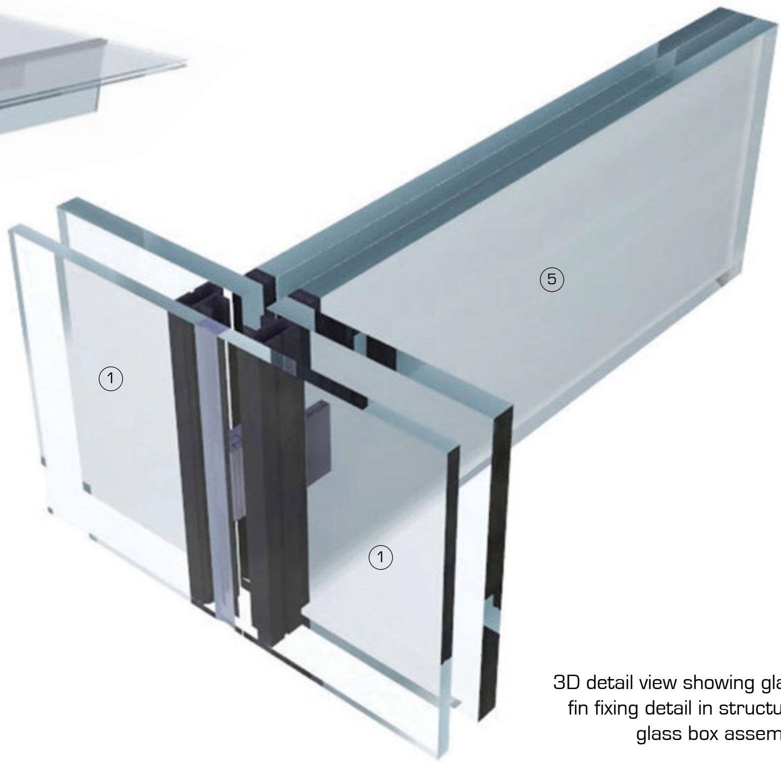
Structural FE analysis of a typical glass box bay: stress distribution under dead loads. Stress concentration points can be identified as they may present potential issues.



Glass pane thicknesses need to meet the required deflection criteria under wind loads. Vertical glass fins may replace standard mullions in providing stiffness to the facade.

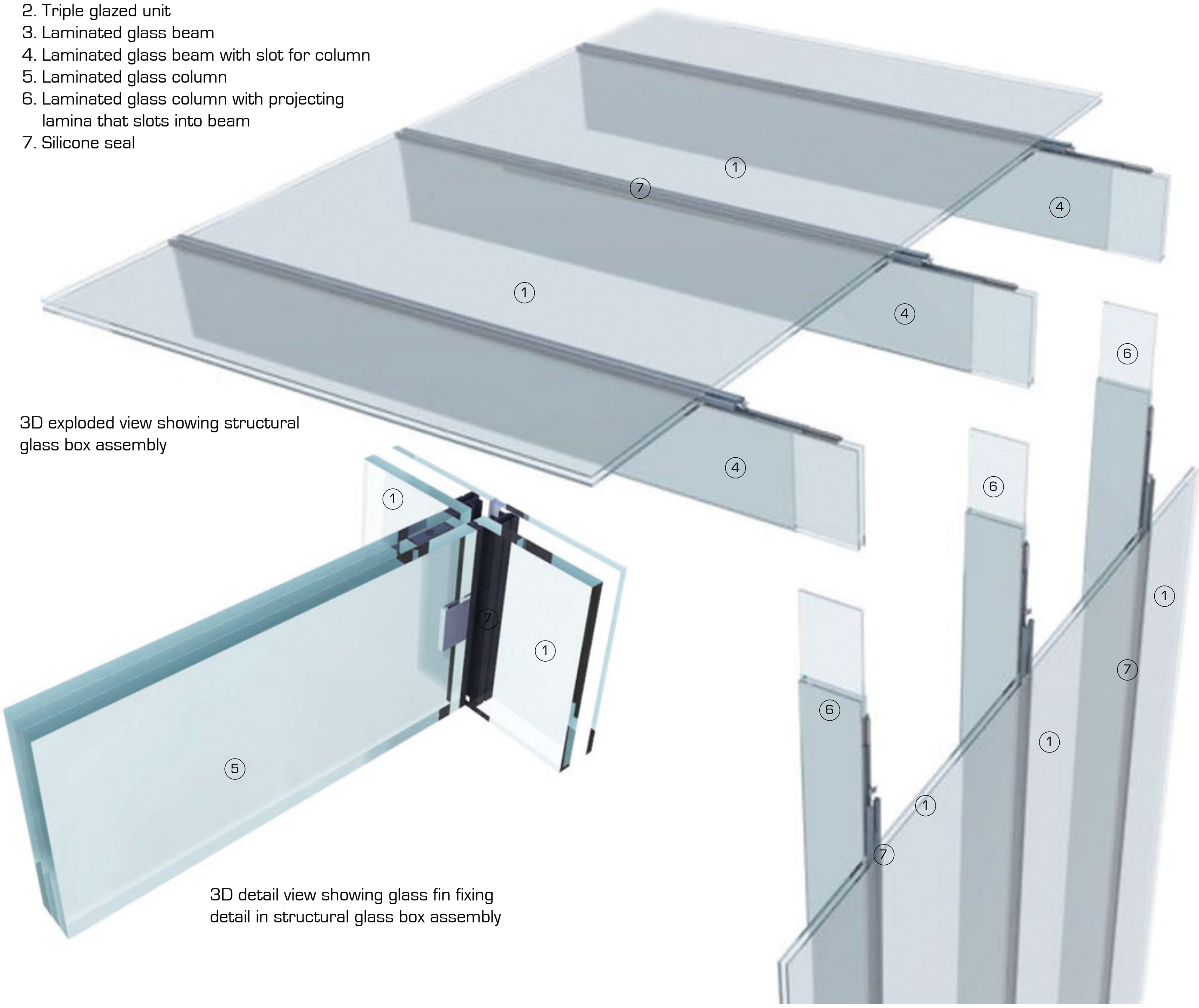


3D view showing structural glass box assembly



3D detail view showing glass fin fixing detail in structural glass box assembly

Details
1. Double glazed unit
2. Triple glazed unit
3. Laminated glass beam
4. Laminated glass beam with slot for column
5. Laminated glass column
6. Laminated glass column with projecting lamina that slots into beam
7. Silicone seal

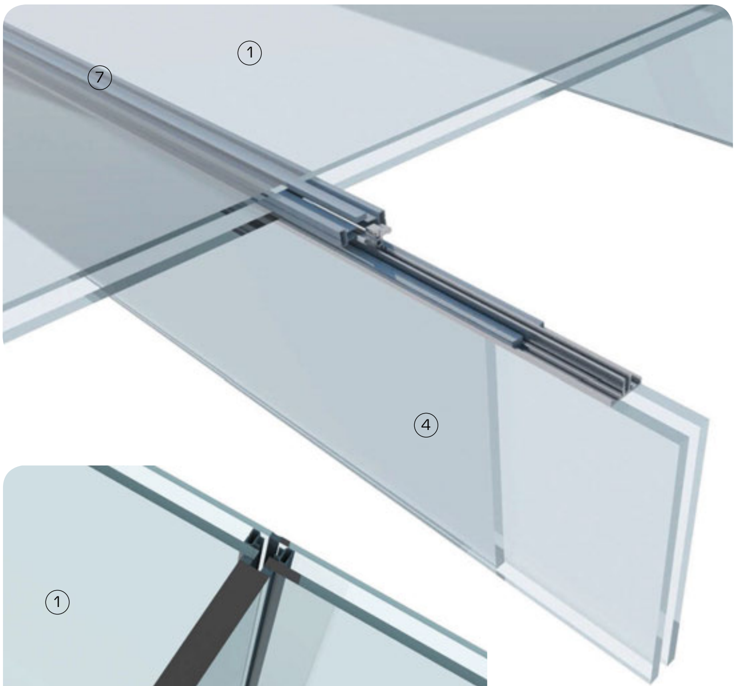


3D exploded view showing structural glass box assembly

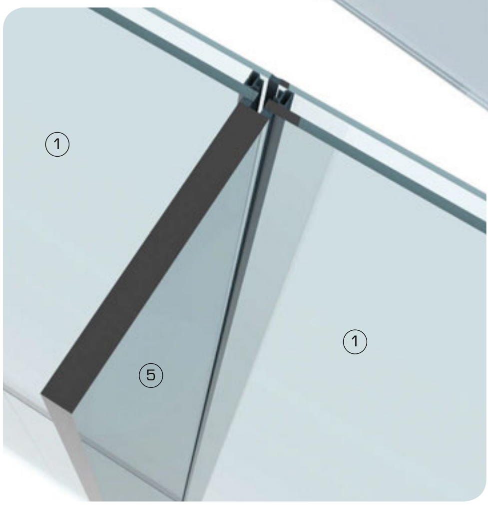
3D detail view showing glass fin fixing detail in structural glass box assembly

All-glass loadbearing structures are a recent development in the design of small scale glass enclosures. Their intention is usually to maximise transparency, and their application on single storey enclosures ensures that glass sheets can form walls without the need for aluminium or steel framing. Typically, double glazed units are set vertically, with examples 1500mm wide x 3000mm high. These larger size panels require glass fins set vertically to take the place of glass mullions, but glass units 2100mm high sometimes do not require any glass fins, depending on the wind load. Double glazed units are also used to form roof panels, set onto glass beams which are fixed to the vertical glass fins. Where no vertical fins are used, the glass beams can be fixed to stainless steel brackets or shoes which are bolt fixed to the double glazed units forming the external wall. The beams, fins, wall panels and roof panels are bonded together, typically with silicone, to form an all-glass structure. In practice, most all-glass structures have additional mechanical fixings to secure all components, as a completely bonded glass structure has obvious risks associated with its design. A typical fixing might be a toggle type fixing where a flat metal plate is used to hold double glazed units in place. The double glazed units have an edge spacer with a groove around the edge to which the toggle plate can be fixed. The silicone between double glazed units can then be silicone sealant rather than a silicone bond. The junction between vertical glass fins and glass beams supporting the roof panels may still use a silicone bond. The glass types used are a combination of tempered and laminated glass which is bonded or bolted together to form beam and column components. In common with bolt fixed glazing, an essential consideration in the design of loadbearing glass structures is the avoidance of any stress concentrations that might lead to glass breakage while the structure is under normal load conditions. Since the techniques used are very recent, no general principles for construction are set out here but two recent examples are shown. Sometimes a glass fin can be used at roof level only, projecting down the wall for a short distance and remaining above head height to avoid risk of injury to users.

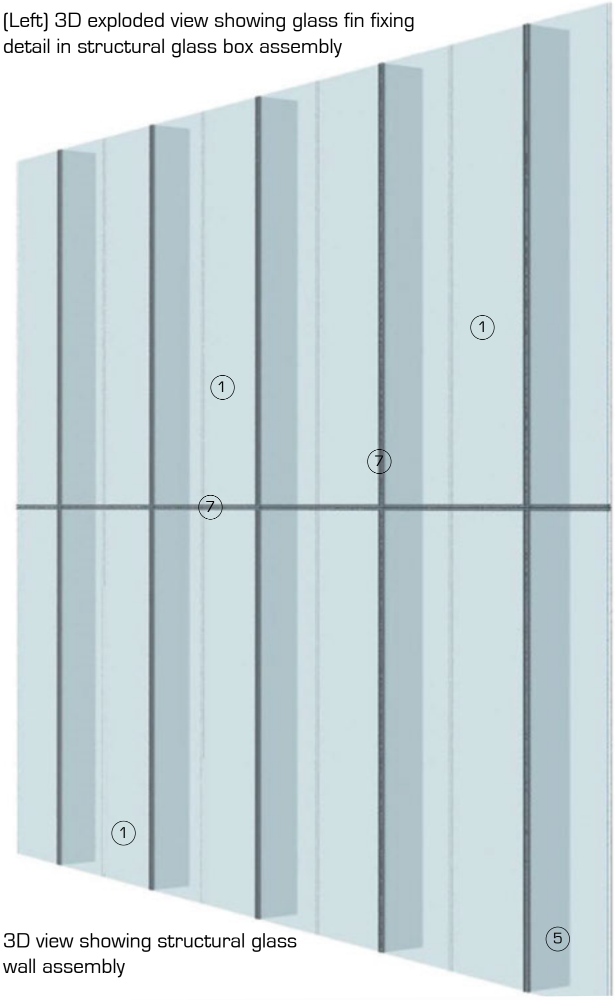
All-glass enclosure, Broadfield Glass Museum, West Midlands, England. (see page 289)
The architect was Brent Richards of Design Antenna working with structural engineers of Dewhurst MacFarlane. The



(Left) 3D exploded view showing glass fin fixing detail in structural glass box assembly



(Left) 3D view showing glass fin fixing detail in structural glass wall assembly



3D view showing structural glass wall assembly

3D view showing structural glass wall assembly

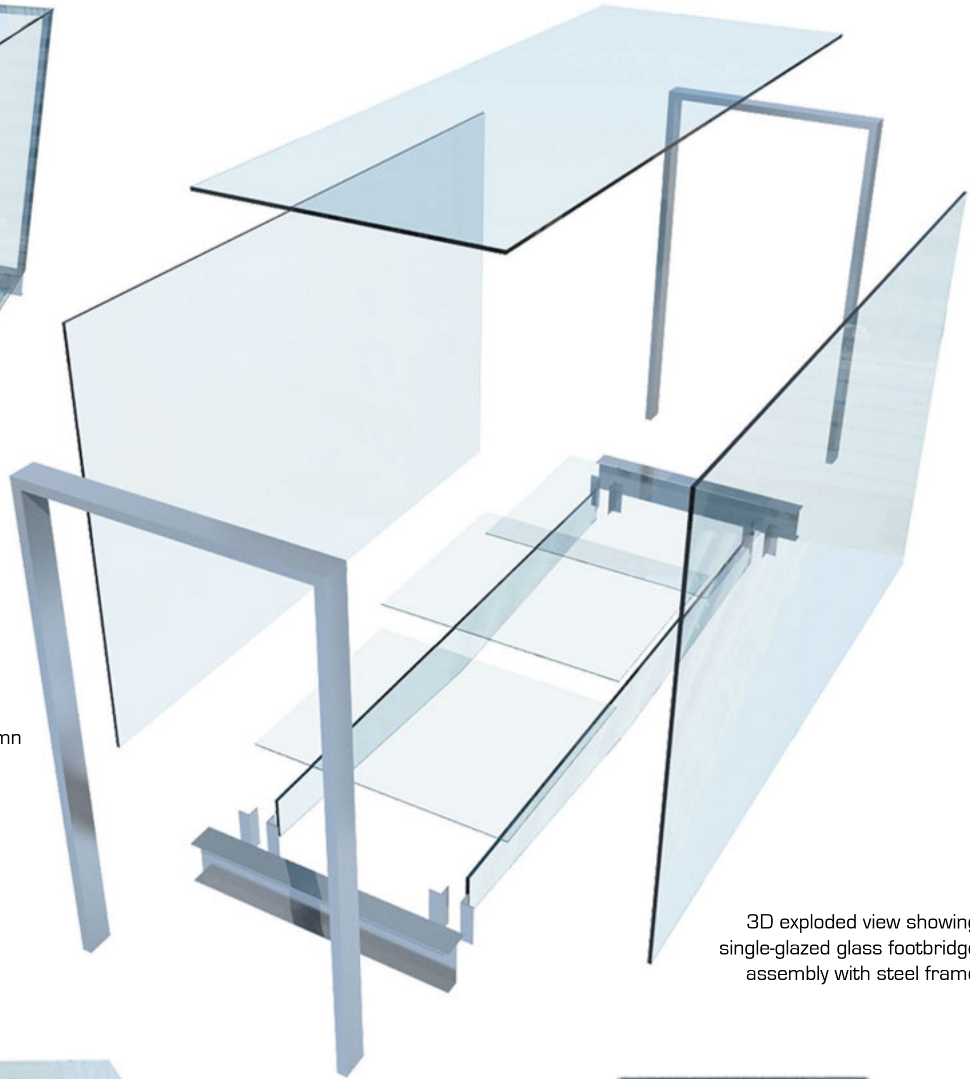
enclosure is constructed without metal fixings or supports in any another material. It is 11m long, 5.7m wide and 3.5m high. The primary structure consists of glass beams 5.7m long x 300mm deep, at 1000mm centres. One end is supported by an existing masonry wall, whilst the other is supported on glass columns 3.5m high and 200mm deep.

The beams and columns are made from three sheets of glass laminated together, making them 32mm thick. At the rear, the beams are secured by shoes in steel fixed to the wall, while on the glazed side they are connected to the columns in an interlocking of the glass layers. The junction was bonded on site with a catalyst-cured resin. The glass roof panels are bonded to the top of the glass beams. The double glazed roof panels have an outer layer of 10mm thick toughened glass, a 10mm air gap and an inner skin of two sheets of 6mm glass laminated together. A silver film on the inner face of the upper sheet reduces solar gain, as does the ceramic fritting on the inside face of the panel.

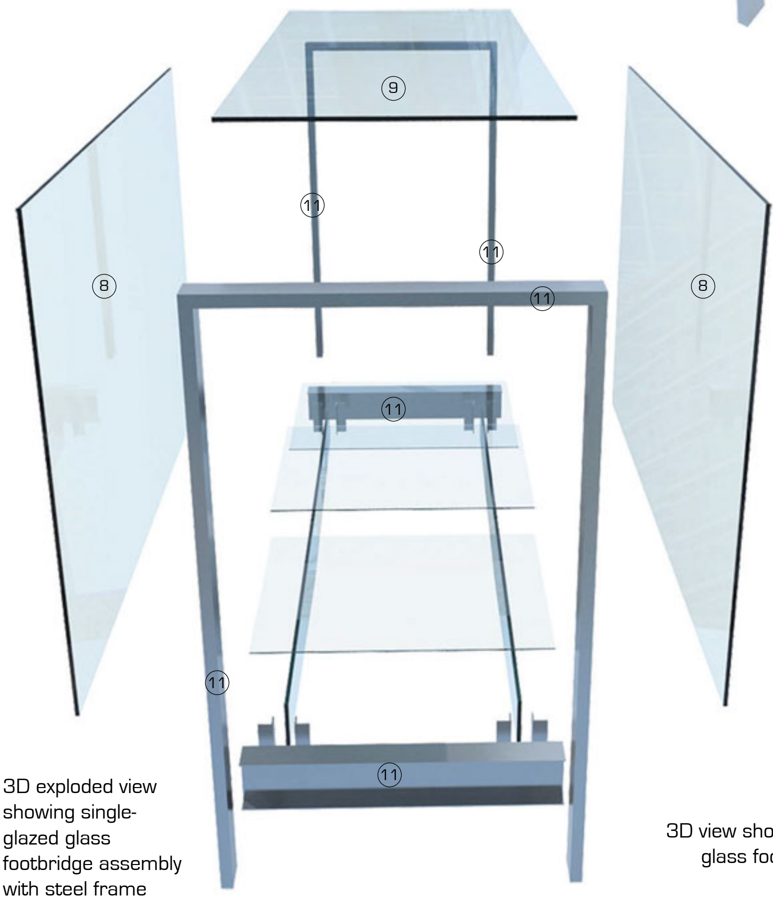
The roof panels are bonded to the beams with structural silicone bead with a rigid foam backing. The gap between the panels is sealed using a silicone-rubber weather seal with a foam backing. The roof slope is 1.5º. The roof can be walked upon for maintenance, and supports expected snow loads. The front walls consist of 3.7 metre x 1.1 metre high double glazed panels composed of two sheets of 8mm toughened glass with a 10mm air gap.

All-glass footbridge, Rotterdam, Holland (see page 289)
This footbridge was designed by the architect Dirk Jan Postel of Kraaijvanger-Urbis, working with Structural Engineer ABT Velpe. The bridge spans three metres with floor plates of 15mm laminated float glass supported on two laminated glass beams made from float glass. The side-walls consist of double glazed units made from 10mm and 6mm thick toughened glass sheet. In addition to being self-supporting, the walls support the glass roof, which has the same type of laminated construction as the walls. The all-glass components are fixed together with stainless steel brackets and plates. The use of stainless steel fixings does not noticeably reduce the transparency of the structure, instead adding a sense of visual refinement, while the curve of the beams supporting the floor deck contrasts with the rectilinear design of the glass enclosure. From a visual point of view, the all-glass design makes it easy to link with existing buildings on either side.

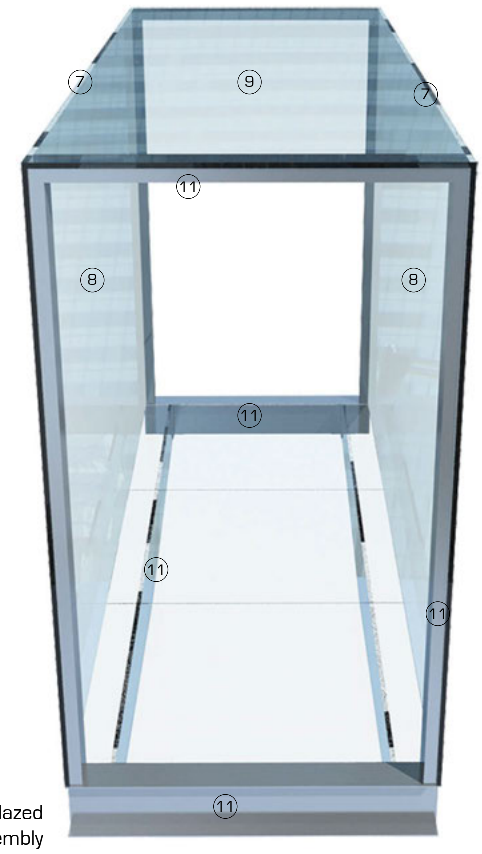
Details
1. Double glazed unit
2. Triple glazed unit
3. Laminated glass beam
4. Laminated glass beam with slot for column
5. Laminated glass column
6. Laminated glass column with projecting lamina that slots into beam
7. Silicone seal
8. Single glazed wall panel
9. Single glazed roof panel
10. Glass as floor deck
11. Steel frame
12. Stainless steel bracket bolt fixed to beam and wall
13. Bonded glass connection



3D exploded view showing single-glazed glass footbridge assembly with steel frame



3D exploded view showing single-glazed glass footbridge assembly with steel frame



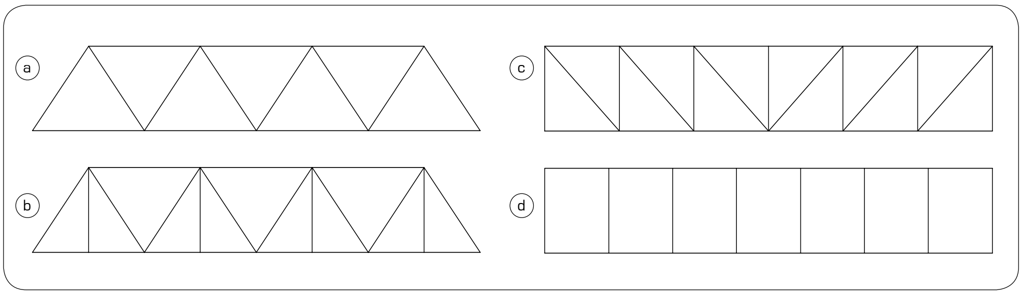
3D view showing single-glazed glass footbridge assembly with steel frame

3D overview showing timber truss roof structure supported on brick walls and clad with slate roof tiles

3D detail views showing timber truss roof structure clad with slate roof tiles

Details
a. Warren truss
b. Modified Warren truss
c. Pratt truss
d. Vierendeel truss

(Right) Traditional timber roof truss assembly types



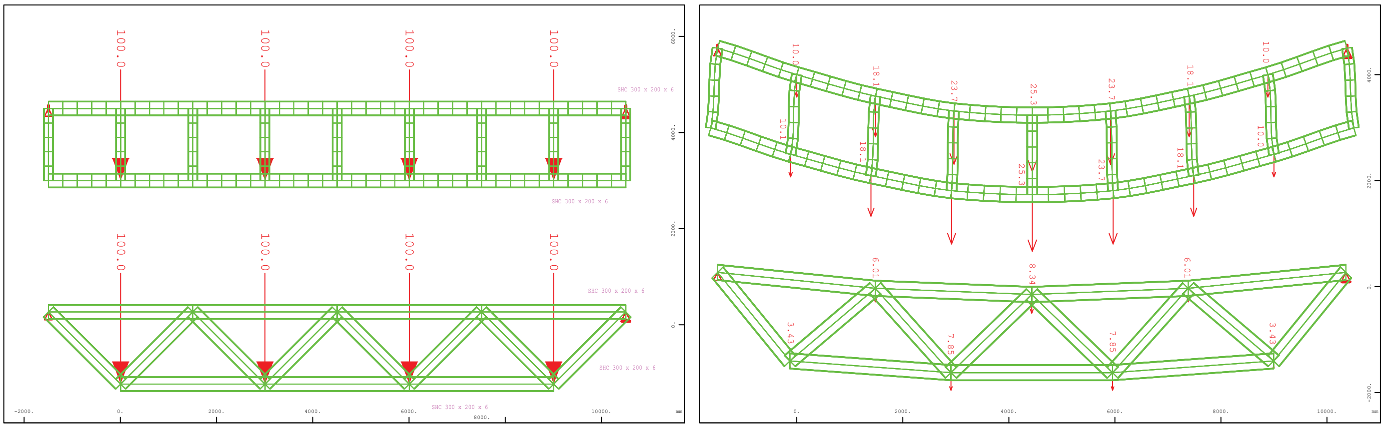
Trusses are used for large spans where a solid girder would be at a disadvantage due to its self-weight. Instead of using a deep solid section, such as a girder, a more economic solution for larger spans can be provided by transmitting forces across a series of diagonally set and connected members to take up the vertical, horizontal and diagonal shear stresses. With the exception of the Vierendeel type, trusses use pin-ended members that utilise tension and compression in a series of ties and struts. While trusses bend along their overall length, local bending within the truss can be largely avoided if loads onto the truss are applied at the node points. Loading trusses away from the nodes introduces local bending into horizontal members with a resulting increase in their design size, as members now have to resist bending as well as axial loads, resulting in trusses that are heavier, usually less elegant and more expensive. The voids between members are often used to accommodate services and mechanical ventilation ducts. These structures maximise the lever arm between the compression and tension flanges to generate a greater moment of resistance in order to provide a greater loadbearing capacity while minimising weight. Simply supported trusses exert no thrust at their supports allowing them to be easily supported on columns or supporting walls within a larger structure.

Truss types vary enormously in their design; the most common types being the Warren trusses, where loads are carried mainly as axial loads in the members, the 'N' truss which has vertical and diagonal members in a rhythm of alternating tension and compression, and the Vierendeel truss, which has an orthogonal rather than a triangulated series of members. In the Vierendeel truss, forces are transferred between members by localised bending, called Vierendeel action, with rigid connections between members. As such, it is not strictly a truss type. The bending makes members slightly larger than in an equivalent triangulated truss, resulting in their being heavier than a Warren truss spanning the same distance.

Whereas beam members are predominantly I-shaped to accommodate the bending effects, the cross-sectional shape for individual truss members can vary enormously, since truss members are generally subject to small direct forces. Consequently, T-sections and tubes can be used in steel trusses, for example, while a mix of timber and steel can be used in other types. Flat shaped sections make the connections easier to form than box sections, but this situation provides opportunities to design elegant connections, which can be one of the most significant considerations from a visual point of view.

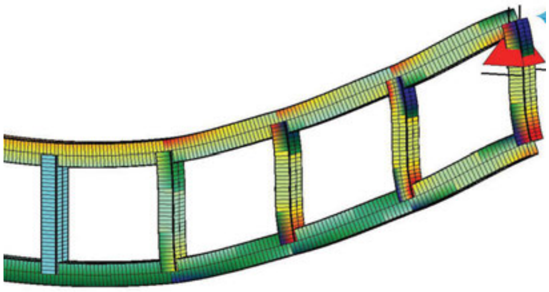
Joints and connections

Trusses are typically formed in timber, mild steel or a combination of the two materials. In trusses using mixed materials, steel rod or cable are used to form the ties, typically on the bottom



Comparative structural analysis: using the same member cross-sections and applying the same loads, the Vierendeel truss shows larger deflections.

Details
1. Purlins spanning between trusses
2. Roof covering
3. Strut
4. Tie
5. Timber wall plate
6. Bolted steel connection
7. Steel connector plate



Structural behaviour of a typical Vierendeel truss: bending moments are carried by the rigid connections, which would normally be pinned in a braced truss.

3D overview showing timber truss roof structure supported on brick walls and clad with slate roof tiles

3D view showing timber truss roof structure supported on brick walls and clad with slate roof tiles

3D detail view showing timber truss roof structure clad with slate roof tiles

3D overview showing timber truss roof structure supported on brick walls and clad with slate roof tiles

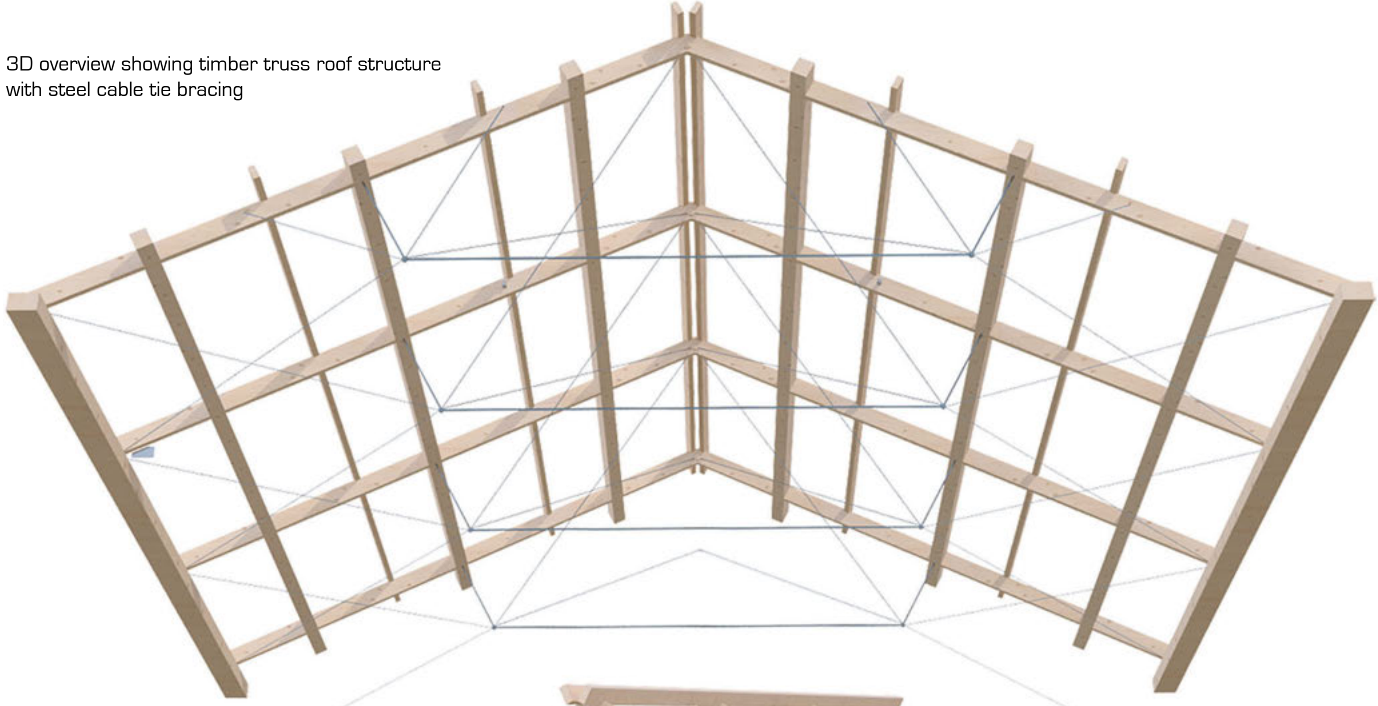
Details
1. Purlins spanning between trusses
2. Roof covering
3. Strut
4. Tie
5. Timber wall plate
6. Bolted steel connection
7. Steel connector plate

3D views showing timber truss roof structure supported on brick walls and clad with slate roof tiles

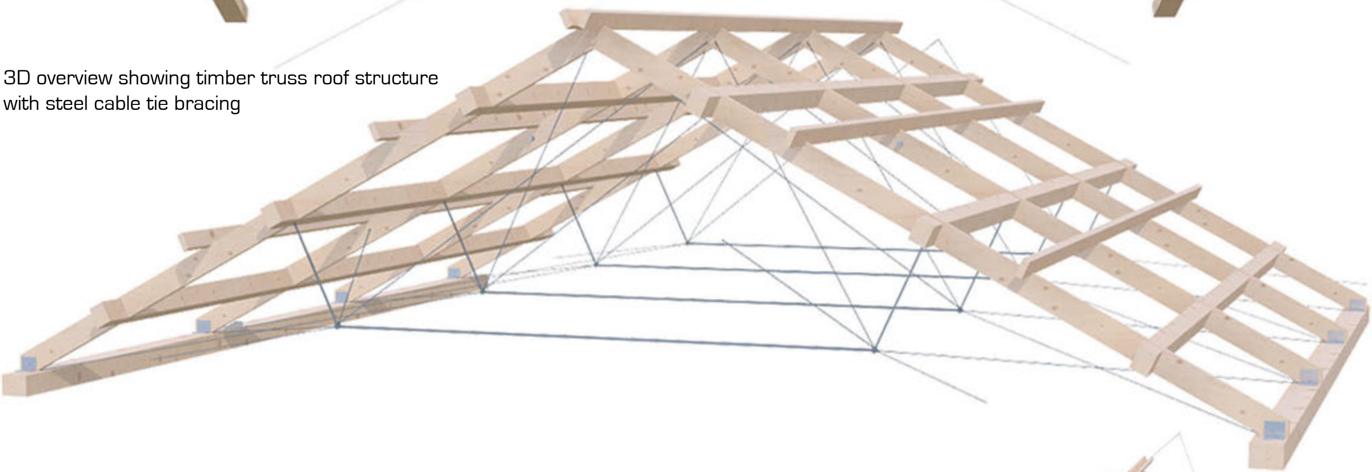
chord of the truss, while steel tube might be used to form the central strut. Timber roof trusses are either large trusses set up to three metres apart linked together with purlins or much lighter nail plate trusses set at around 450mm centres. Larger trusses often use double timber members forming the main rafters and joists that are spaced apart with secondary ties and struts linking the primary members. Timbers are bolted together using large steel washers that spread the load imposed by the bolt head and prevent it from crushing the timber locally as the connection is tightened. The exposed steel components are painted to avoid their corrosion. Timber trusses can also make use of ties made in steel rod where they are visible components. Smaller trusses are factory assembled with nail plates and split ring connectors as described in the Materials chapter. Steel trusses can range from a modest set of angles bolted together with linking gusset plate connectors to welded tubular structures that can incorporate cast node connections to allow connections with complex geometries to be formed. These cast connectors allow the loads to meet at the intersection of the centrelines of members in order to minimise the diameter of the tubes. Modest steel trusses use angles set back to back and bolted together with gusset plates set between them to allow several members to be joined together at a single node. They are in widespread use as economic long span supports to roof structures. Larger scale trusses are made from laminated timber or LVL (laminated veneer lumber), which resembles plywood in its construction but is made in long lengths. These materials use similar bolted connections to smaller trusses, but typically with bigger metal connector plates. Truss members can be made from single lengths of LVL but for high loads, LVL is glue-laminated to make large cross-section members, typically square in profile. Reinforced concrete trusses are usually precast either as a series of prefabricated components which are stitched together or as a single completed component. They are much less commonly used than those in timber or steel due to their self-weight, which tends to reduce the lightness and economy associated with trusses.

Interface with external envelope

Trusses are tied together by the secondary members called purlins which connect trusses together typically points on the rafter which intersect with other truss members, called node



3D overview showing timber truss roof structure with steel cable tie bracing

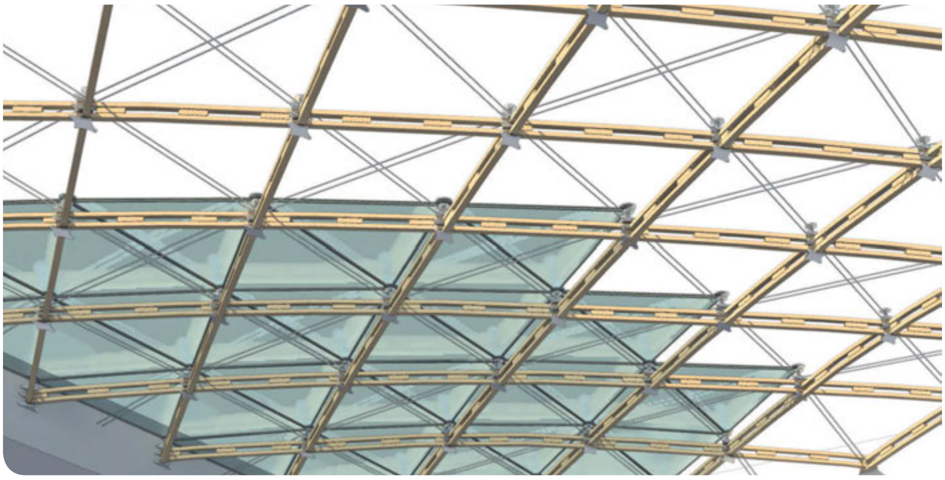


3D overview showing timber truss roof structure with steel cable tie bracing

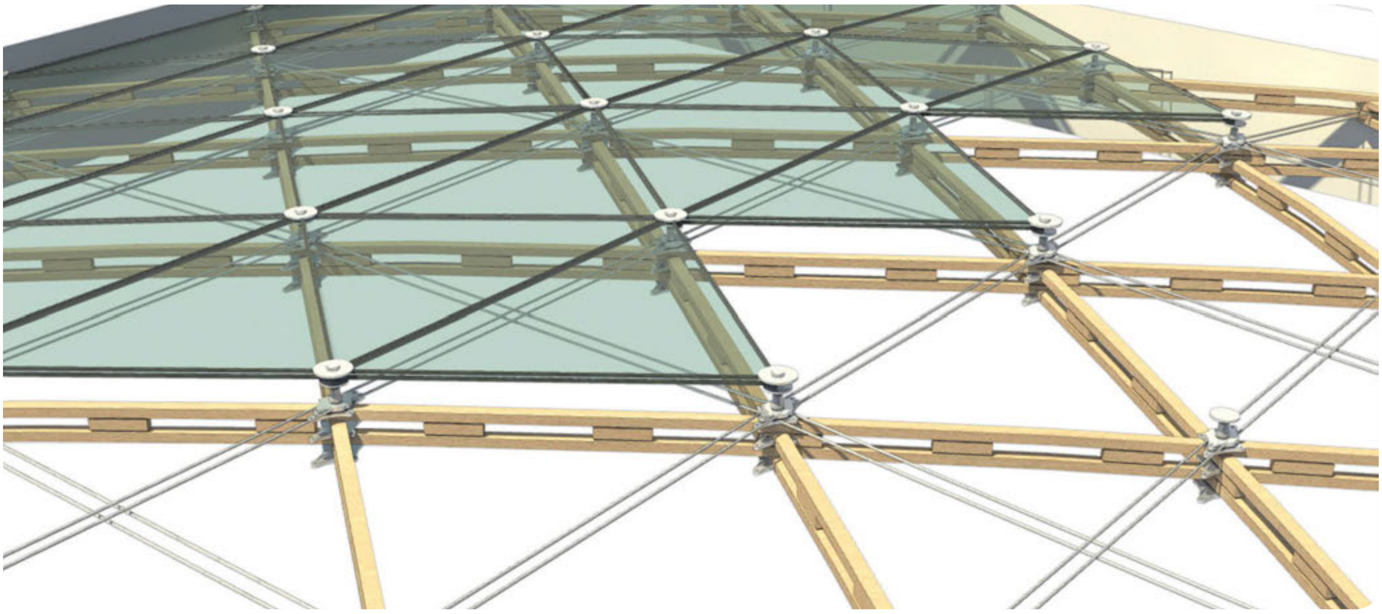
points. The purlins are set on top of the outer face of the truss in order to form a support for the build-up of the roof covering and to make a simple connection between truss and purlin. Purlins can have an internal finish applied, such as timber boards or dry lining in order to expose the trusses within the building, but this varies with the design of the trusses. In addition to avoiding local bending in truss members, the fixing of cladding to secondary supports permits the use of simple bolted or screwed connections that avoids any complexity in fixing to a primary member. The bases of trusses are set either onto a supporting structural frame or onto a supporting wall. The wall plate or purlin joining the base of the trusses is typically used to form an interface between roof covering and the external wall below, where a gutter is typically required. The arrangement of purlins is often adjusted to suit the needs of supporting the roof covering, which may range from profiled metal sheet to traditional roof tiling. Steel trusses may also have brackets fixed to the top of the truss to provide connectors to the roof covering, typically with the aim of providing a visual separation between structure and roof covering.

3D view showing timber truss roof structure supported on brick walls and clad with slate roof tiles

Details
1. Timber member
2. Steel rod
3. Steel node connector
4. Doubled glazed unit



3D views showing timber shell structure with tension cable support and double glazed roof



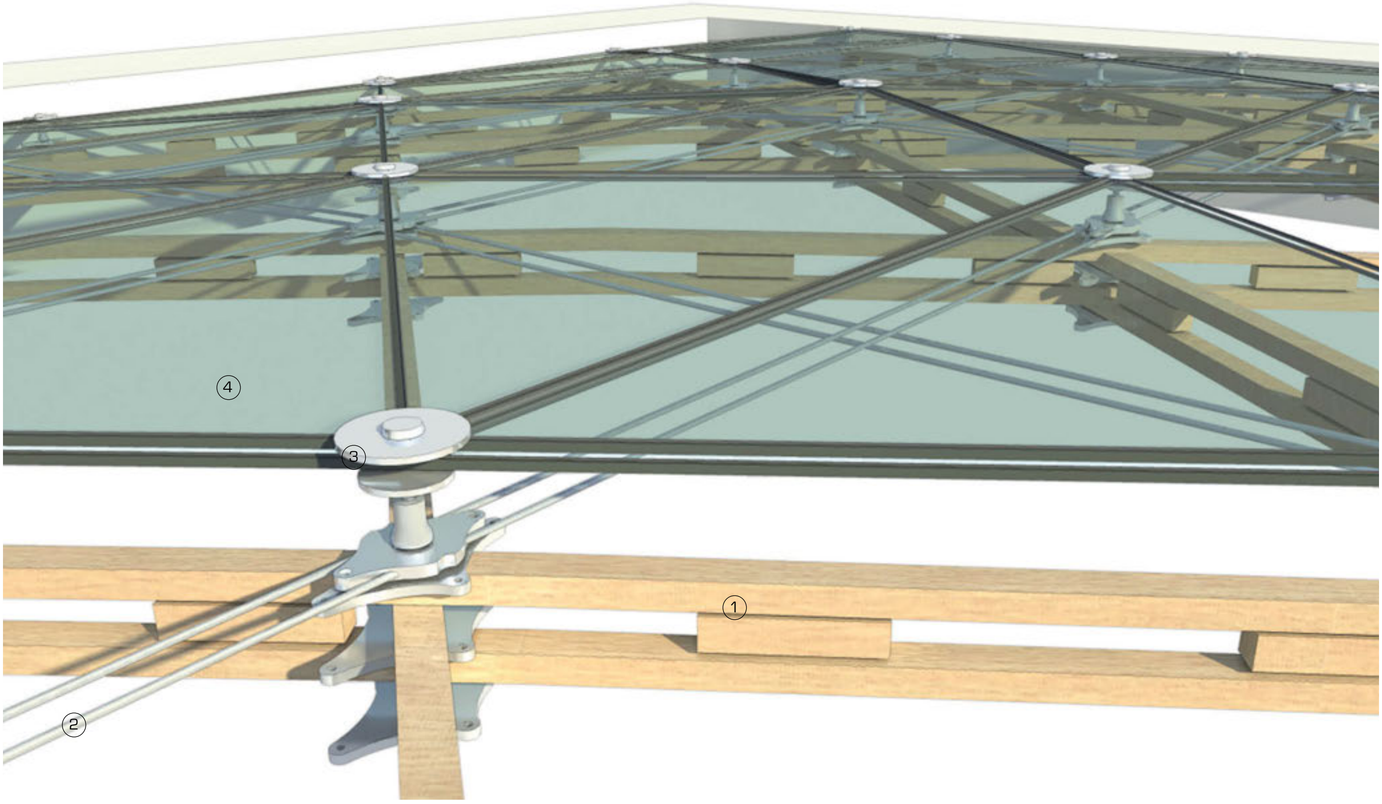
The essential concept of the arch is to support loads primarily as compression forces in the plane of the structure, with abutments at the base to resist the outward thrusts generated by its shape. Since arches exert outward forces at their bases, they require a tie such as a floor slab or beam, for example. This is quite different to some portal frames, which do not exert such forces at their base points. Consequently, a variation to this type is the 'tied arch' in which a tension member links the base points across the arch to resist these outward thrusts and control spread of the arch. The three most common types used in modern construction are the rigid arch, the two-pin arch and the three-pin arch. These two-dimensional structures are linked together in bays with purlins to form a complete structure. Alternatively, the arch concept can be extended into three dimensions as a shell. Both arches and shells can be formed either from truss components, as 'gridshells', which are in increased use, or as monolithic structures in reinforced concrete.

Arches

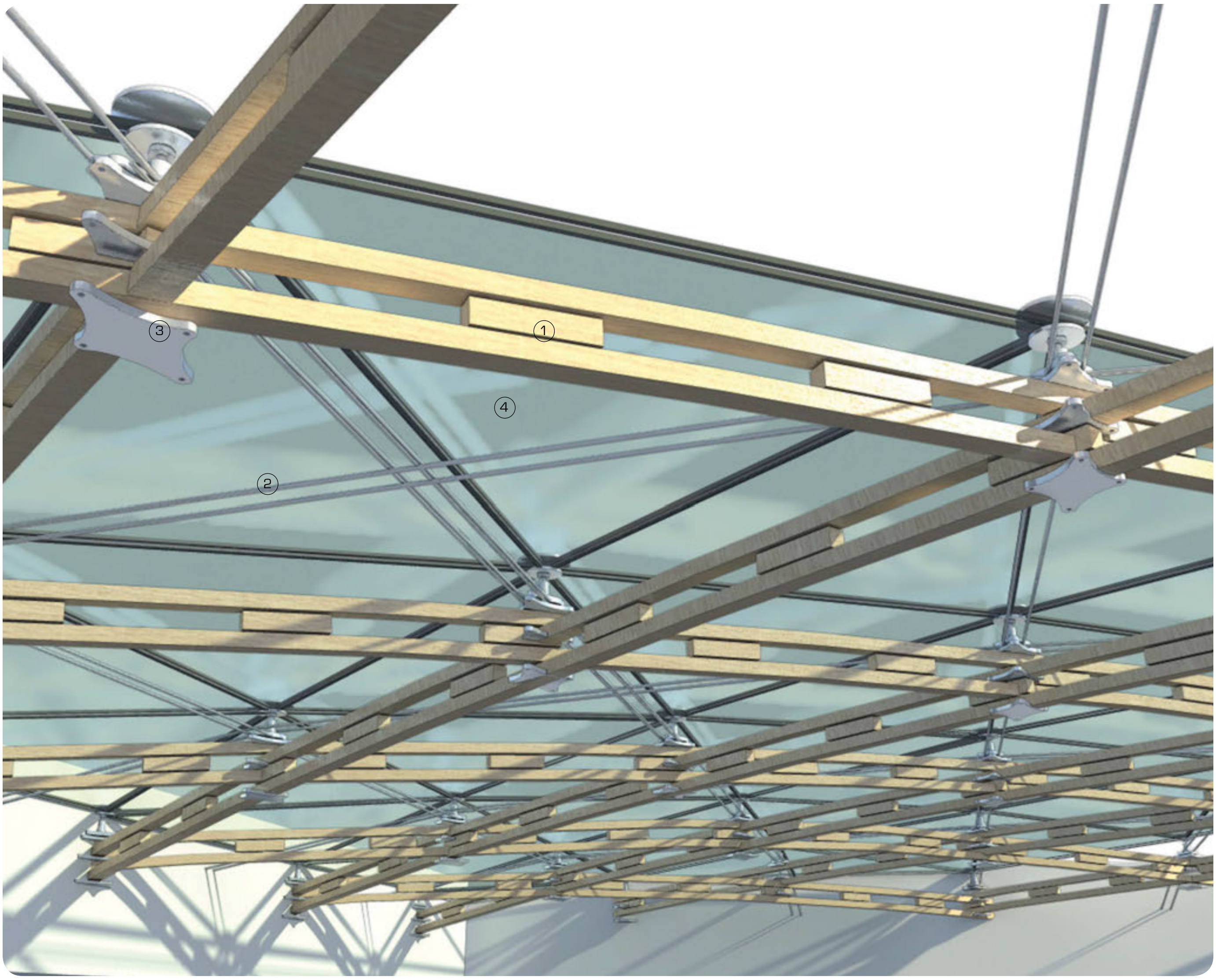
The rigid arch has no pin joints, but instead has rigid connections at both base points. This arch type is generally considered to be more economical than the two other types, but has bending moments at its base that are transmitted into the foundations, which may need to be linked by ground beams to resist the thrusts, in the manner of a tied arch, unless the ground is sufficiently firm to withstand the thrusts without a beam. The two-pin arch has pin joints at the abutments only. It is more economical in material than the three-pin type and bending moments are more evenly distributed than in the three-pin type, minimising the amount of material used. The three-pin arch is hinged at three points, which are at the apex and at the two base points. Bending does not occur at the pin joints, which behave as pivots or hinges. Bending moments away from the pins are greater than in other types. As with the traditional masonry arch, there are horizontal thrusts at the supports. Thrusts at the base of an arch increase as the arch profile becomes shallower. Both the three-point and two-point arches suit larger spans which would present difficulties for transport and handling if made in a single piece. The most common materials used are steel, laminated timber and reinforced concrete.

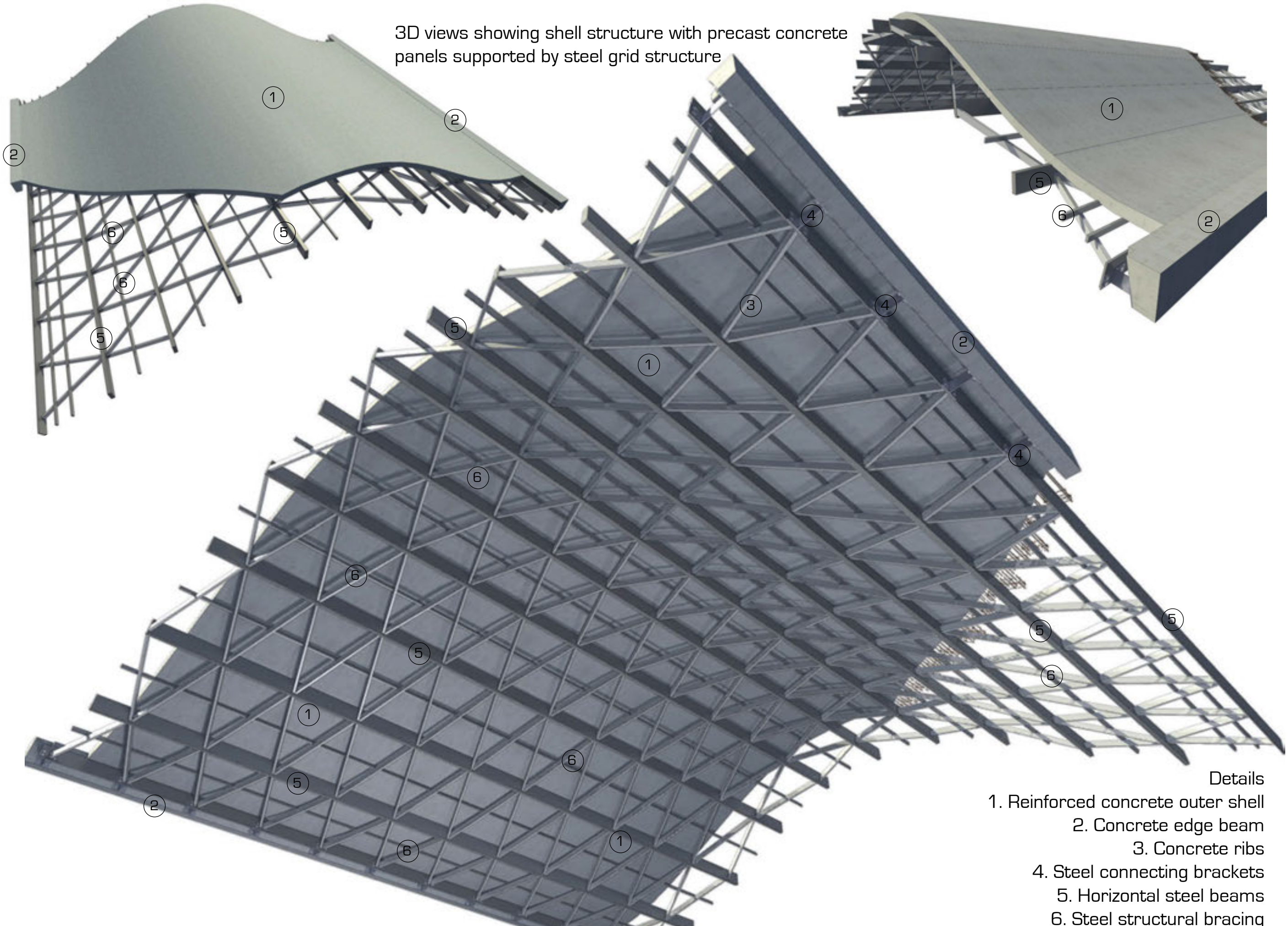
Shells

Shells are of two generic types; those made from framing members to which cladding is applied and monolithic shells which are made either by casting concrete in place over complex formwork or as precast sections which are stitched together. In both cases, the loads are carried in the plane of the structure with the outward thrusts being taken out at the base. Shells constructed from framing members often have a ring beam at the edge to contain the effects of the outward thrusts. Monolithic concrete types may either follow the same principle or have a continuous abutment at their base to deal with the higher loads associated with concrete. Shells in which



3D views showing timber shell structure with tension cable support and double glazed roof





3D views showing shell structure with precast concrete panels supported by steel grid structure

3D view showing underside of shell structure with precast concrete panels supported by steel grid structure

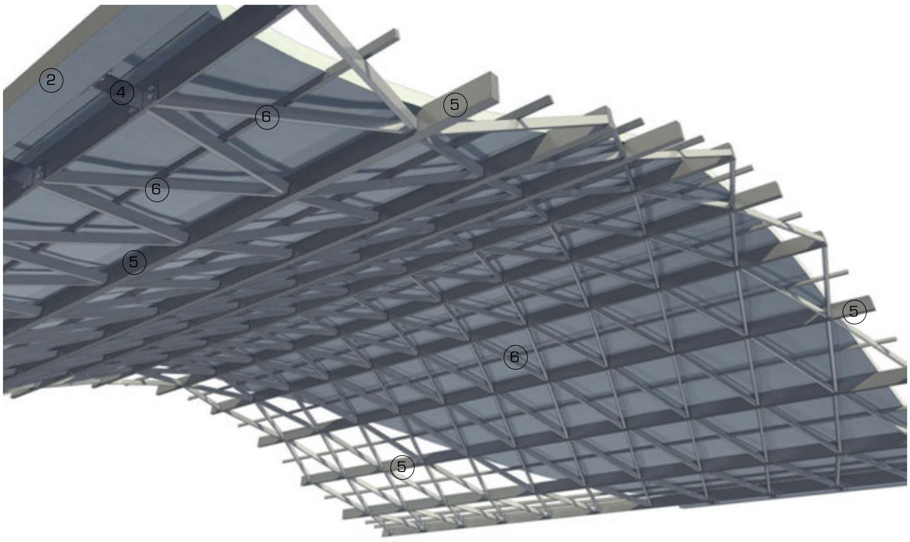
Details
1. Reinforced concrete outer shell
2. Concrete edge beam
3. Concrete ribs
4. Steel connecting brackets
5. Horizontal steel beams
6. Steel structural bracing
7. Curved steel primary edge beams
8. Steel horizontal structural members

the structure and enclosure are combined in a single form, as found in an egg shell, are referred to as monocoques. Shell forms vary enormously, from the relatively simple shell vault resembling an extruded arch, to the complex ribbed structures resembling seashells.

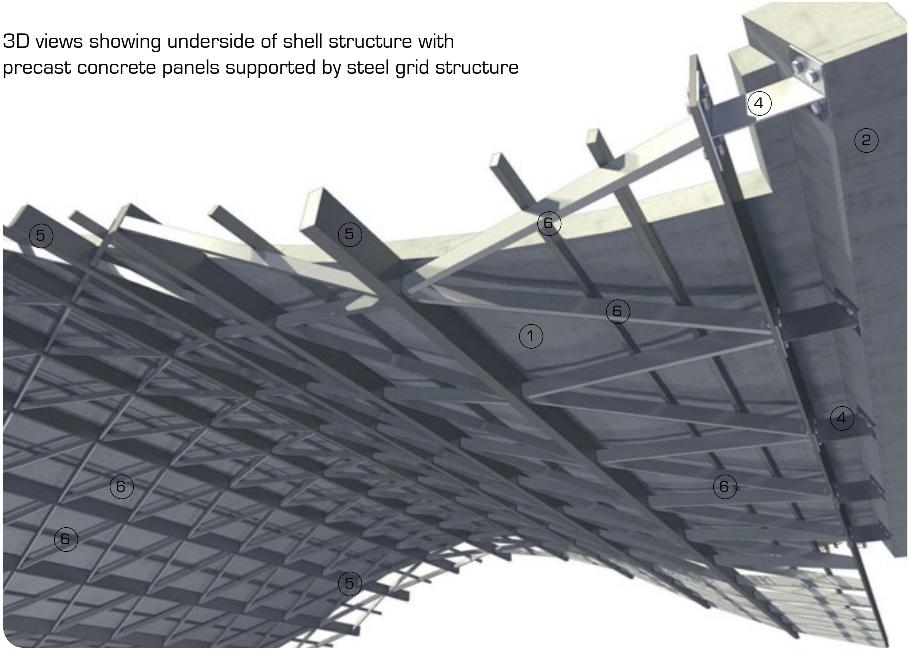
Joints and connections
Arches and shells made from framing members (rather than reinforced concrete) are formed using the pinned and moment connections associated with each material and are illustrated here. An interesting recent development has been in using a mix of materials to form shell structures, such as those in timber and stainless steel cables or rods. The mixing of materials has benefits in economy of weight, allowing forces in different members to be matched to a suitable material. An essential aspect of framed shells or 'gridshells', with their double curvature, is the connector node which is typically made in steel and which can also be used to support the roof covering. Where a single material is used for the gridshell, such as steel, node connectors are not required if regular cleat and bracket connections can be used economically. This allows the roof covering to be supported directly on the structural members. Shells can be supported at their base on a variety of supports, from columns to loadbearing walls or floor slabs. The choice of support may be related directly to the need to provide an economic weathertight seal at their junction, though structural ring beams are often needed to contain the outward thrust forces.

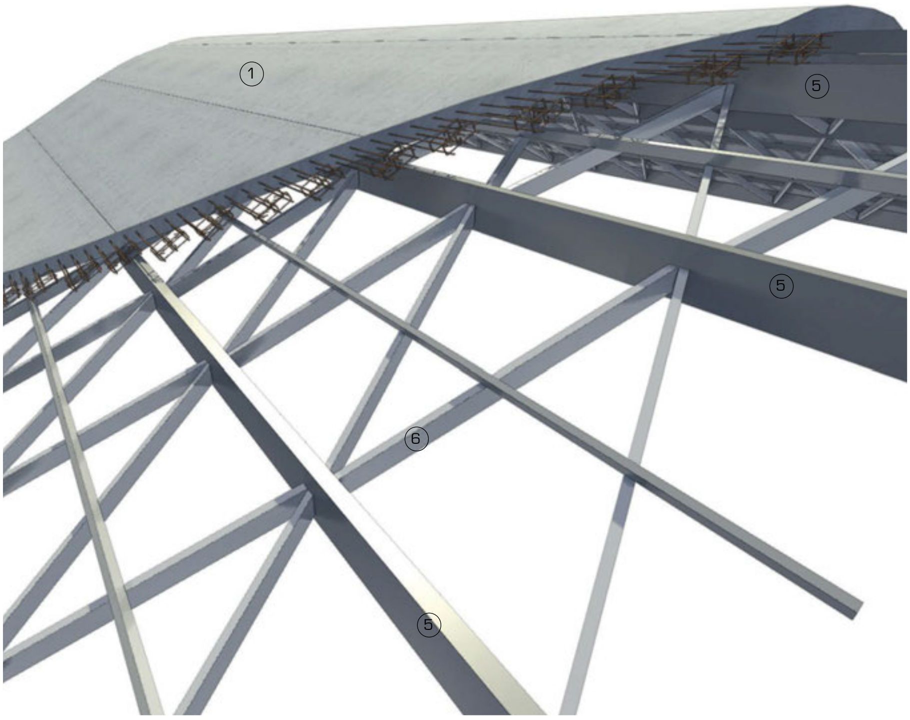
Interface with external envelope
Monolithic arched structures and shells are covered externally in continuous membranes where rainwater is collected at the base of the structure. Membranes used vary from polymer-based types that are bonded to the structural substrate to standing seam metal sheeting.

Trussed arches and gridshells provide the opportunity for transparency, where glazed roof systems can be used in addition to metal clad roofs. Where metal is used, a covering of sheet metal or metal rainscreen panels are used, typically with a profiled metal substrate serving as a deck, though the double curvature of the shell can make it easier to form a substrate from triangles, which are always flat. Double glazed units can be supported as clamped glazing supported at the node connector points, or alternatively from a secondary metal frame also connected at these node points. The external envelope is fixed in a way which allows the structural movements of gridshells, which can be higher than other types of roof structure, to occur without damage to joints in the roof covering. While movements can be more easily accommodated in metal roofs, glazed roofs require careful particular attention to detail to ensure that the support points for the glazed units do not experience significant amounts of movement. Consequently, the principles associated with point fixed glazing are often used, even where part of the support system involves a metal supporting frame.

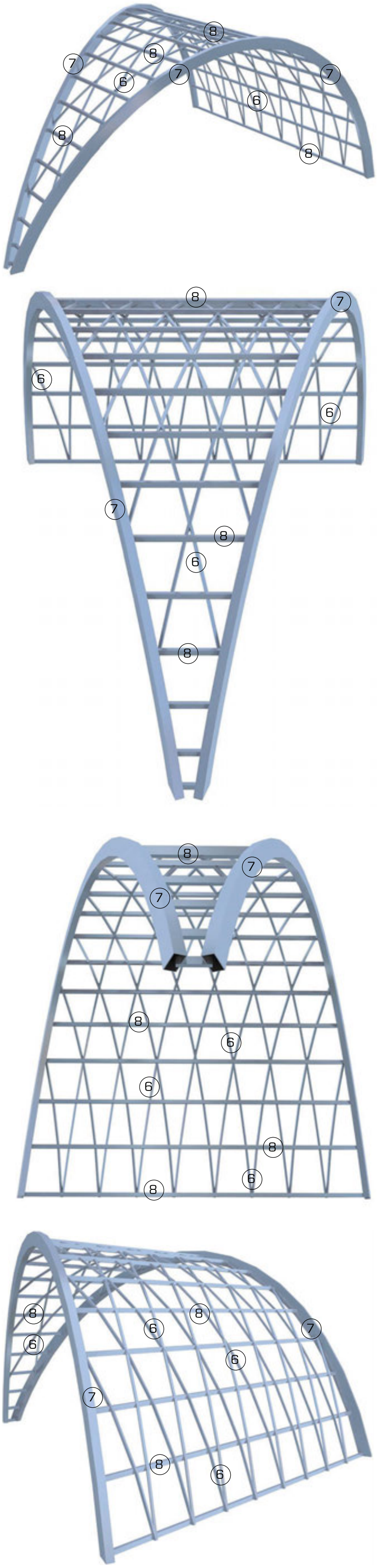


3D views showing underside of shell structure with
precast concrete panels supported by steel grid structure

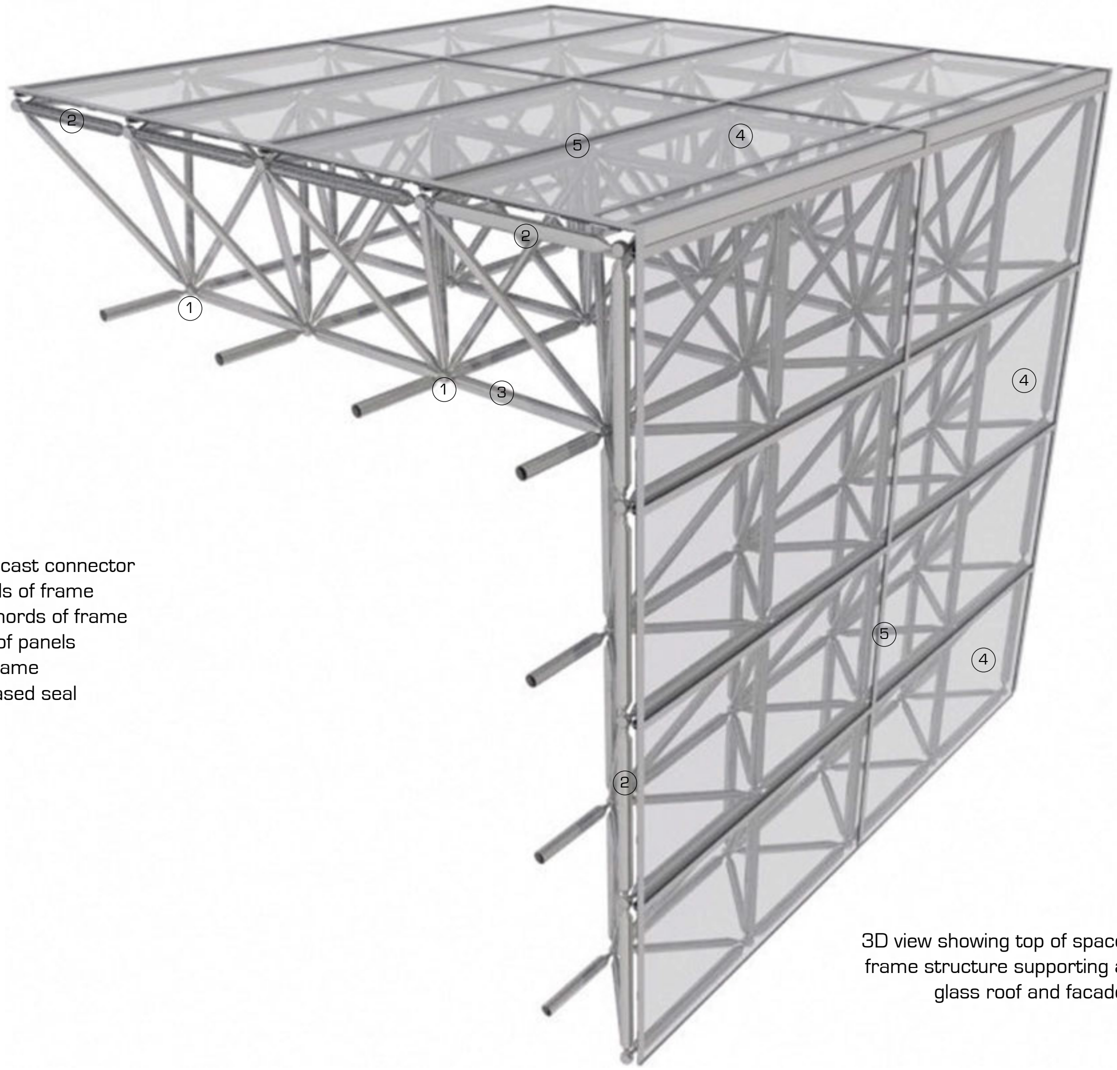




3D view showing underside of shell structure with precast concrete panels supported by steel grid structure



3D view showing arched steel structural frame
with diagonal cross-bracing



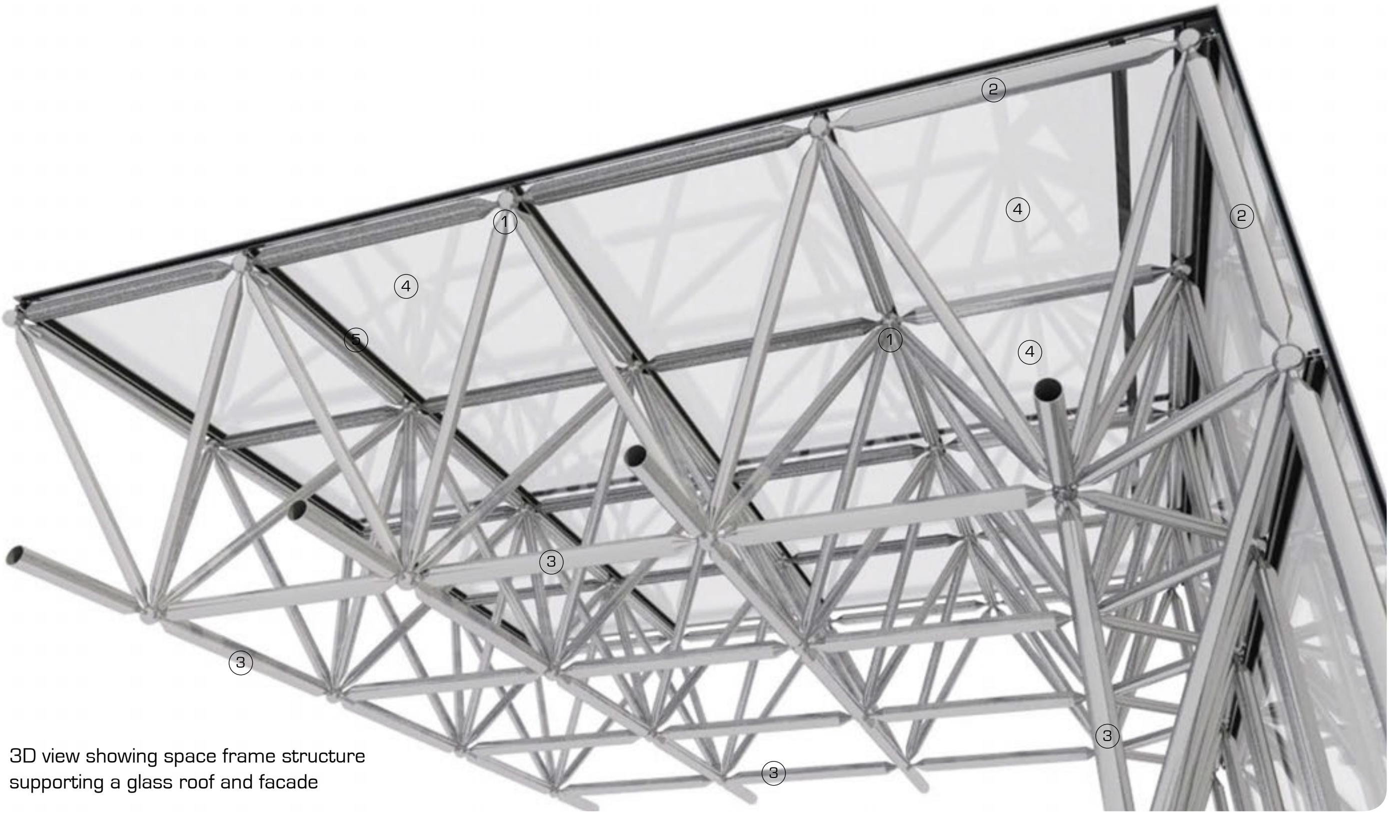
Details
1. Spherical cast connector
2. Top chords of frame
3. Bottom chords of frame
4. Glazed roof panels
5. Glazing Frame
6. Rubber-based seal

3D view showing top of space frame structure supporting a glass roof and facade

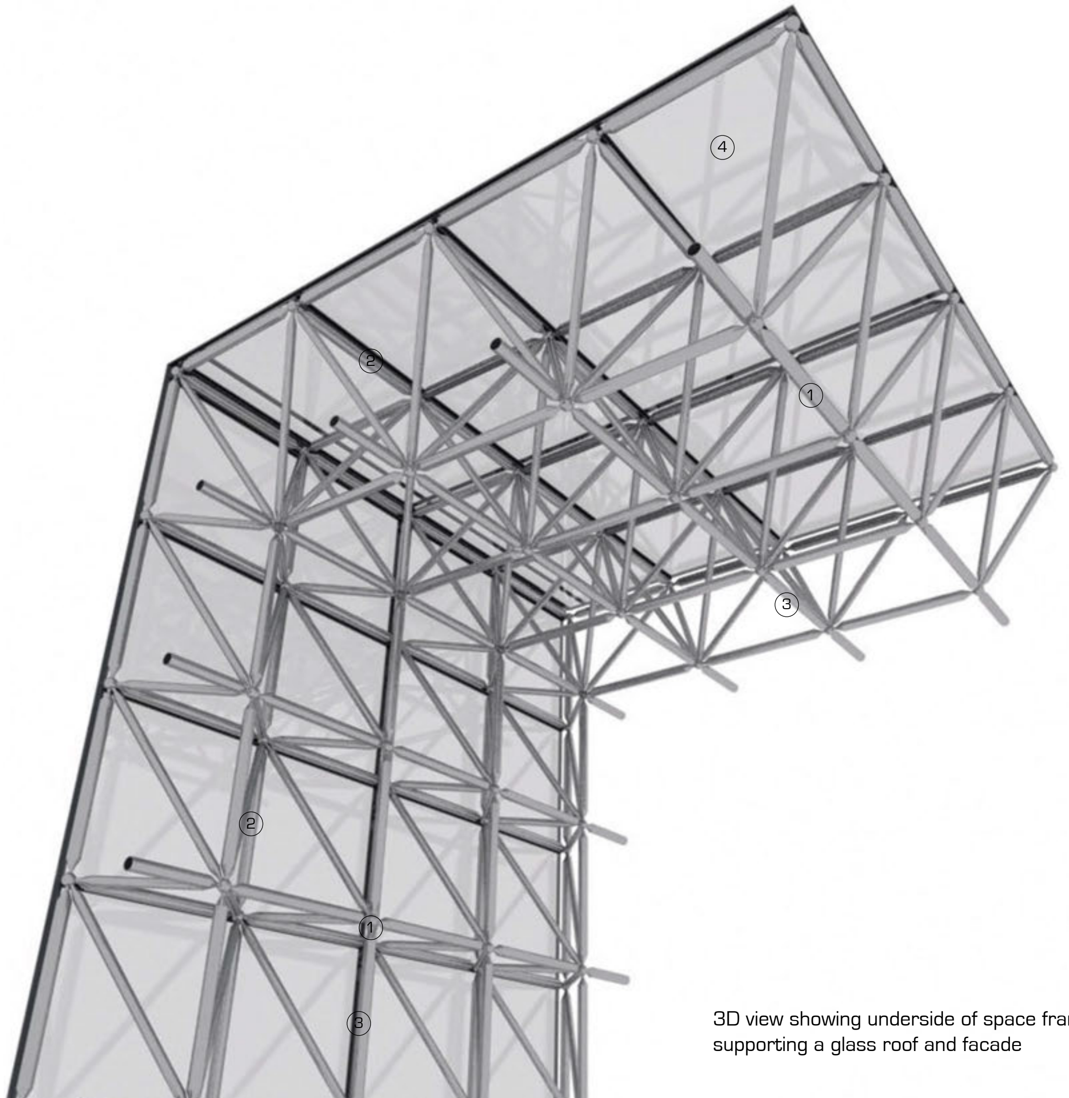
Space frames and geodesic domes are the most well known types of space grid. They can be regarded, from a conceptual point of view as being three-dimensional trusses. One of the earliest space frames was the Mero system designed in the 1940s by Max Mengeringhausen, and is still used today, though much evolved from that time. A development by Konrad Wachsmann in the 1950s was based on the geometric form of the tetrahedron. The space frame comprises a series of triangulated members linked by node connectors that, effectively, form a series of linked trusses in directions perpendicular to one another. The material system is made economic and fast to install by using a single node type wherever possible, though different connectors may be used at the edges where they meet the external wall. Some geometries require a 'family' of connectors to form complex shapes, particularly those space frames that depart from the square, rectilinear format that has been used until recently. An equivalent of the space frame for curved surfaces is the geodesic dome, originally developed by Richard Buckminster Fuller in the 1940s. Fuller believed that structures in nature behave such in a way that internal forces usually act in the direction of minimum effort with a maximum gain achieved for a minimum of energy input. Rather than apply this idea to the form of the plant leaf or the animal shell, Buckminster Fuller interpreted triangular crystalline forms found in nature, using triangulated frames. Like the space frame the geodesic dome is essentially a continuous triangulated structure but its geometry often allows it to be used as a single-layer structure without the need for introducing triangulation into the depth of the structure. Space grids provide long-span structures for roofs and walls. They can take on a huge variety of forms from vaults to supporting structures for large glazed walls. Deflections in space frames are small due to the overall stiffness of the frame. Steel is most commonly used because of the strength and stiffness of the material combined with its comparatively low cost.

Joints and connections

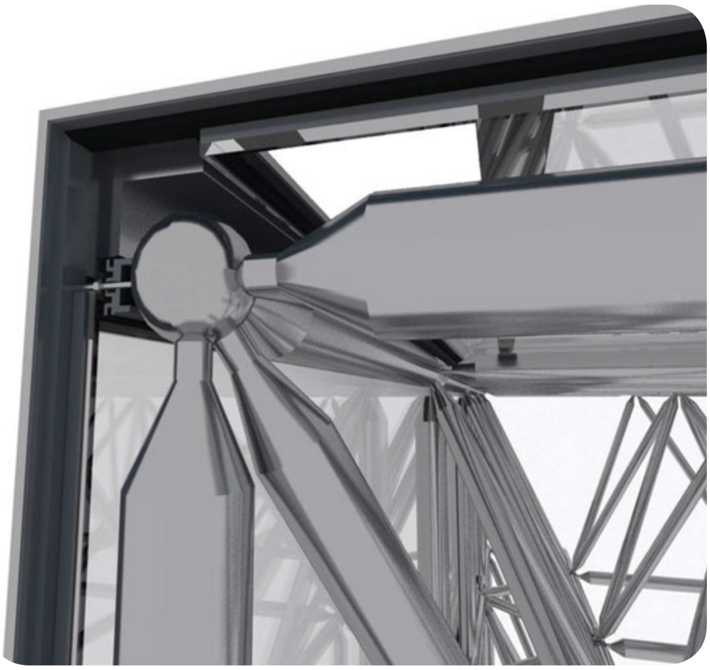
The 'base' component of space frames and geodesic domes can be considered as a square-based pyramid-shaped frame, assembled with rods or tubes connected by a single node connector. The early Mero systems used a spherical node, set with threaded holes into which eight connectors fixed to structural members forming the space frame could be connected. Four holes were set in order to allow members in the same horizontal or vertical plane to be connected together, with four additional holes at angles that allow triangulated members forming the depth of the space frame to connect to form the characteristic triangulated shape. More recent versions use square and polygon-based geometries to form the node connector, allowing triangular grids to be used rather than the square-based versions. The new generation of nodes can be used for single layer structures that are more based on the idea



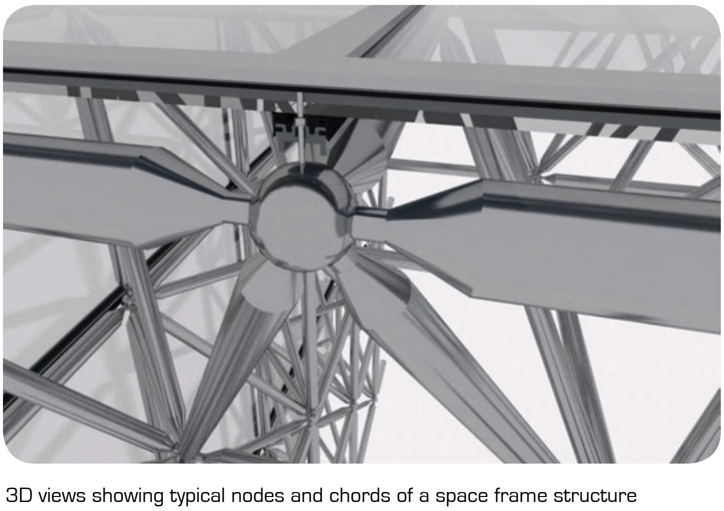
3D view showing space frame structure
supporting a glass roof and facade



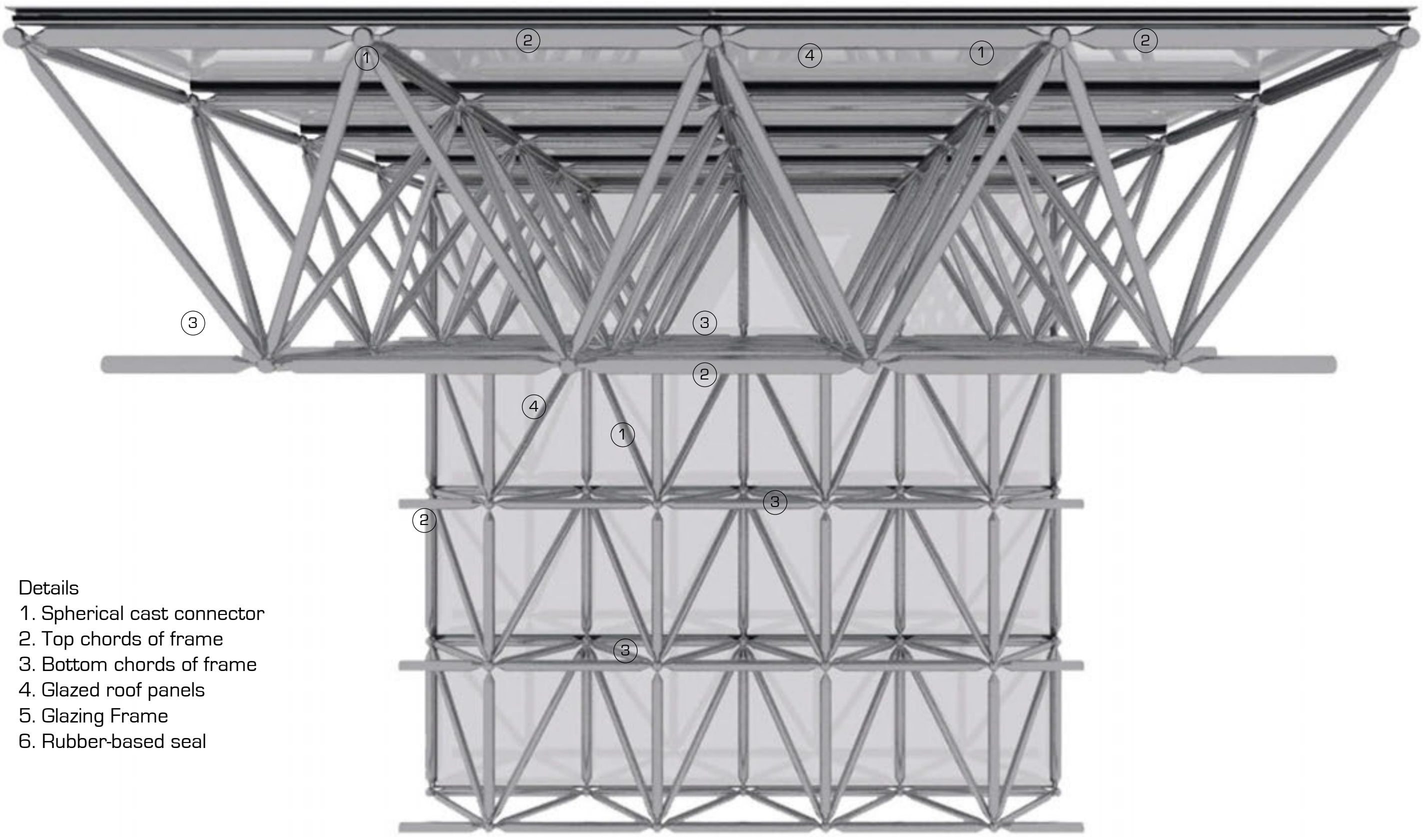
3D view showing underside of space frame structure
supporting a glass roof and facade



3D views showing typical nodes and chords of a space frame structure



3D views showing typical nodes and chords of a space frame structure



Details
1. Spherical cast connector
2. Top chords of frame
3. Bottom chords of frame
4. Glazed roof panels
5. Glazing Frame
6. Rubber-based seal

3D view showing space frame structure supporting a glass roof and facade

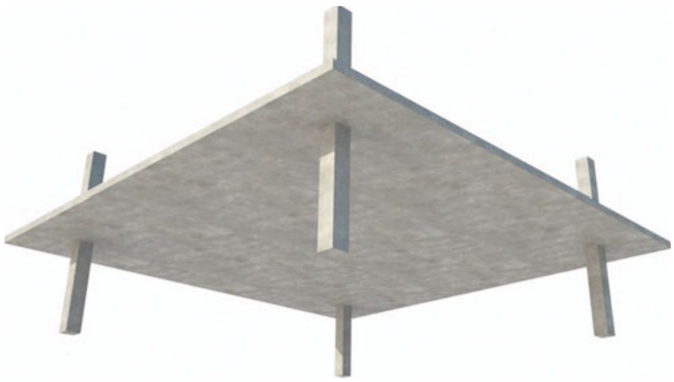
of gridshells than space frames, and allow more freedom in the range of angles that can be accommodated in order to allow more geometric variation in the form of the grid. The design of nodes is currently moving towards this preference in design for a wider range of forms than are afforded by the rectilinear frame arrangement.

The essential component of the space grid is the node connector. Very simple types with simple geometries use a flat plate connector to which steel angles are bolted in the manner of a truss. Complex geometry types use a cast or machined node that has threaded holes to receive the ends of the threaded connectors of the ties and struts. These form part of proprietary systems designed by manufacturers.

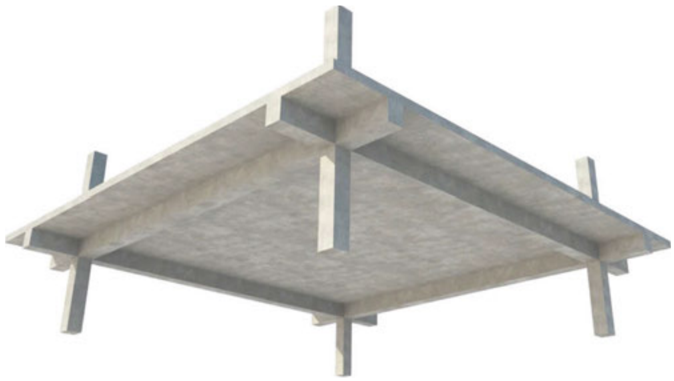
Interface with external envelope
An essential advantage of the space grid is that cladding panels can be fixed directly to the structure without the need for additional rails or purlins. For glass roofs, a typical distance of 1500mm between horizontal structural members in the space frame allows economic sized double glazed units of the same size to be used. Where a profiled metal desk is used, there is greater flexibility in the size of the structural bay, as the decking can span up to around 3500mm with standard profile depths. Roof cladding or glazed panels are fixed either with lugs or brackets welded to the structural members, which may be tubular or rectangular. Alternatively, the roof covering can be fixed to the node connectors where the node is designed for this purpose. More typically, the nodes are used as structural connectors only. Where a rectangular hollow section is used, cladding can be fixed directly to structural members without the need for welded lugs, provided that the potential corrosion caused by penetrating the tube is taken into account.

Point fixed glazing is also suitable for space grids since the connectors for the glazing can be fixed directly to the structural node. Cladding conditions can vary from flat to inclined to curved, following the geometry of the supporting structure to which they are fixed. In conditions where the roof is horizontal, the roof covering can drain to gutters set between roof panels, following the direction of structural members beneath.In conditions where the roof is inclined, the roof covering is drained like a glazed roof, with water running across the roof surface to gutters at the edges. Glazed roofs in most geometric conditions use glazing which is toggle fixed or point fixed, with a single silicone-based seal set flush with the surface of the glass, in order to allow rainwater to run freely across the roof.

Junctions between wall and roof in glazed space frames typically use either a glass to glass joint, or one where an insulated metal panel is used to form the junction. The choice is largely based on design preference and the visibility of the glazed edge.



1. Flat slab



2. Slab with downstand beams

3. One-way spanning ribbed slab

4. Two-way spanning ribbed slab

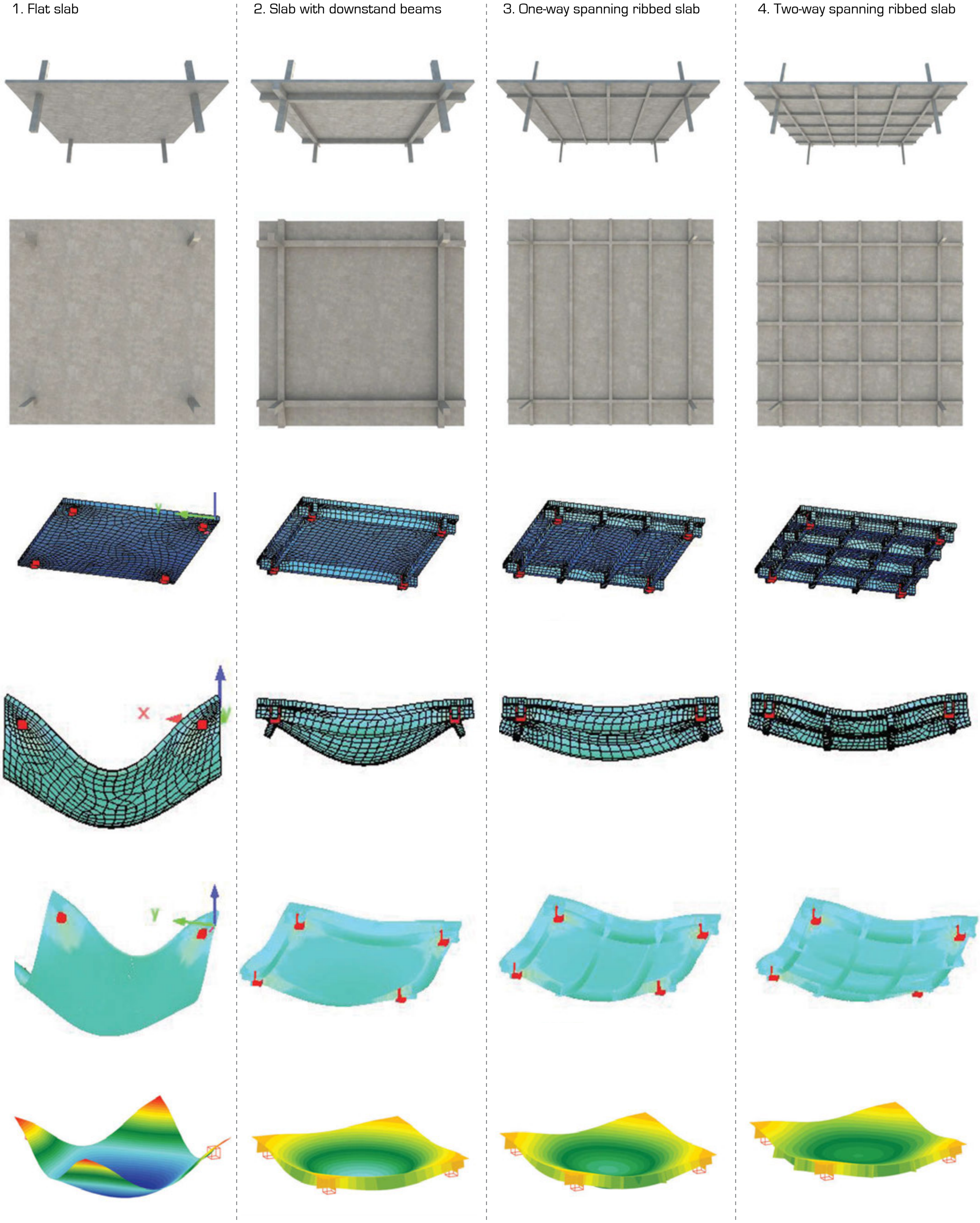
3D views showing various in-situ cast concrete floor slab configurations

The flat slab is the simplest type of cast-in-place floor and is suitable for spans of up to around nine metres. It can be used in a one-way or two-way span, approximately 300mm deep, depending upon span and loading. In a one-way span, steel reinforcement is introduced into the bottom part of the slab and the floor is designed to span in one direction only, like a beam. In a two-way slab, the reinforcement is laid in a perpendicular grid so that the total load of the floor is more evenly distributed at its perimeter as the floor spans in two directions. Reinforcement is concentrated on the lines between columns to create beams connecting columns within the depth of the slab. The soffit is flat, providing a smooth ceiling and allowing a straightforward type of formwork to be used. Providing the tops of columns with protruding caps where the transfer of forces is concentrated can reduce the depth of flat slabs. These caps provide greater rigidity for the structure and reduce the span of the slab between columns.

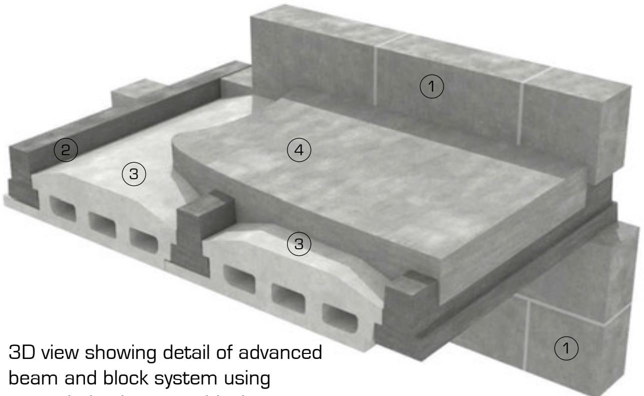
Floor spans can be increased economically from six metres to 15 metres by forming a series of downstands in the floor soffit to create a ribbed floor. Steel reinforcement in the bottom of the ribs makes this type of floor lighter than the flat slab because of the structurally efficient ribbing but the formwork is more complex.

The two-way coffered floor slab is a ribbed floor for large spans of up to around 17 metres in two directions. The hollow coffers are often used to house lighting and service outlets. The floor structure gives better resistance to shear when the beams are set diagonally to the structural grid of columns but as with ribbed floors, the formwork must be specially made.

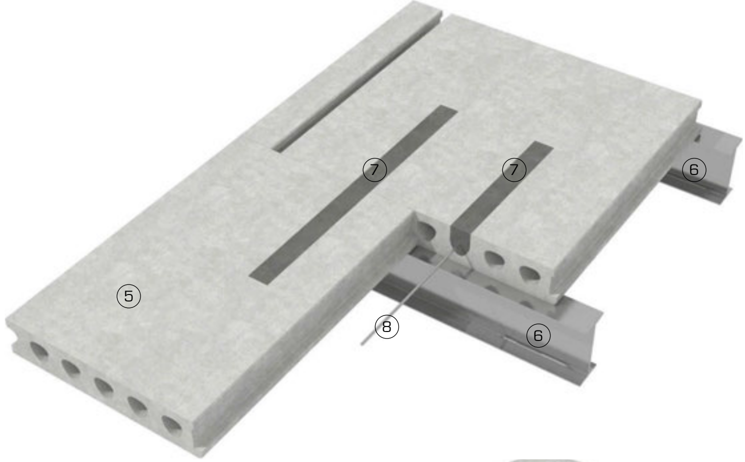
Ground-bearing slabs may be either reinforced or poured as mass concrete, depending on the degree of strength and rigidity required. Where ground-bearing conditions permit, they are supported directly by the ground beneath. Where the ground is too soft, a suspended floor is used. Ground-bearing slabs can be designed either as a raft or as a slab supported by separate foundations beneath. Ground slabs are laid on a compacted base of hardcore (gravel), which provides a level and well-drained base. The hardcore is blinded with a smooth layer of sand onto which is laid a damp-proof membrane (DPM: vapour barrier). The sand prevents the DPM, usually a thick polythene sheet, from being punctured by the hardcore. The DPM prevents moisture rising up through the slab. The concrete is poured directly over the DPM. In addition, a DPM can be laid between the concrete slab and the screed. A liquid material is used to provide a bond to the surface of the slab. This results in a loss of bond between the screed and the slab, and a thicker screed (about 75mm) is used. The DPM is joined to the wall DPC (damp-proof course: vapour barrier) to provide continuity of damp-proofing . A DPM laid on top of the concrete, usually in the form of a liquid-applied layer, is used as an alternative where sealing the underside and edges of the slab is not practical. Distribution bars (reinforcing mesh) are set near the reinforcing bars in order to avoid cracking in the underside of the slab due to its being in tension under load. Reinforcement used in concrete floors can be either conventional reinforcement bars or welded mesh fabric.



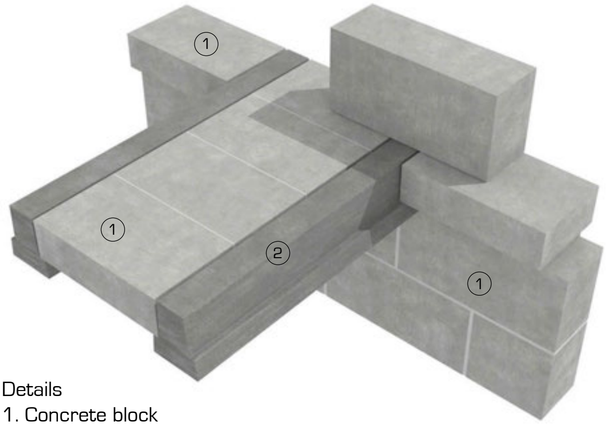
Finite element analysis of different concrete slab systems showing the effect of adding structural ribs.

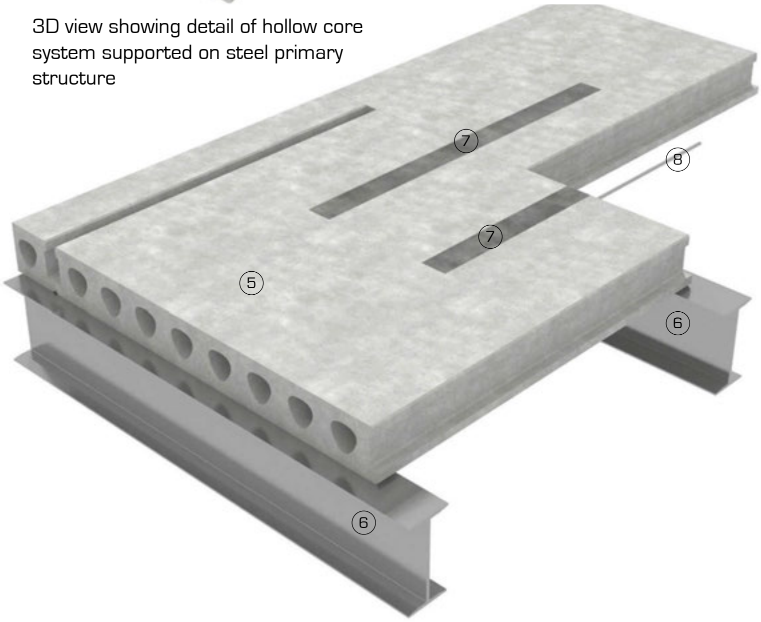


3D view showing detail of advanced beam and block system using expanded polystyrene blocks



3D view showing detail of hollow core system supported on steel primary structure





Details
1. Concrete block
2. Prestressed concrete beam
3. Expanded polystyrene block
4. Structural concrete topping
5. Hollowcore slab
6. Primary steel structure
7. Structural concrete infill
8. Reinforcement tie

3D view showing detail of traditional beam and block floor system

Precast concrete floors consist of prefabricated planks or beams connected together to form a deck. Proprietary systems provide longer spans than in-situ-cast concrete floors but they span in one direction only. Precast floors that span two ways have been developed for specific projects such as the Richards Medical building shown here, and go beyond the constraints imposed by standard systems.

Proprietary systems
The generic types produced by manufacturers are as follows:
1. Beam and block, spanning to around 7.5 metres
2. Hollow core slab, spanning to around 12 metres

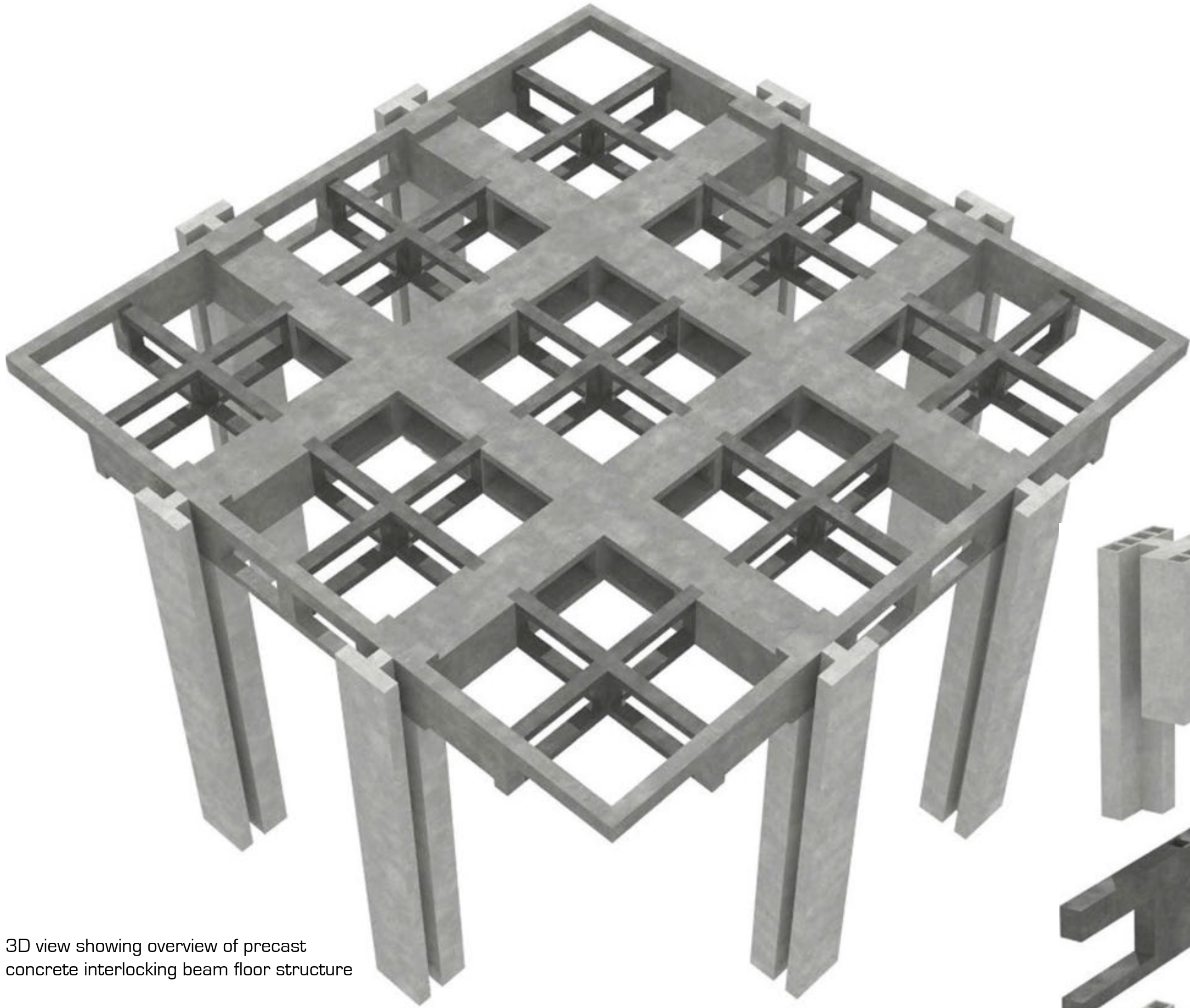
These are all essentially prestressed beams, which are stitched together to form a complete deck. Ends are supported either on beams or by a loadbearing wall, typically forming part of an overall precast concrete construction, which has the advantage of a rapid rate of construction. All types can be left either exposed, as is sometimes the case with parking garage construction, or be topped with a layer of concrete to form a composite structure. Openings for service runs need to be fixed at an early stage, since the size and position of openings in precast floor systems is much more constrained than is the case for cast-in-place floors.

Beam and block System
A traditional beam and block floor uses pre-stressed concrete beams to support aggregate concrete blocks. The beams are spaced at various centres depending on the applied loads and internal plan configuration. Beams may need to be staggered or doubled up to support internal walls.

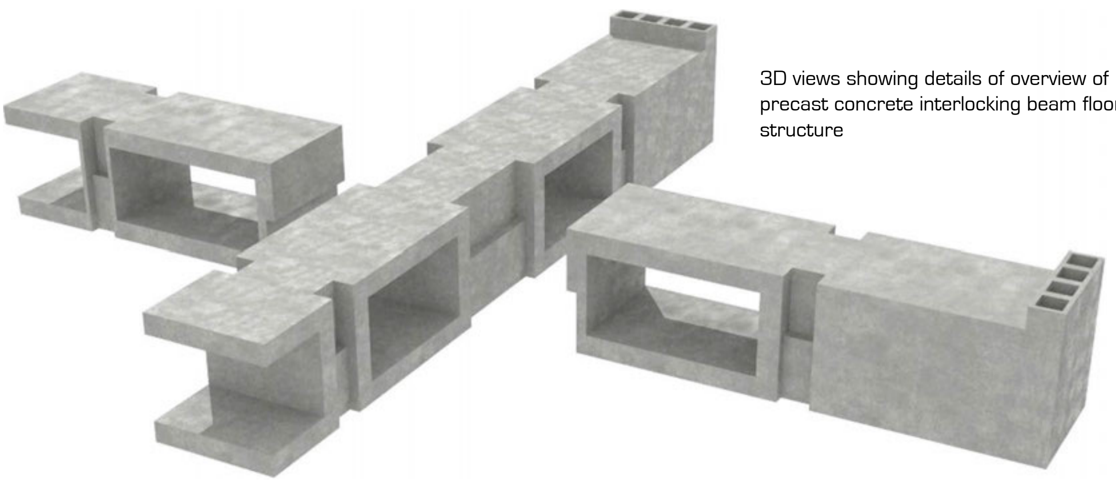
After the blocks have been positioned, a grout consisting of a mixture of sand and cement is brushed across the floor to ensure all joints are evenly filled. The use of expanded polystyrene blocks in the place of concrete blocks eliminates the need for additional sheet insulation within the floor system. Prestressed concrete beams are placed at 620mm centres before the polystyrene blocks are fitted between them. A structural concrete topping adds strength to the system and provides a smooth topping to which internal finishes can be applied.

Hollowcore systems
Hollowcore flooring systems use large precast slab elements supported from a structural frame to create large clear spanning floor systems. The hollowcore system can be used with the majority of structural framing systems including masonry, steel and concrete. Masonry bearings need to be in the region of 100mm, whereas 75mm is needed for bearings on steel or concrete.

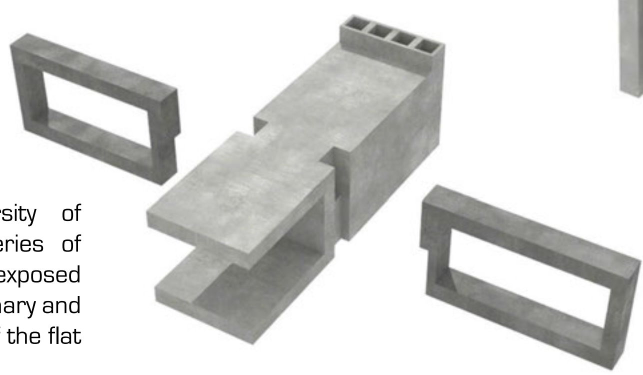
Hollowcore slabs can span up to 12 metres and panels are typically tied over supports with a tie reinforcement and structural concrete infill. Holes smaller than 100mm should be drilled on site. Larger holes can be formed during manufacture and may need steel trimming supports.



3D view showing overview of precast concrete interlocking beam floor structure

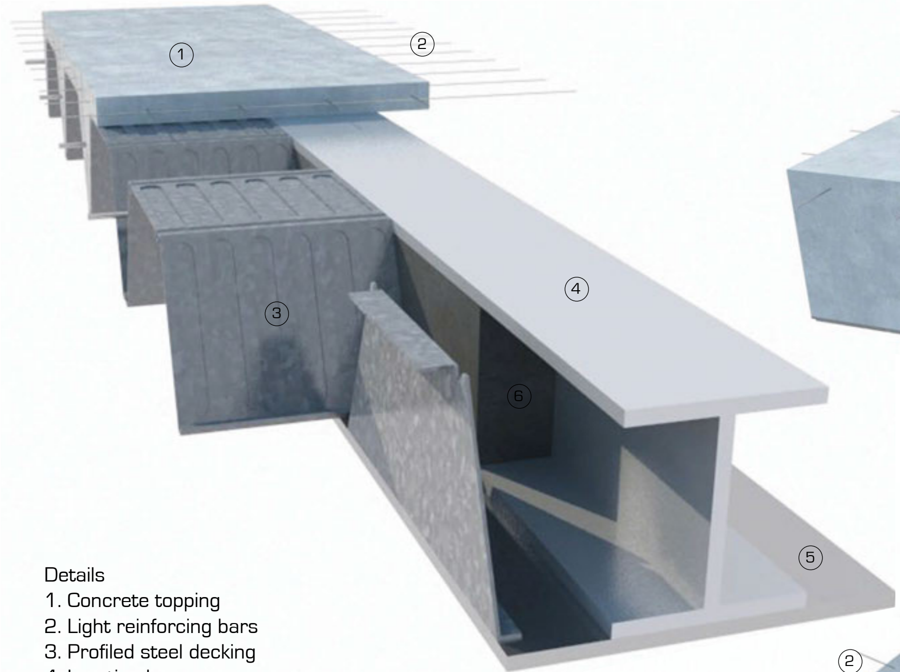


3D views showing details of overview of precast concrete interlocking beam floor structure



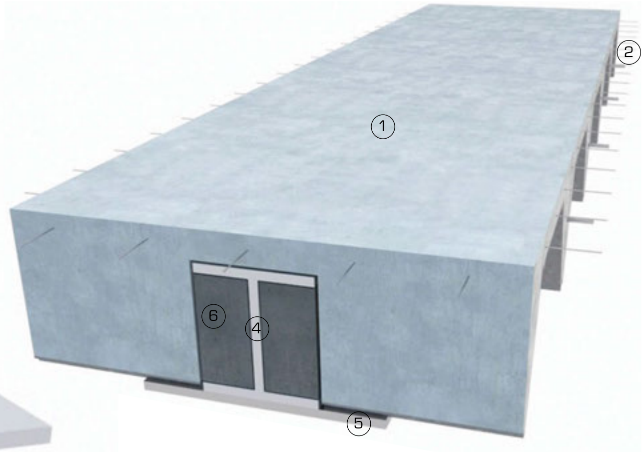
Richards Medical Research Laboratories

Richards Medical Research Laboratories, University of Pennsylvania, Philadelphia, U.S.A. Louis Kahn. A series of interlocking beams provides a floor structure whose exposed soffit could be clearly articulated as bays formed by primary and secondary beams. This approach contrasts with that of the flat slab.

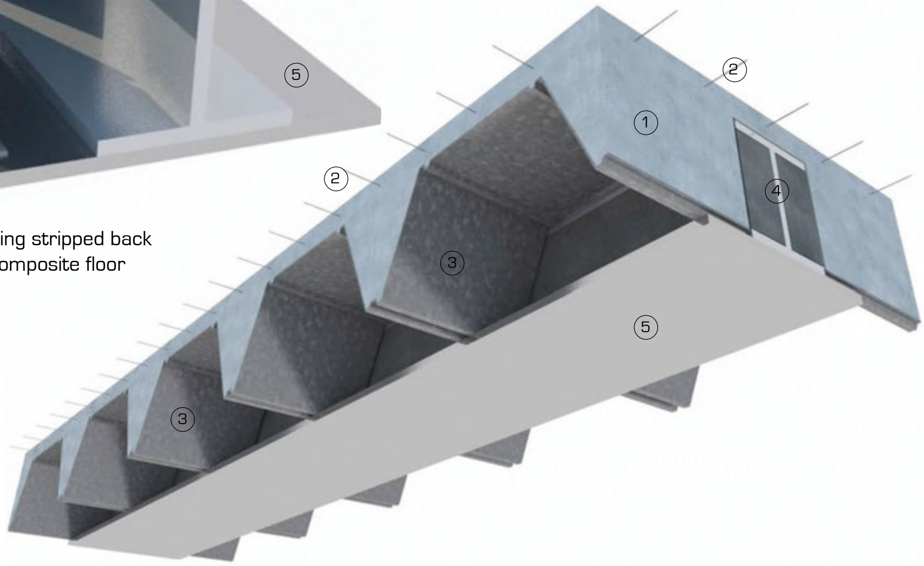


Details
1. Concrete topping
2. Light reinforcing bars
3. Profiled steel decking
4. I-section beam
5. Steel plate bolted or welded to I-section
6. End filler piece to form edge of poured concrete
7. Steel mesh
8. Supporting steel structure, typically I-sections or channels

3D view showing stripped back fragment of composite floor construction



3D overview showing detail of composite floor construction



3D overview showing detail of composite floor construction

Although it is possible to make an all-steel floor, in practice it is structurally inefficient and difficult to provide the necessary fire resistance, impact resistance and sound insulation. In addition, the amount of steelwork fabrication required would make it very expensive. The use of all-steel floors is restricted to steel grating in areas that are not required to provide fire resistance. All-steel floors in sheet and plate are most commonly used in industrial buildings.

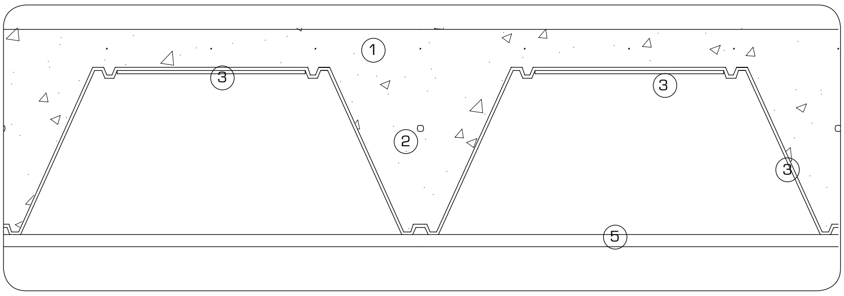
Steel composite floors

An alternative to precast concrete floors is to use a composite deck made from deep profiled steel sheet with concrete poured on top. During construction, the profiled decking provides permanent formwork to the concrete. Since the steel deck requires little or no temporary propping when the concrete is cast, construction time is reduced in comparison to other cast-in-place techniques. The steel deck and concrete perform structurally in a composite action where, in a simply supported situation, the concrete is in compression and the steel is in tension.The economic use of this type of floor is limited by its span. Over large distances, the supporting beams become very deep, resulting in an increased floor-to-floor height.

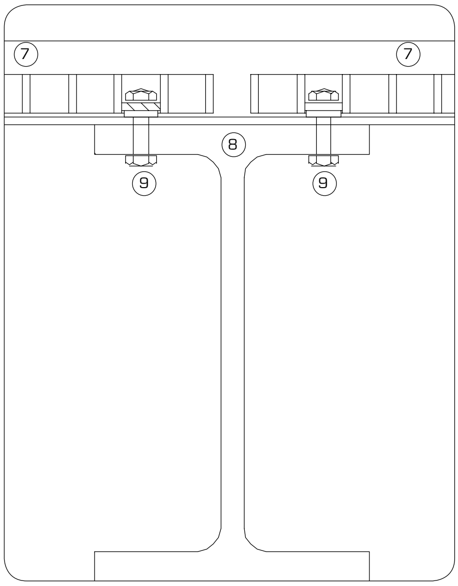
The profiled decking is fixed to the supporting steel beams with shear studs which provide the composite action between slab and beam. The concrete grips the shear studs, transmitting the shear forces through the metal deck to the supporting structure. The bond between the profile and the concrete is improved by the additional ribbing on its surface. The profiled sheet can be set either onto the top flange of the beam or onto a plate projecting from the bottom flange. The second method reduces the overall structural depth of the floor, with a consequent reduction in floor-to-floor heights; it also stiffens the web of the beam, increasing its performance.

Steel mesh floors

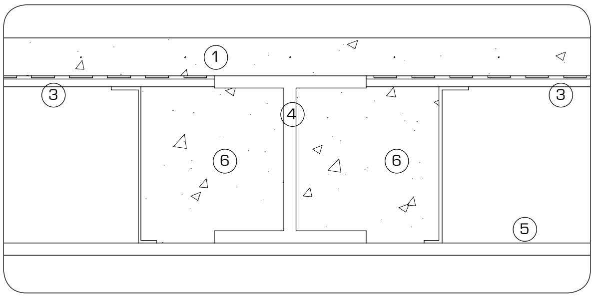
Steel grating is used primarily in industrial buildings and on maintenance access decks in other building types such as offices. It provides a lightweight, economic deck material that allows rainwater to drain off it immediately, making it less susceptible to corrosion when painted or galvanized. Steel grating is used to make structural decks by making a span between supports up to about two metres (6ft), depending on the depth of the grating. The choice of grating depends upon the spacing between the bars and their depth. Steel grating is made by one of two processes: welding or pressing. Lightly loaded small panels are manufactured by welding flats and rods together. Larger panels are made by a process that involves pressing together rows of notched flat bars positioned at right angles to one another to form a grid.



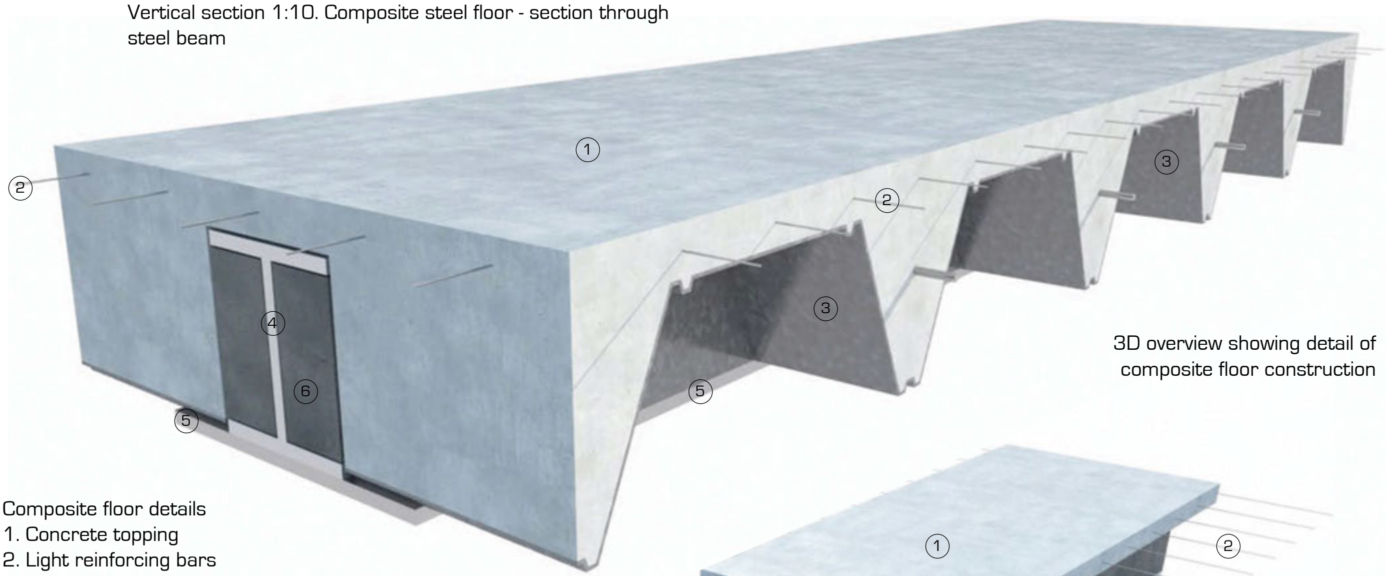
Vertical section 1:10. Composite steel floor - section through slab



Vertical section 1:5. Steel mesh deck and support

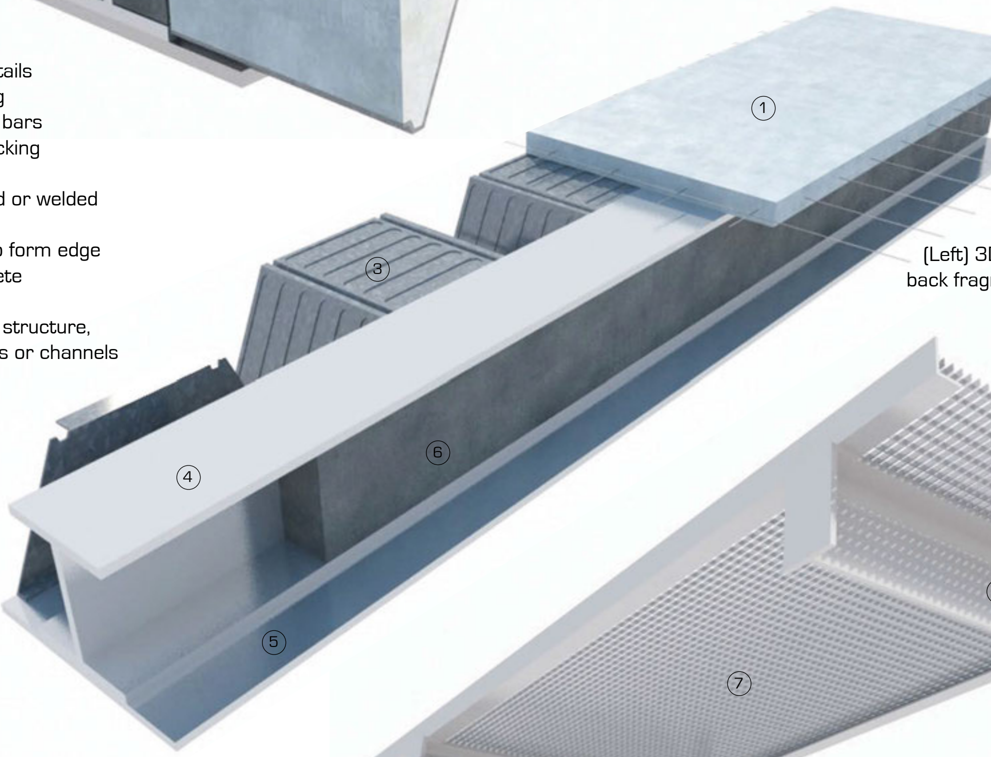


Vertical section 1:10. Composite steel floor - section through steel beam



3D overview showing detail of composite floor construction

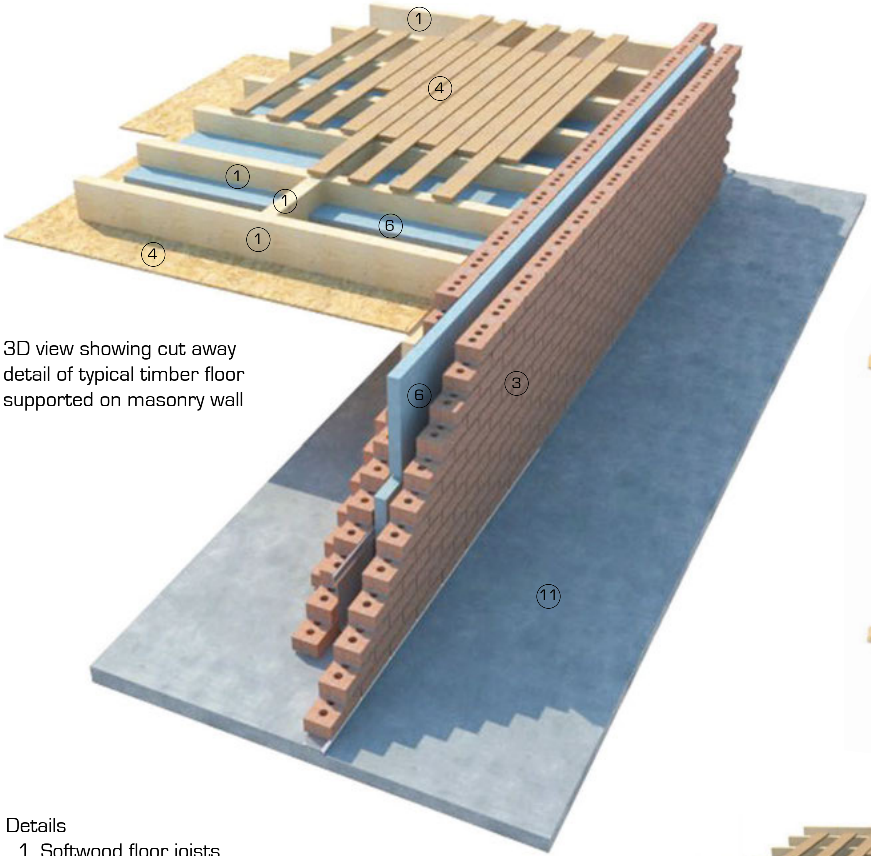
Composite floor details
1. Concrete topping
2. Light reinforcing bars
3. Profiled steel decking
4. I-section beam
5. Steel plate bolted or welded to I-section
6. End filler piece to form edge of poured concrete
7. Steel mesh
8. Supporting steel structure, typically I-sections or channels



(Left) 3D view showing stripped back fragment of composite floor construction

(Right) 3D view showing detail of underside of steel mesh deck

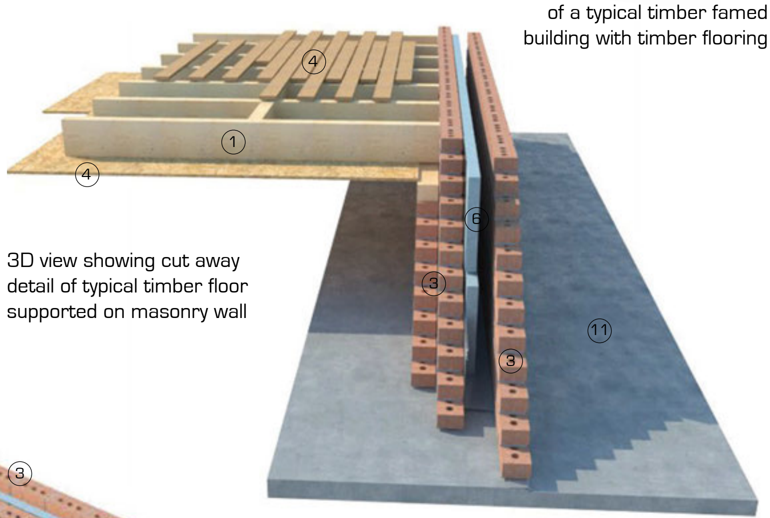
Structure 04
Floor structures 4: timber



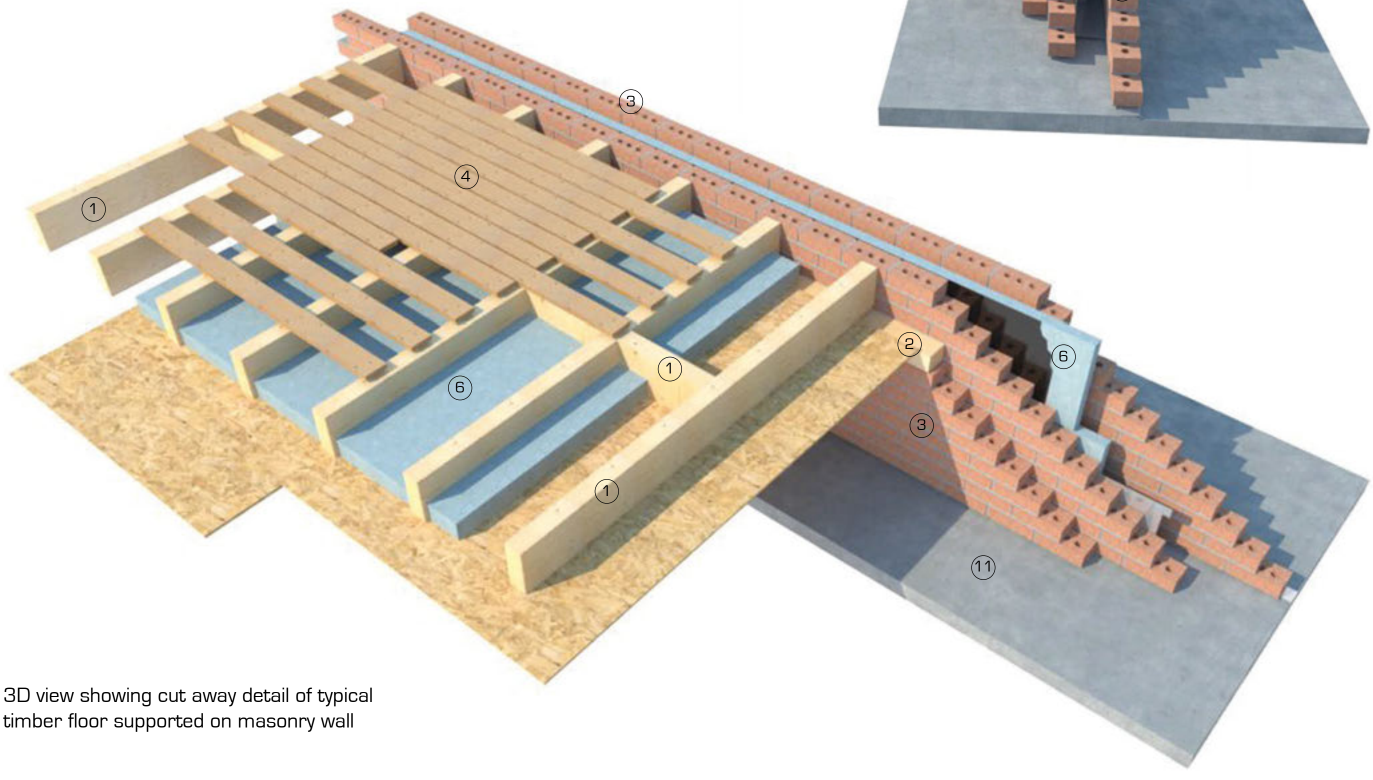
3D view showing cut away detail of typical timber floor supported on masonry wall

3D view showing cut away of a typical timber famed building with timber flooring

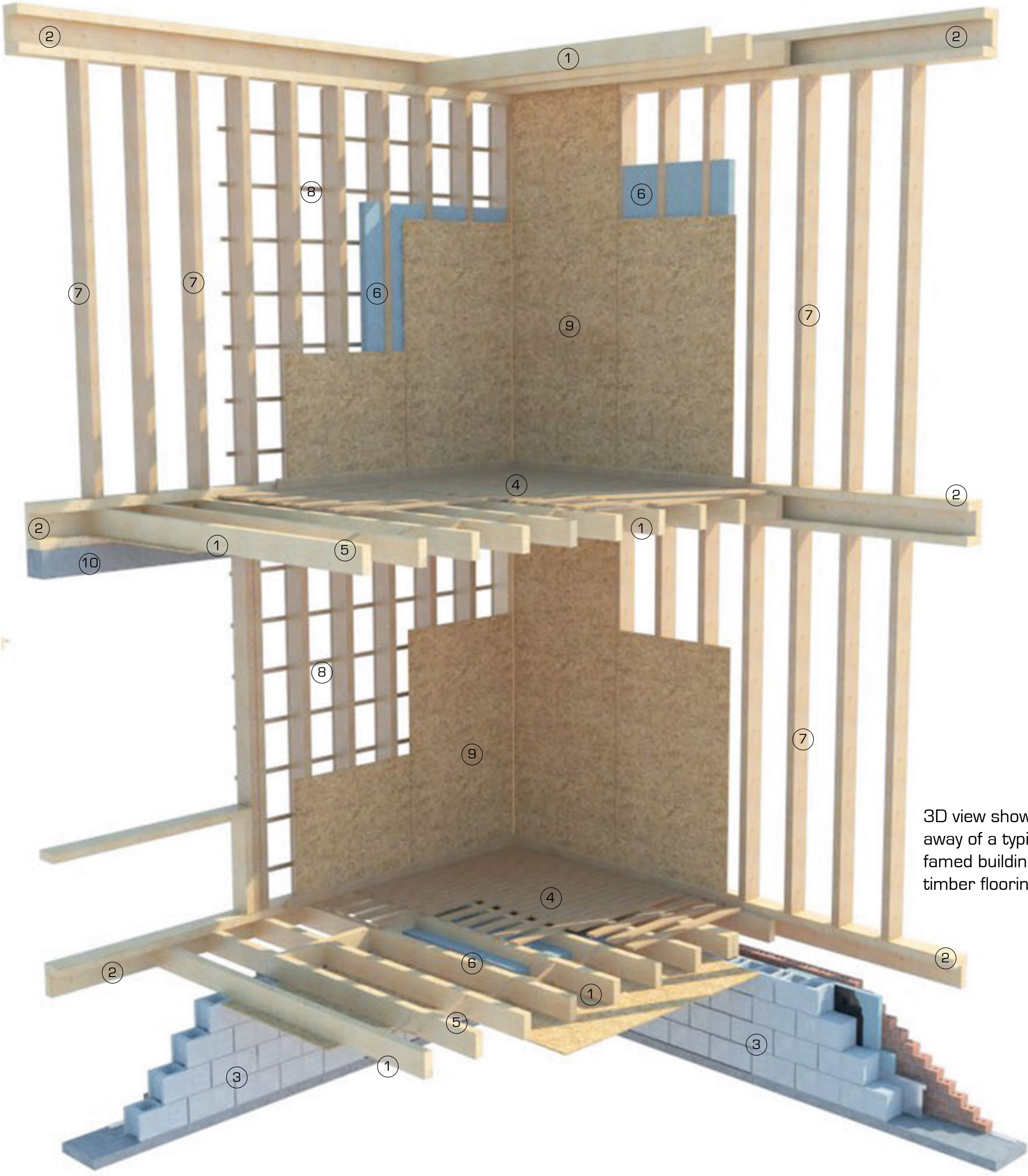
Details
1. Softwood floor joists
2. Softwood floor plate
3. Loadbearing wall
4. Floor boards or plywood/chipboard
5. Strutting to stiffen floor construction
6. Insulation
7. Timber wall studs
8. Timber battens
9. Plywood/chipboard wall boards
10. Concrete Lintel
11. Concrete foundation



3D view showing cut away detail of typical timber floor supported on masonry wall



3D view showing cut away detail of typical timber floor supported on masonry wall



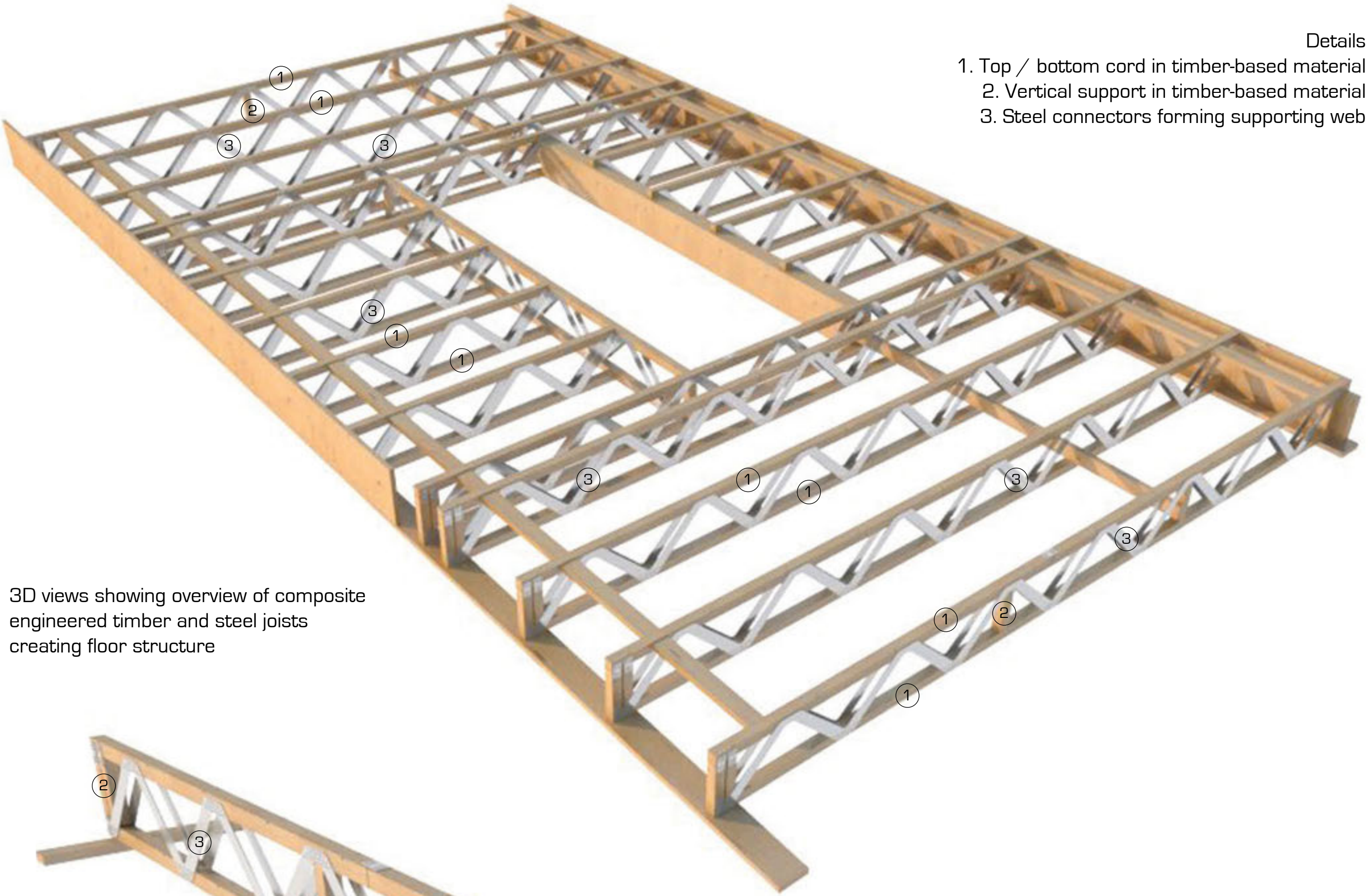
3D view showing cut away of a typical timber famed building with timber flooring

Timber floors are used typically with either loadbearing masonry walls, usually in cavity construction, or as part of a timber-framed structure. A typical floor for residential use, spanning up to around 3500mm might consist of softwood joists supported at each end by galvanized metal shoes or timber plates. Timber struts provide lateral stability and rigidity. Softwood boards are typically used as decking which is either butt-jointed or tongue-and-grooved. Alternatively, thicker boards are used, which have the advantage of bracing the floor structure horizontally. Plywood sheet provides superior stiffening action but its use makes access to the void beneath more difficult, particularly if the floor void is used for the passage of services. Additional stiffness is provided by herring-bone strutting set into the depth of the floor joists at centres to suit the span and design of the floor.

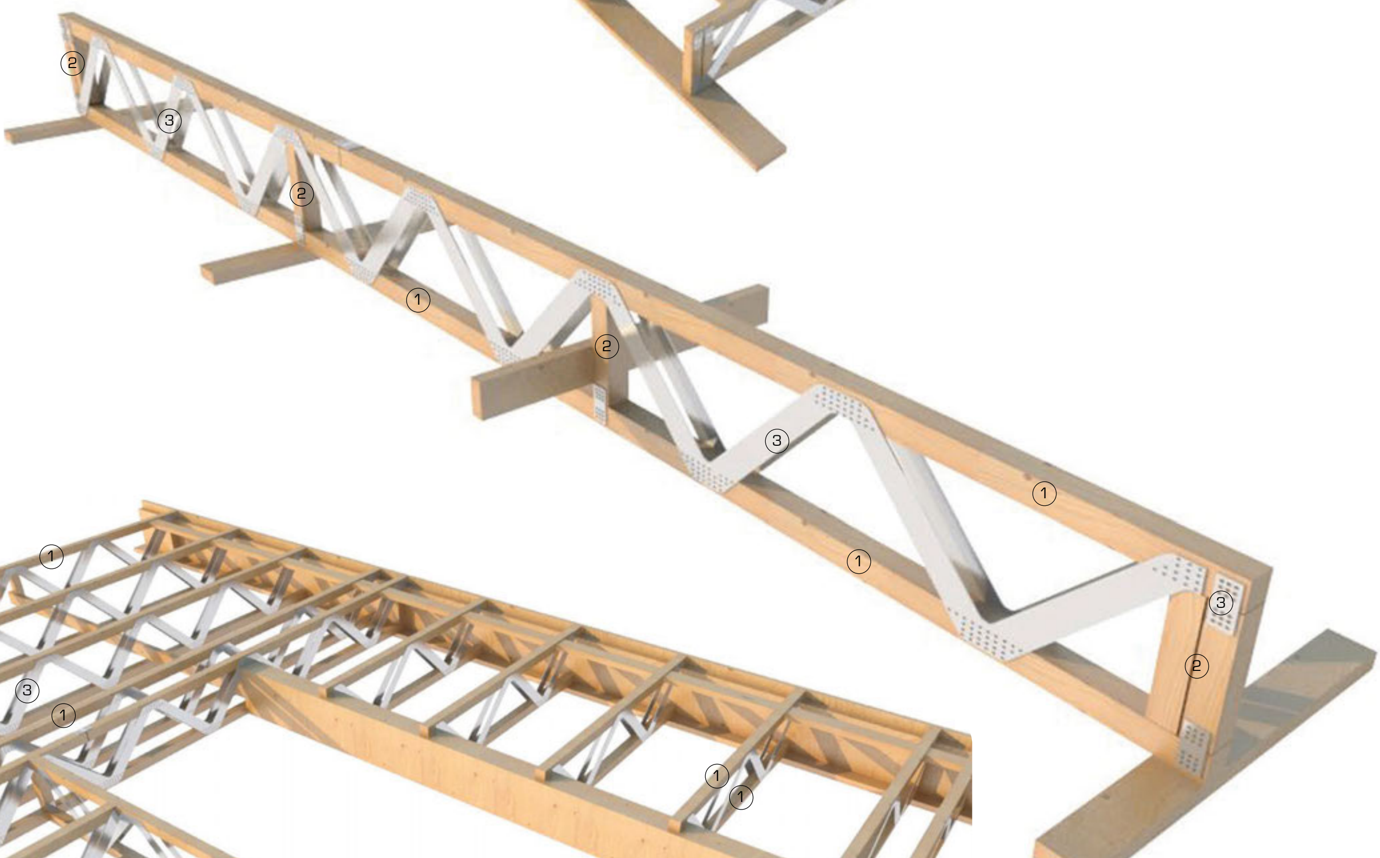
A recent development has been the introduction of 'engineered joists' in timber as an alternative to cut timber sections. They make use of a combination of cut timber sections and timber composites that combine wood or wood fibre with adhesives. The main composite materials used in the joists are mainly LVL (laminated veneer lumber) or OSB (oriented strand board).

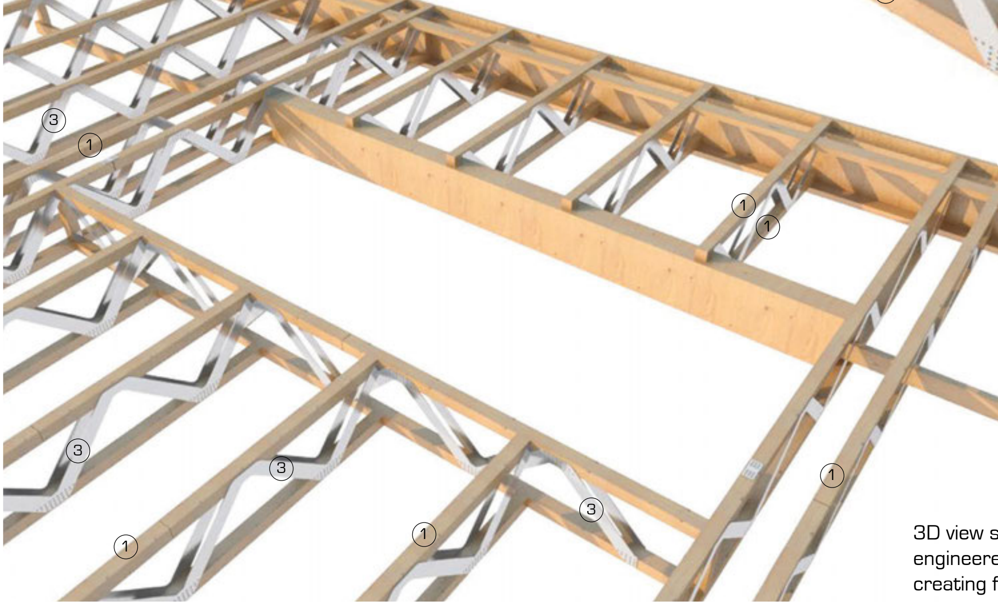
Engineered joists are of two generic types, those which resemble the form of a steel I-beam and those which resemble open web trusses. The solid joist I-beam type is made from top and bottom chords in timber which are connected by a solid web made in wood-based products such as LVL or OSB. The open web types often have a series of V-shaped and triangulated connectors forming the equivalent of truss members with narrow timber flanges top and bottom connected by a vertically set timber-based board material to form a structural web. These

Details
1. Top / bottom cord in timber-based material
2. Vertical support in timber-based material
3. Steel connectors forming supporting web

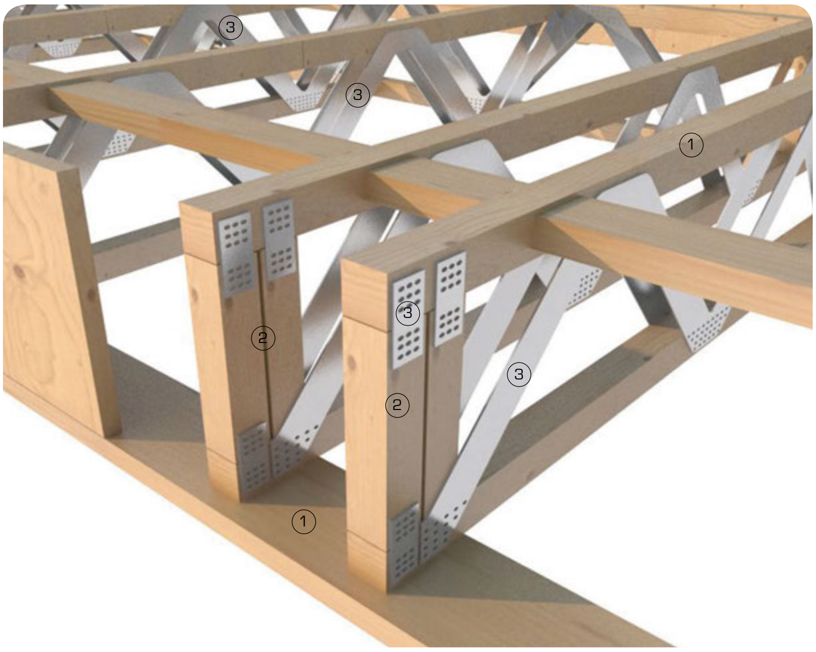


3D views showing overview of composite engineered timber and steel joists creating floor structure

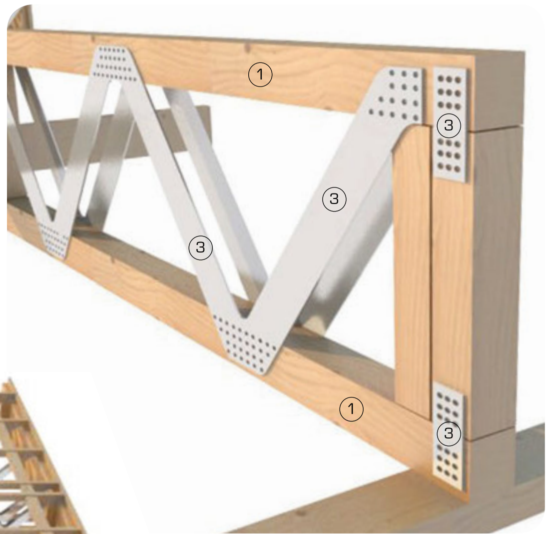


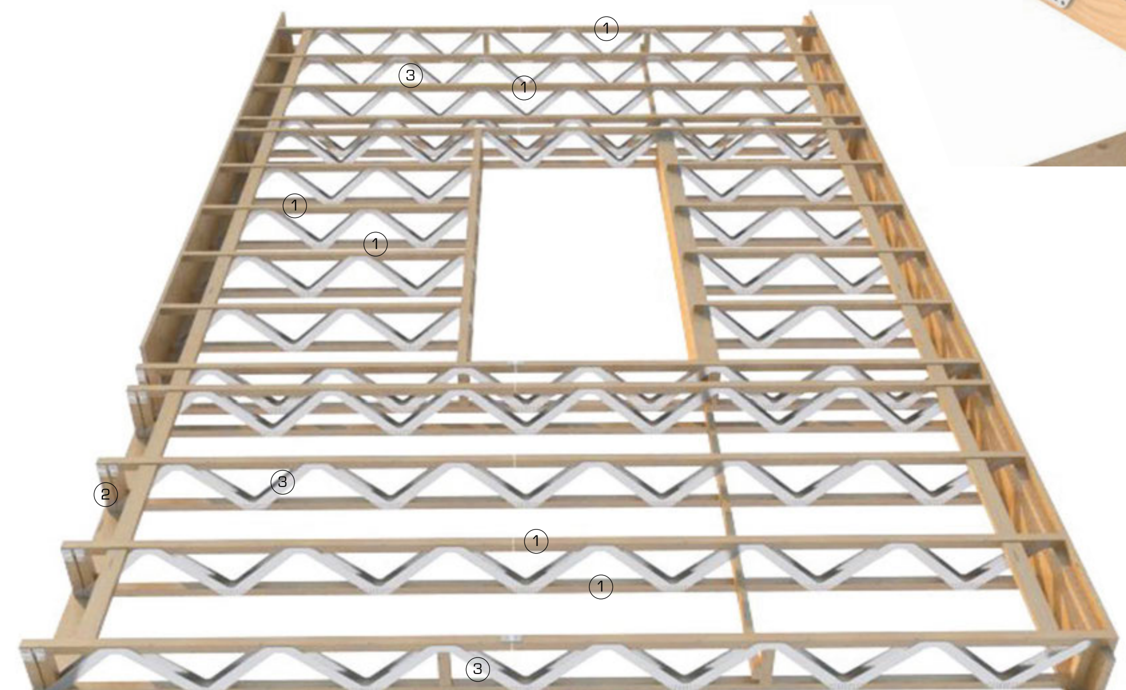


3D view showing overview of composite engineered timber and steel joists creating floor structure



3D view showing detail of composite engineered timber and steel joists creating floor structure

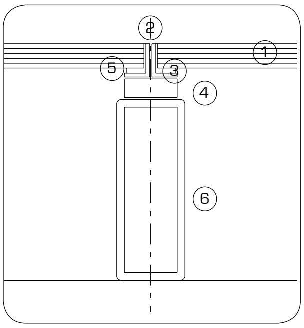




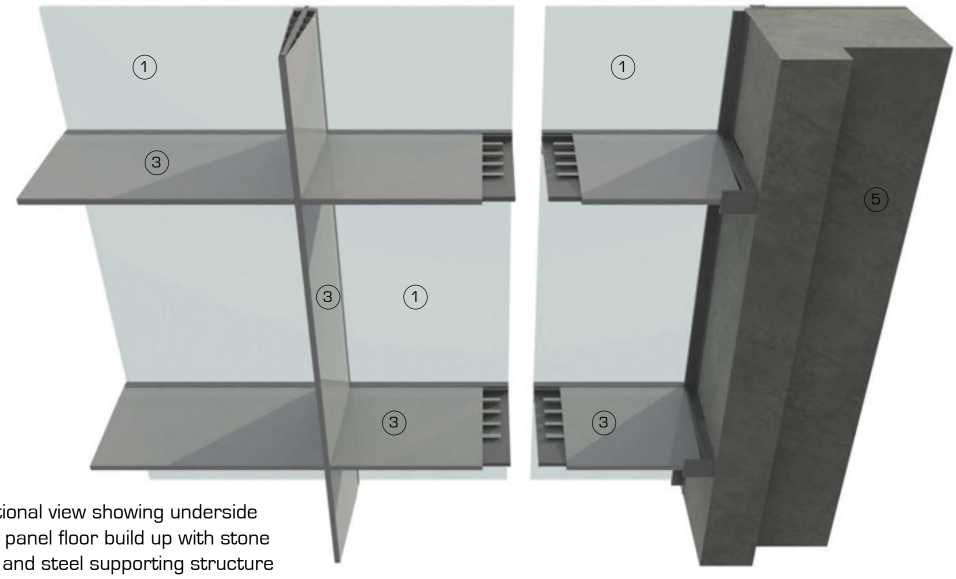
3D view showing overview of composite engineered timber and steel joists creating floor structure

V-shaped connectors are made as proprietary products with fixing systems to suit a factory-based manufacturing process rather than for assembly in a small workshop. The idea of these engineered joists has been taken further by joining them into prefabricated floor panels, also called 'cassettes'. These are made in standard modules to suit reduced construction time on site, and where there is sufficient repetition to suit prefabrication methods. Panels arrive on site with a timber deck and soffit lining attached, as well as thermal insulation when used as panels for roof decks.

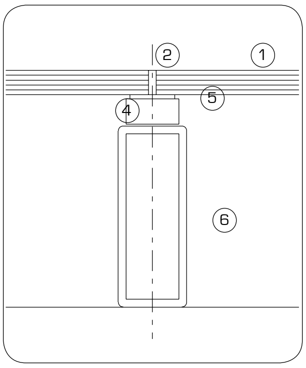
An advantage of engineered joists is their ability to form longer spans than sawn timber sections, with spans of up to 12 – 14 metres depending on the proprietary system used. The open web joists also have the advantage of being able to pass service ducts and cables through the depth of the floor construction, which is an advantage in mechanically ventilated buildings. These new forms of floor construction are finding a use in commercial buildings as well as their use in the more obvious application in domestic construction. Engineered joists also have the advantage of using less material than an equivalent solid timber joist, which is also typically heavier than the engineered type. The lower moisture content of the materials makes it less susceptible to moisture movement and reducing the risk of squeaking noises associated with timber floors.



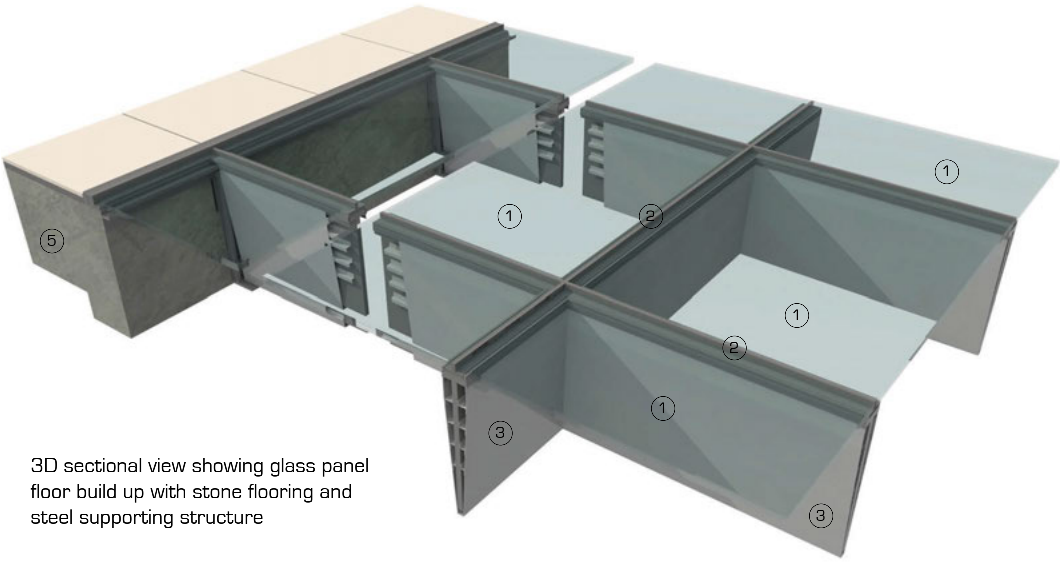
Vertical section. Alternative fixing method



3D sectional view showing underside of glass panel floor build up with stone flooring and steel supporting structure



Vertical section. Alternative fixing method



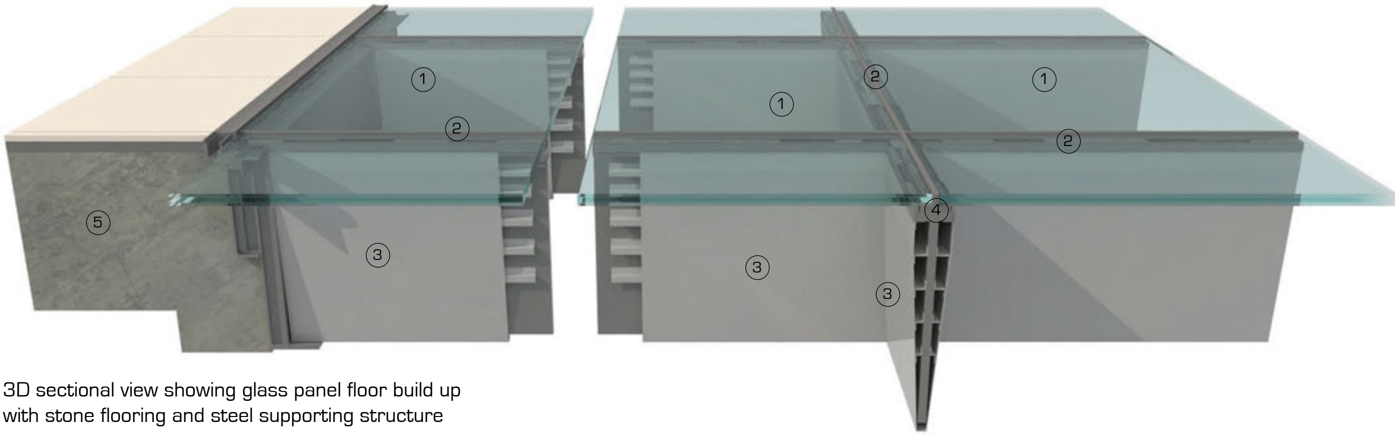
3D sectional view showing glass panel floor build up with stone flooring and steel supporting structure

Details
1. Laminated glass sheet, single glazed or outer layer of double glazed unit
2. Silicone seal
3. Stainless steel angle
4. Spacer
5. Supporting structure

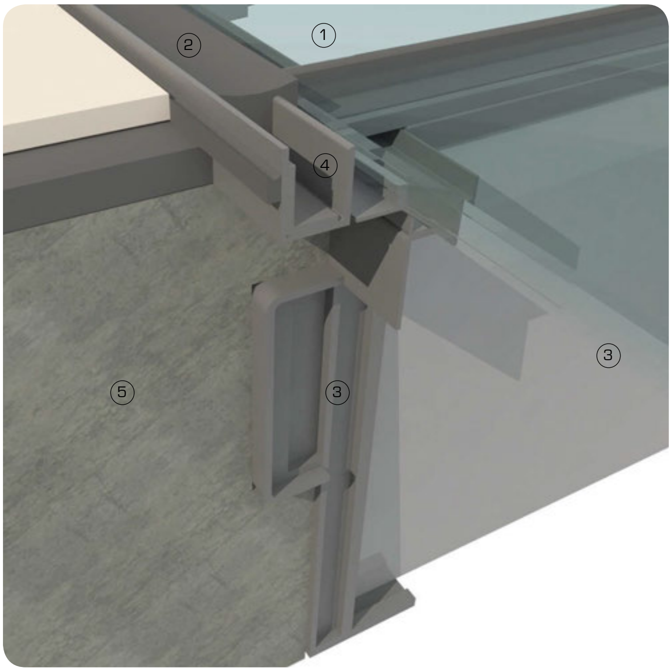
Glass floors are used to enhance naturally lit spaces by allowing light to pass through to spaces below. The primary material used is typically either glass sheet or glass blocks. Where glass sheet is used, laminated glass is set into a steel frame, giving it as much lightness and transparency as possible. Where glass blocks are used, they are set into a supporting frame of steel or concrete with reinforcing bars. Each block is individually supported, which has the effect of limiting the effects of lightness and transparency.

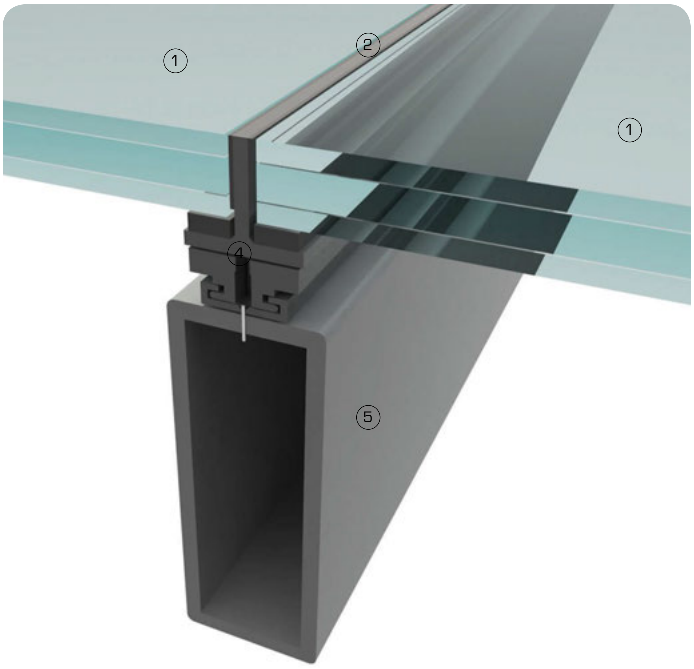
Economic spans for glass sheet are currently in widths of one metre, but panel sizes of 1200mm by 2600mm can be achieved, at significantly higher cost. The glass is usually bedded within the frame on a flexible, rubber-based material such as neoprene or EPDM, or alternatively bonded to the frame with silicone. This allows the supporting structure to move independently of the glass, as well as allowing each to move with thermal expansion. Junctions with the frame are closed with a silicone sealant. Sandblasting grooves into the glass can provide transparency and slip resistance. In addition, a translucent laminated interlayer can be used to control views through the glass. Sheet glass floor panels are currently restricted to relatively low loadings. Supporting structures can be in either steel or reinforced concrete. If the supporting structure is constructed to the correct height and fall, then the laminated glass sheets if used externally can be bonded directly to it rather than setting them into a steel sub-frame. Steel frames to support the glass use T-sections in order to provide a bearing for the glass at the top, but avoid a bottom flange to the supporting beam that would make the frame appear wider.

Glass blocks with textured or ribbed surfaces are often used as they have good slip resistance. This type of construction has a high resistance to shock, and is capable of very high loadings. Because each glass block requires support, the number of junctions in the frame becomes very high. Since joints in materials are usually expensive to form in relation to the cost of components, junctions are kept as simple as possible. For this reason, frames are often made as castings, where the material is poured in place to form a frame. Cast iron, cast steel and reinforced concrete are commonly used. An advantage of concrete is that it can be cast directly against glass blocks which become a permanent formwork. Reinforcing bars are laid in a grid in the joints between the blocks.



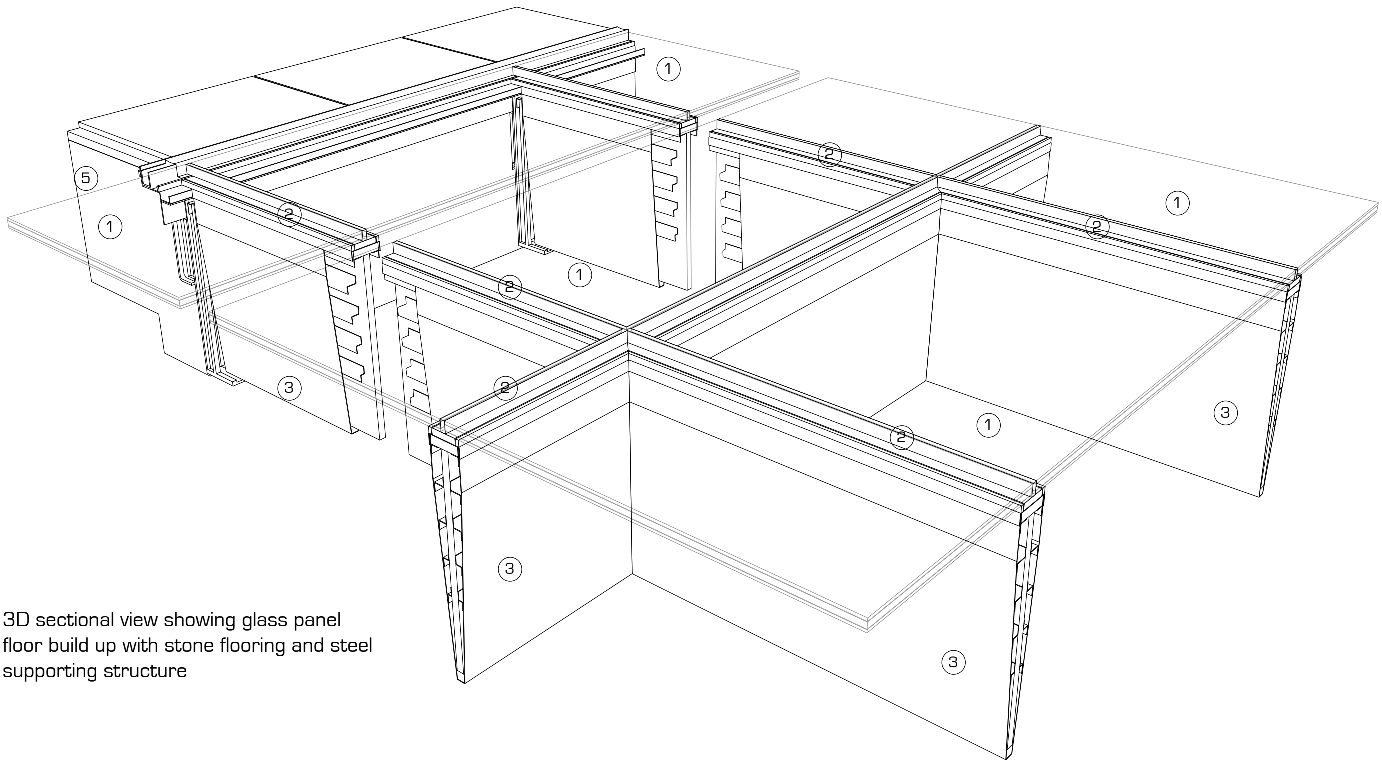
3D sectional view showing glass panel floor build up
with stone flooring and steel supporting structure



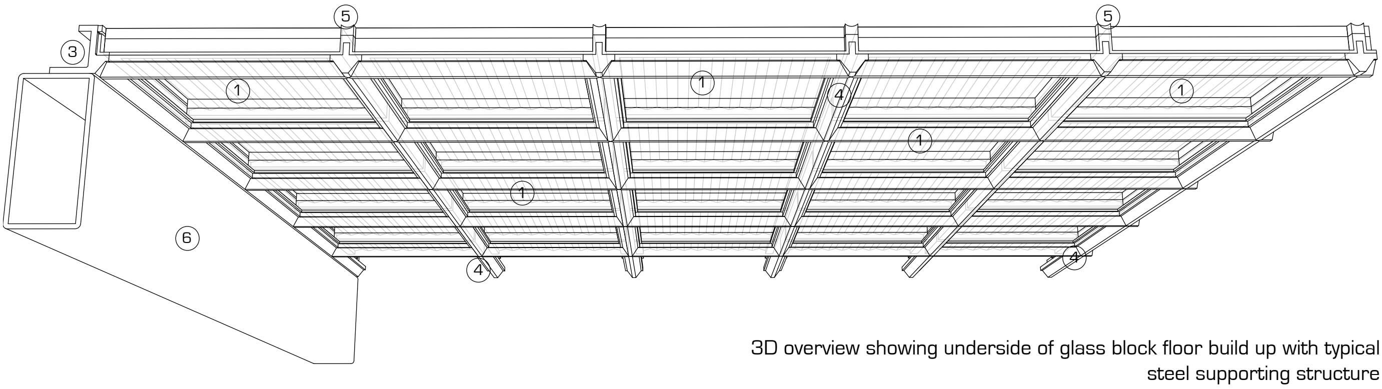


3D detail view showing glass panel floor build up with stone flooring and steel supporting structure

3D detail view showing glass fixing method for glass floor

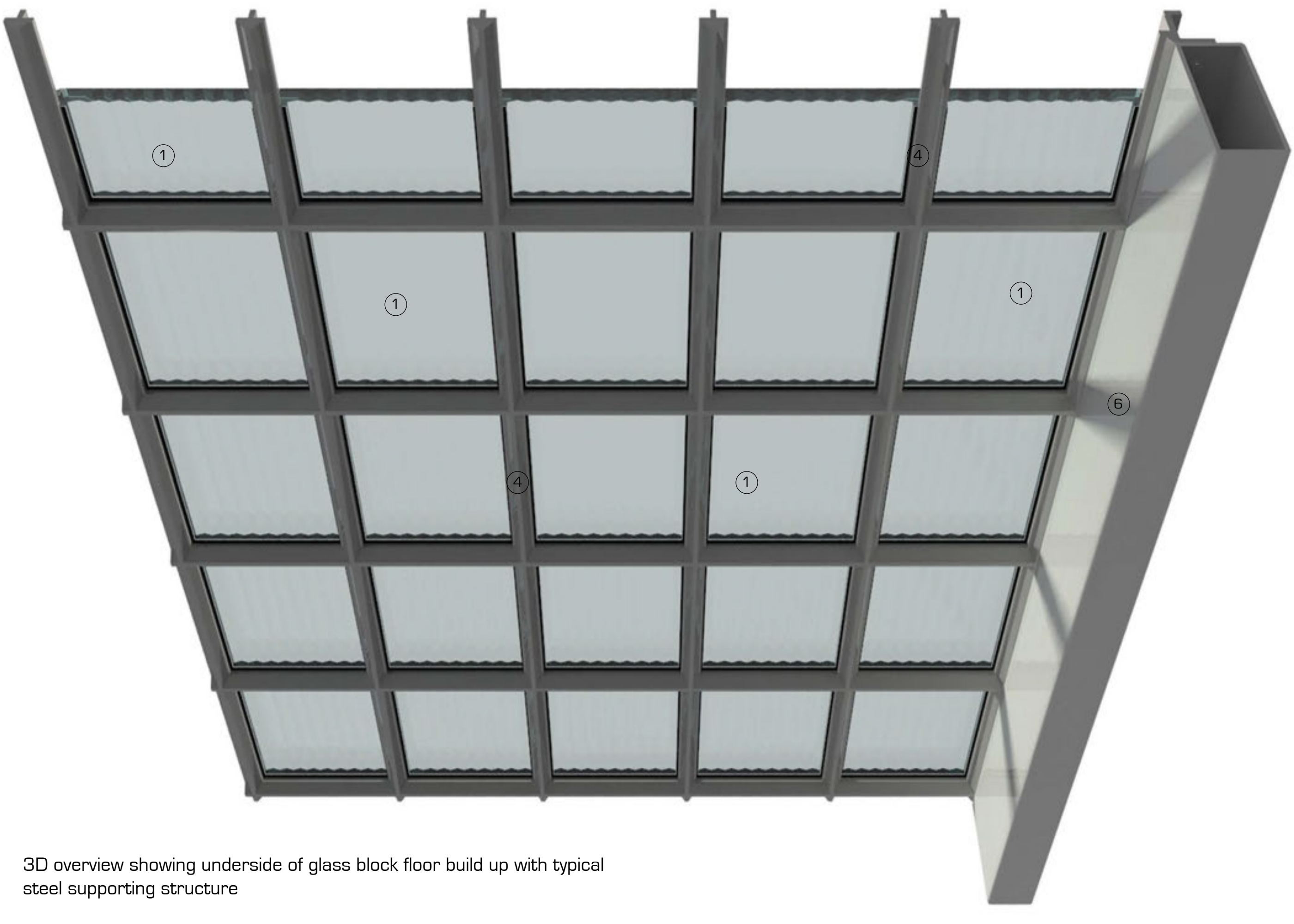


3D sectional view showing glass panel
floor build up with stone flooring and steel
supporting structure



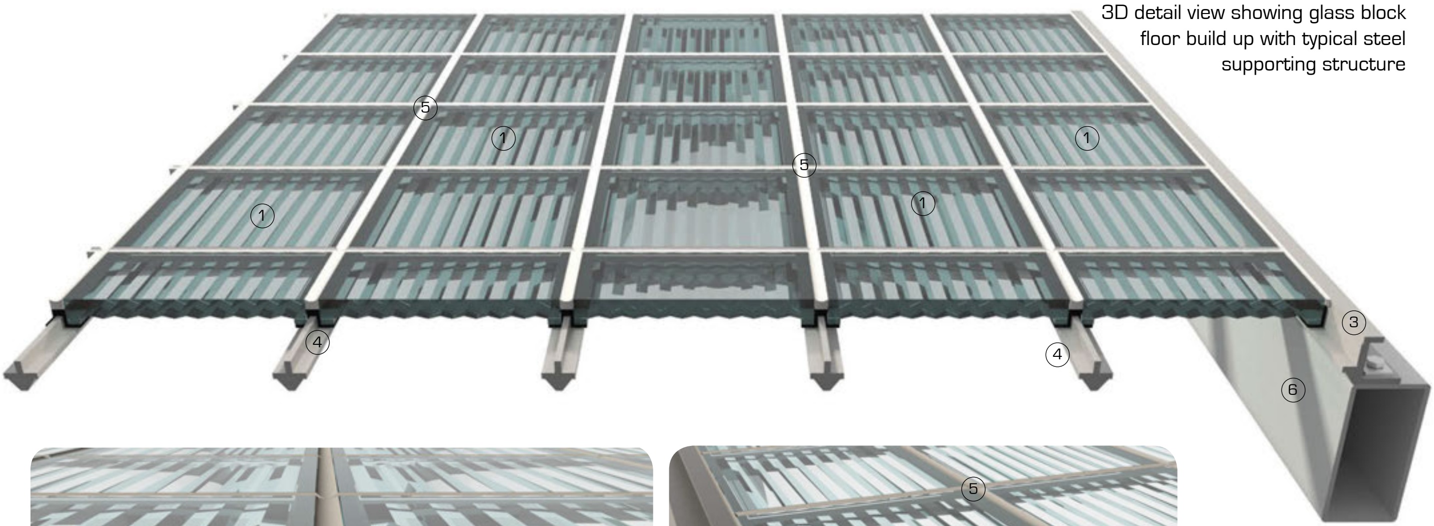
3D overview showing underside of glass block floor build up with typical steel supporting structure

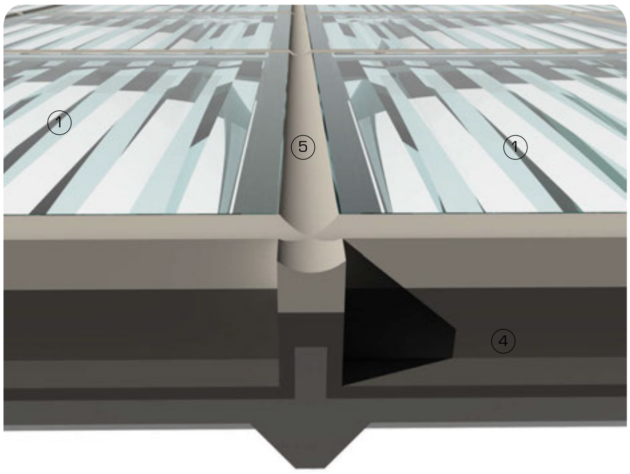
3D detail view showing glass block floor build up with typical steel supporting structure



3D overview showing underside of glass block floor build up with typical steel supporting structure

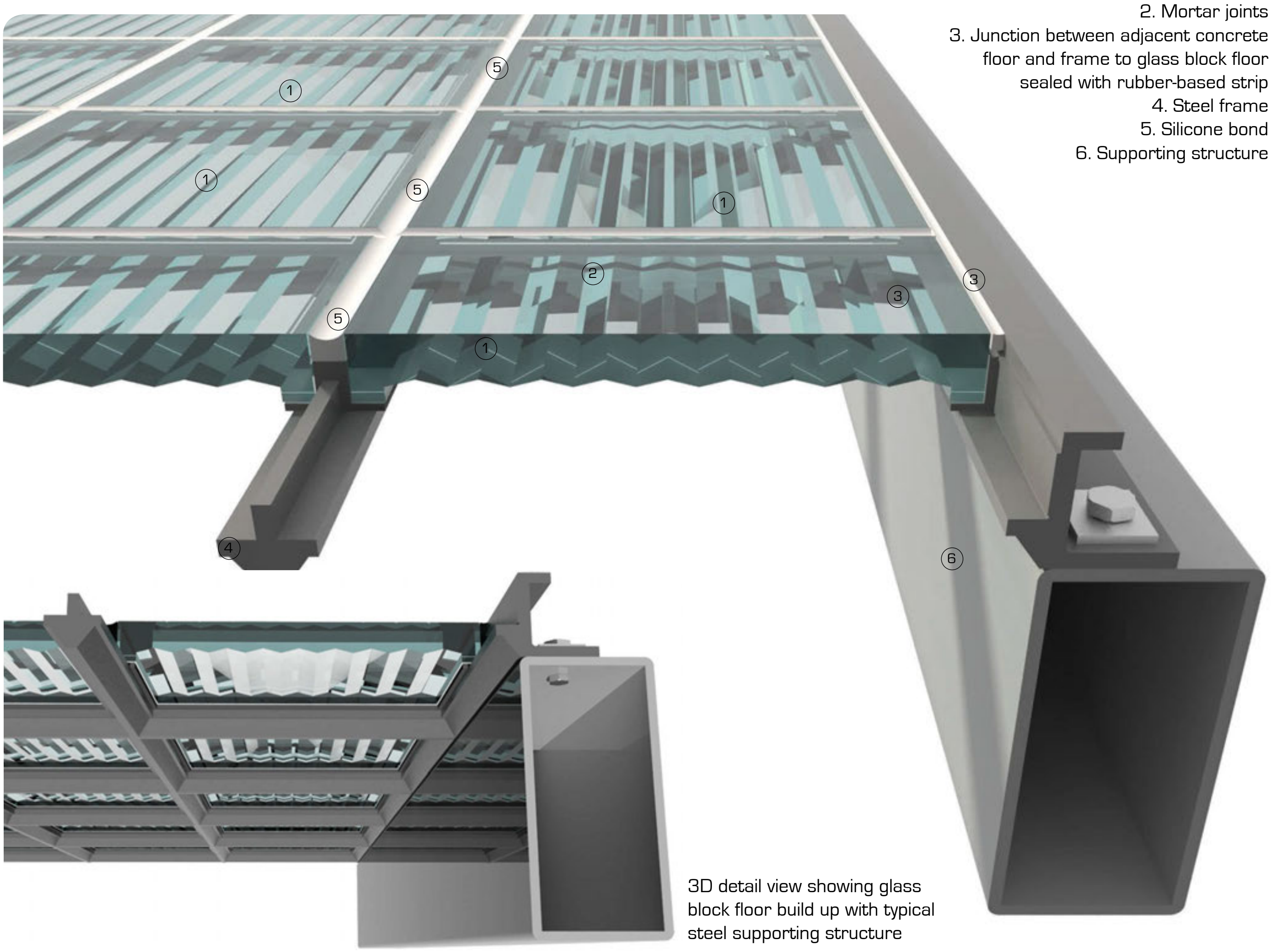
3D detail view showing glass block floor build up with typical steel supporting structure





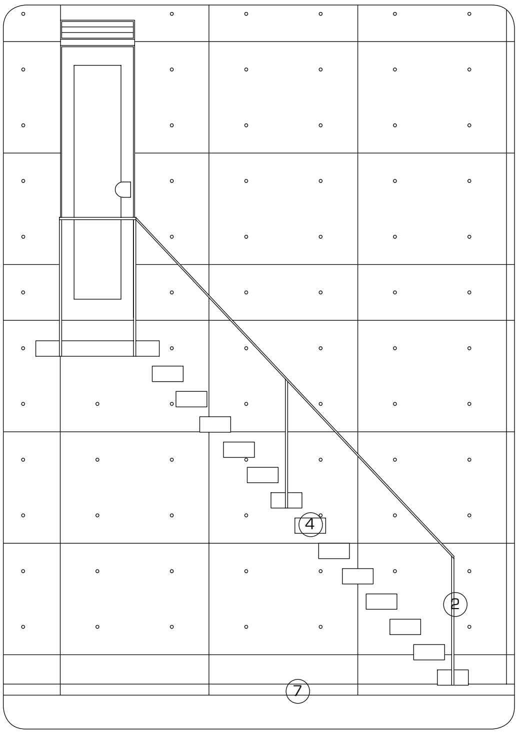
3D detail view showing glass block floor build up with typical steel supporting structure

Details
1. Glass blocks
2. Mortar joints
3. Junction between adjacent concrete floor and frame to glass block floor sealed with rubber-based strip
4. Steel frame
5. Silicone bond
6. Supporting structure

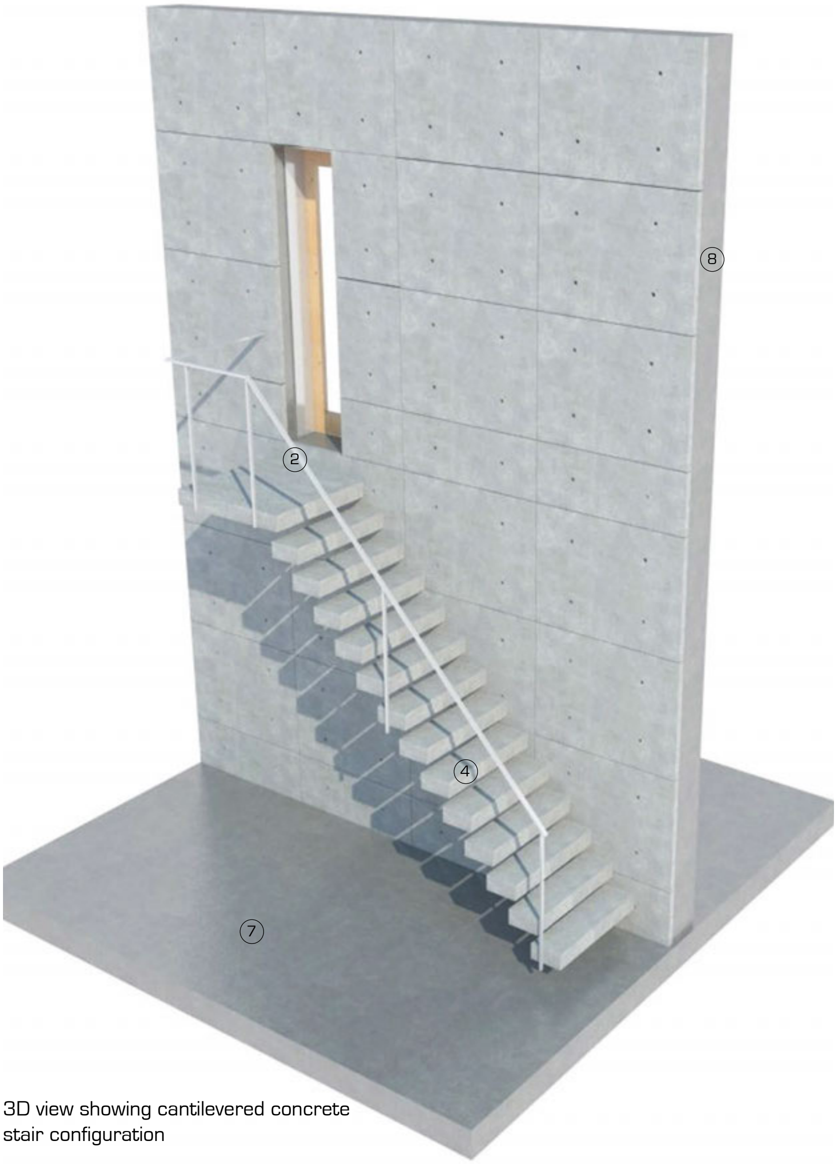


3D detail view showing glass block floor build up with typical steel supporting structure

Details
1. Guarding
2. Handrail
3. Staircase
4. Treads projecting from concrete wall
5. Cast-in-place staircase
6. Precast staircase
7. Floor slab
8. Loadbearing concrete wall



Part elevation of concrete cantilever stair



3D view showing cantilevered concrete stair configuration

Concrete stairs have the advantage of good fire resistance combined with the ability to absorb impact sound. Concrete can be used in conjunction with both steel and concrete structures. Stairs can be of cast-in-place or precast types, but the type used must be compatible with the overall type of construction used.

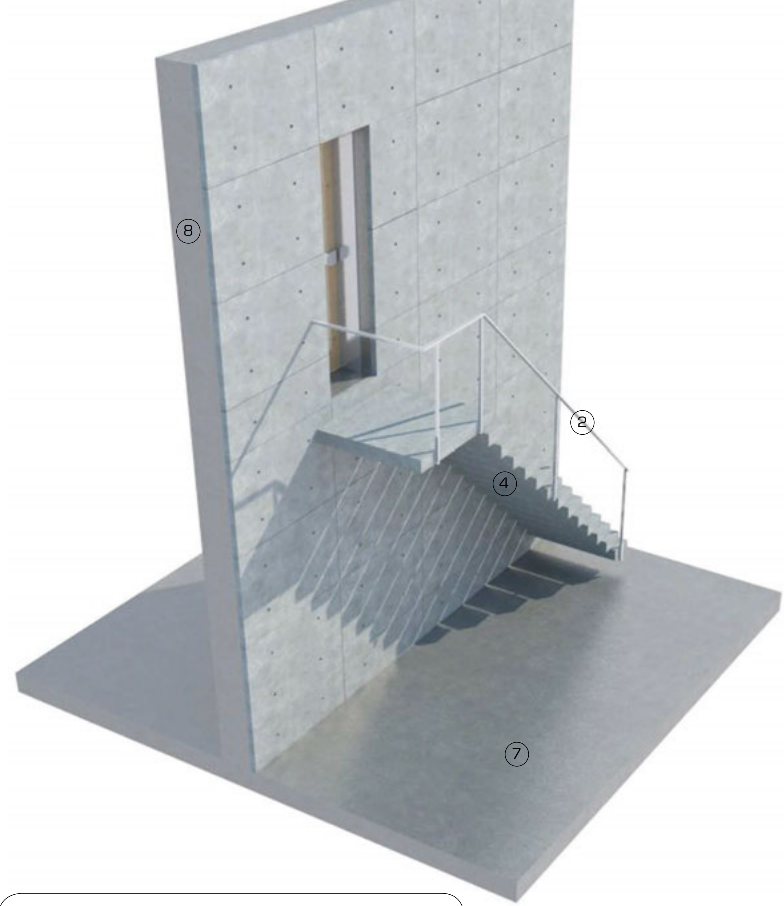
In-situ cast concrete
In-situ cast concrete stairs are made by setting steel reinforcement into reusable steel or timber formwork. A screed is added afterwards to provide a smoother and more exacting finish to the exposed surfaces. The screed can be used as a self-finish, when used internally, but the dusty nature of concrete walking surfaces often leads to the use of floor paint, polishing the concrete, or inserting treads in another material such as timber. Where the screed is used as a self-finish, anti-slip nosings are added. They can be recessed or surface fixed. Where the stair is exposed to view, the formwork into which the concrete is cast has to be designed and built carefully to reflect the quality of the finish demanded.

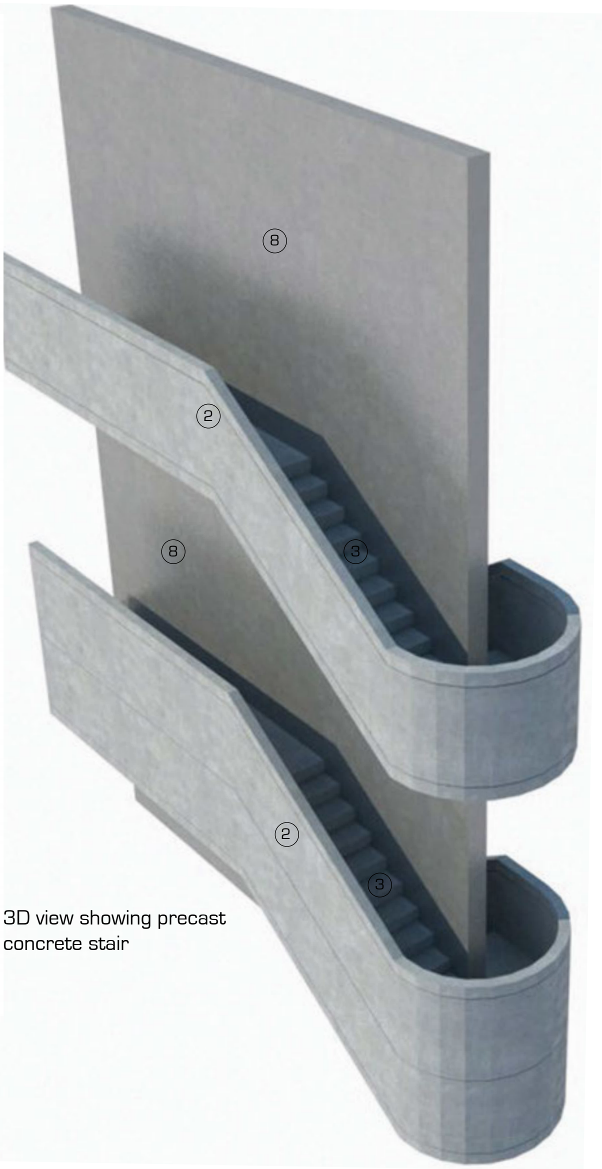
The junction at stair landings is often designed to create a single arris line across the soffit. This allows handrails on different flights to be properly aligned, achieved by offsetting flights by a distance equal to one tread width.

Precast concrete
Precast stairs are manufactured either as complete flights, sometimes with a landing attached to one end, or as individual treads which are fixed together on site. Precast stairs are used primarily where there is a large number of stairs of the same design used in a single project, and where a shorter construction time is an important factor. These stairs also assist in the construction process itself by providing convenient access. This is particularly important if the design of the stair is complex, where the cost of precast staircases can be considerably more than the cast-in-place type.

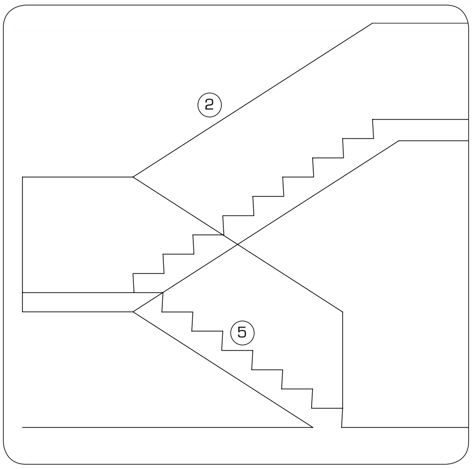
Guardrails
Guardrails on concrete stairs are most often pre-fabricated in parts, typically in steel, and then grouted into slots or holes drilled into the sides or treads of the stair. Alternatively, they can be fixed to the side of the stair with steel brackets. Handrails in metal are either integral with the guardrails or fixed to an adjacent wall.

3D view showing cantilevered concrete stair configuration

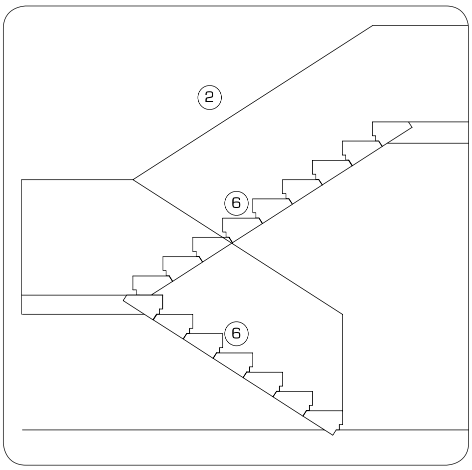




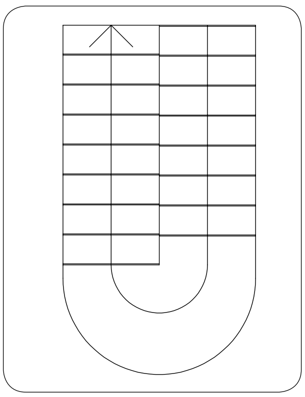
3D view showing precast concrete stair



Cast in-situ stair

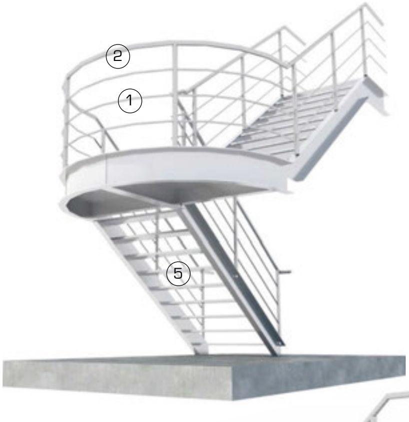


Precast stair with individually cast treads

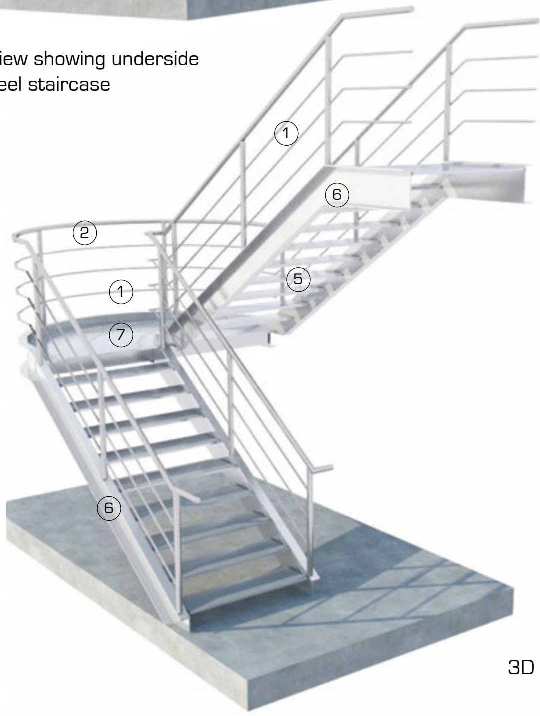


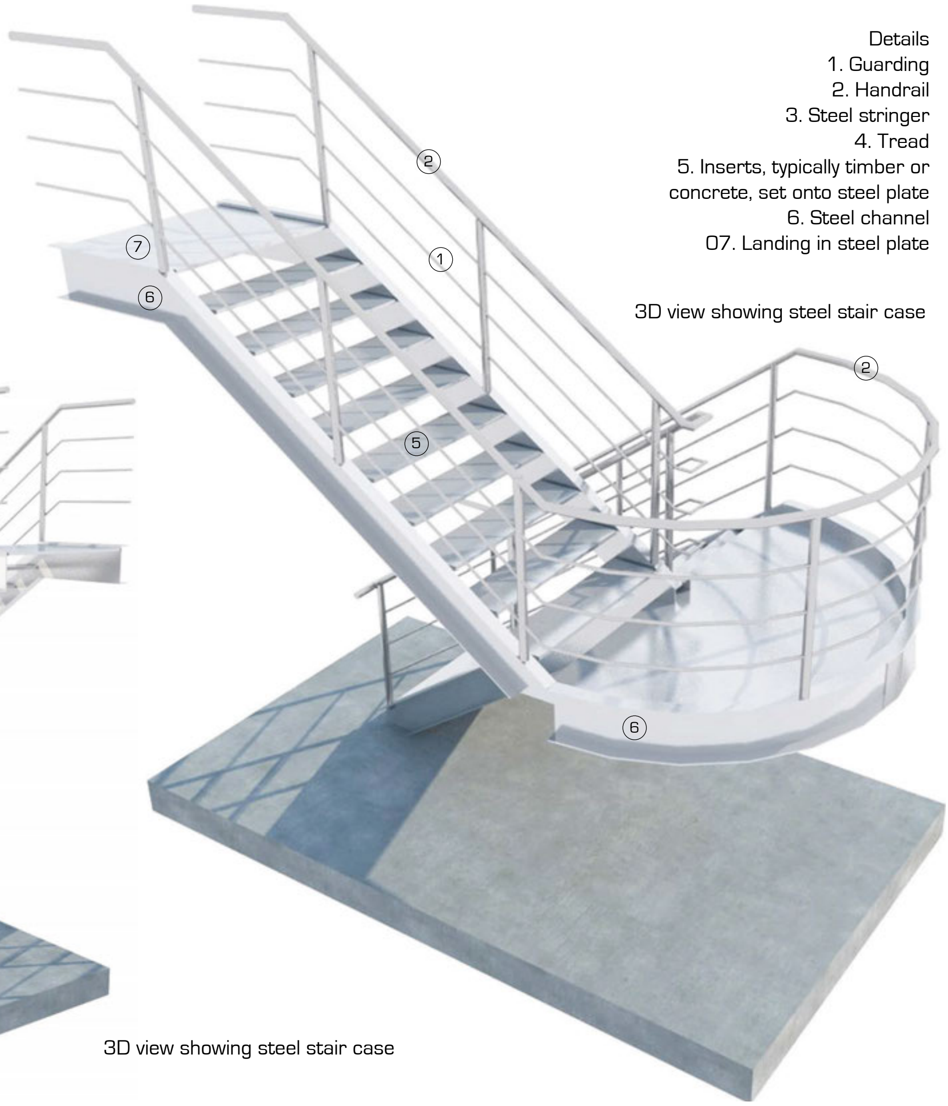
Plan view of stair

3D view showing cantilevered concrete stair configuration



3D view showing underside of steel staircase





Details
1. Guarding
2. Handrail
3. Steel stringer
4. Tread
5. Inserts, typically timber or concrete, set onto steel plate
6. Steel channel
07. Landing in steel plate

3D view showing steel stair case

3D view showing steel stair case

Steel stairs have the advantage of being lighter in weight, allowing them to be prefabricated and delivered to site as completed sections of flights and landings. They can be lifted into place more easily than concrete stairs, but lack the high fire resistance associated with that material. There are two generic types, with either treads as plates set between stringers, or with folded sheet set between stringers. In addition, spiral stairs in cast iron and steel are available as proprietary products in a range of standard sizes. These comprise a central post to which radiating treads are fixed.

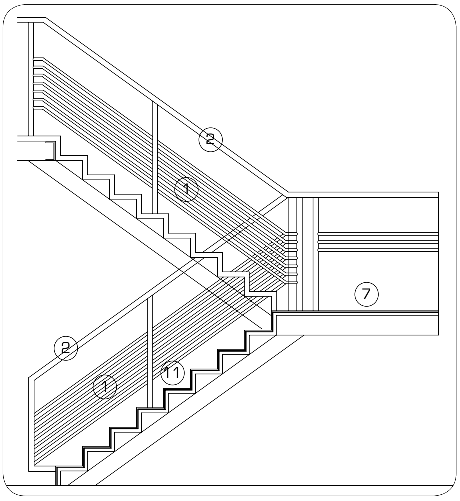
Flat plate type

Stairs with plate set between stringers are made by bolting or welding treads formed from either smooth- or checker-plate. Stringers, which form the beams at the sides of the stair, are usually made from steel channel which provides a straight vertical face to which the treads can be fixed. The position of the treads within the depth of the stringer is critical in order that stringers can be aligned neatly where they intersect at landings. Bolted or welded connections are made to be sufficiently stiff so that the stair does not rattle or experience any significant movement while in use. Depending on their width, treads may need to have either their edges folded to provide stiffness which can accommodate an additional finish such as a decorative timber tread, or formed as a composite steel tray with a concrete fill. An alternative method of stiffening treads is to weld a vertical steel plate to their underside to form a T-section.

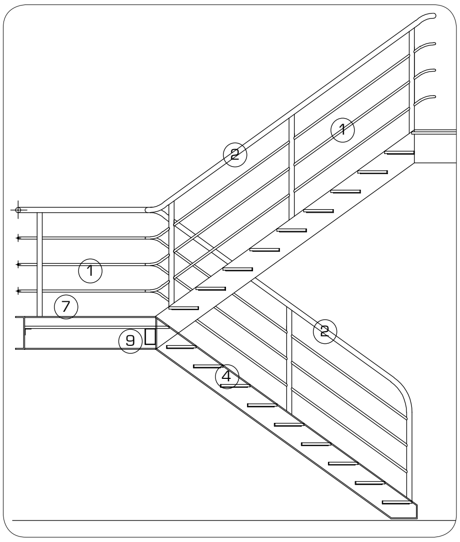
Stairs can be formed by folding a steel sheet and supporting it, either on stringers set at the sides or by a single central stringer set beneath the plate. The inherent rigidity of the folded sheet allows a wide range of economic solutions for the arrangement of the stringers. As with the flat plate type, the assembly can be either bolted or welded, and decorative inserts in other materials such as timber can be added. Both stair types can be finished in a variety of coatings from galvanizing to painting to polyester powder coating. Softer coatings such as PVDF are rarely used due to their poorer wearing qualities. In addition to visual considerations, the choice of finish is determined by the required degree of durability and appearance.

Guardrails

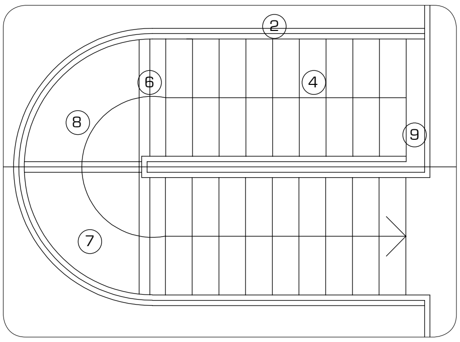
Steel guardrails are prefabricated but are not often fixed to staircases before delivery to site in order to make the stair both easier to install and to make it easier to align the guardrails with adjacent walkways or enclosing walls. Guardrails are usually finished before delivery to site. If a paint finish is used, the guardrail will at least be prepared and primed before arriving on site where finish coats can be applied after its installation.



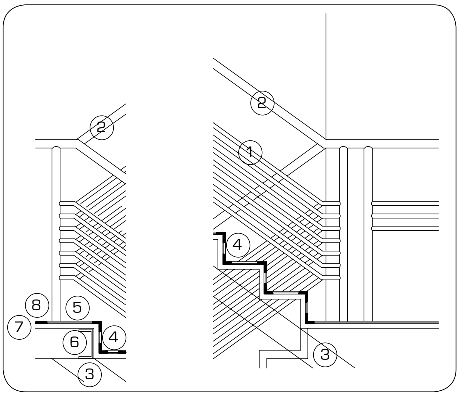
Vertical section through treads



Vertical section through treads

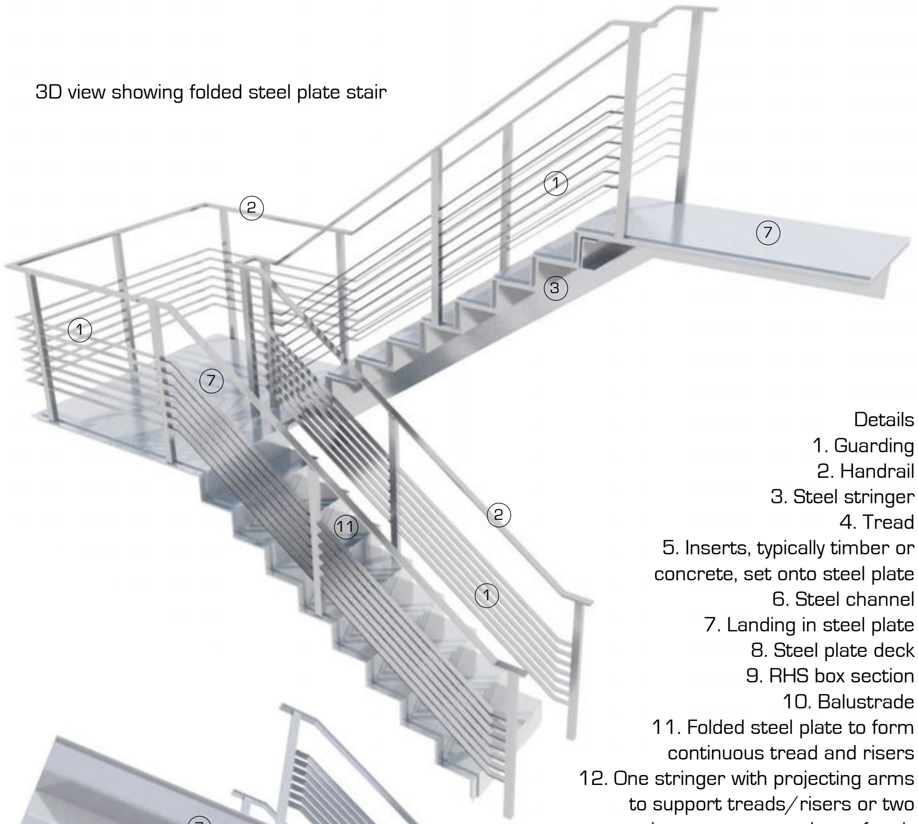


Horizontal section

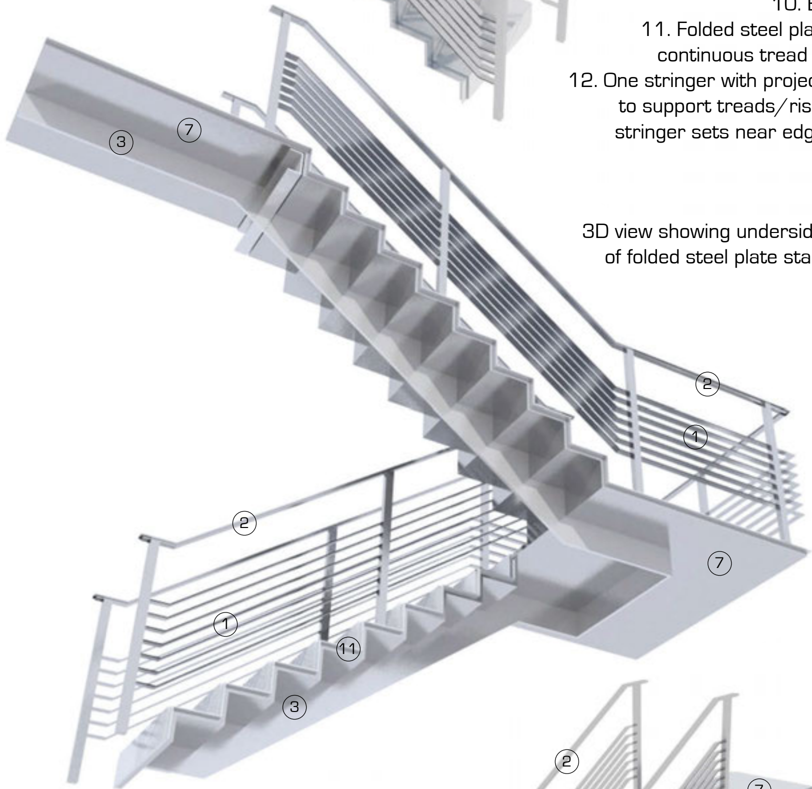


Vertical section

3D view showing folded steel plate stair

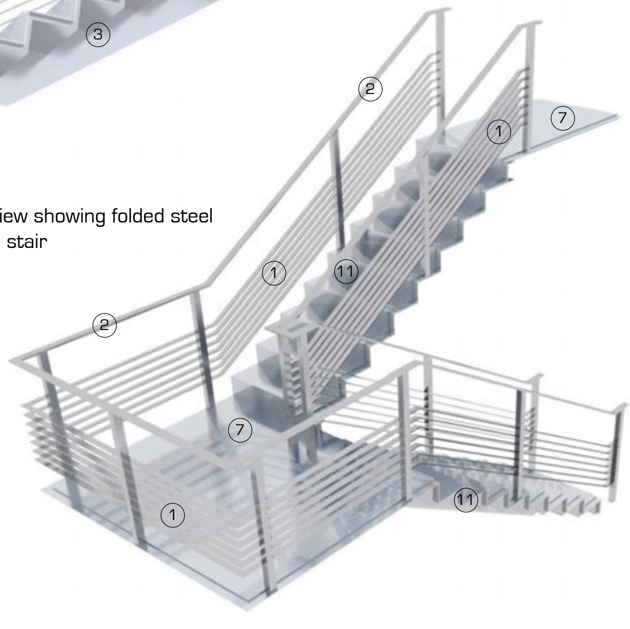


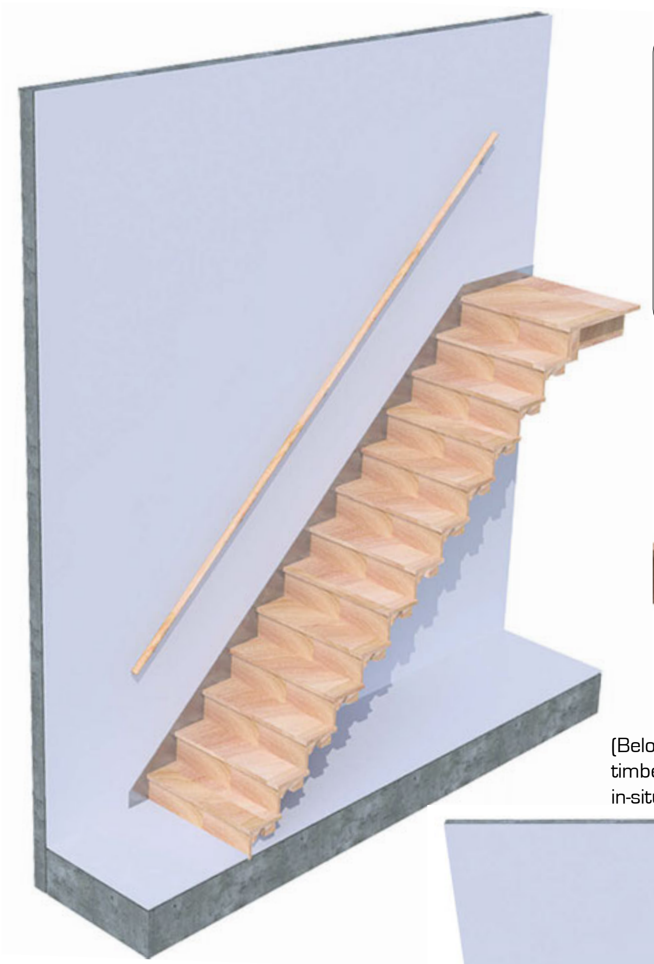
Details
1. Guarding
2. Handrail
3. Steel stringer
4. Tread
5. Inserts, typically timber or concrete, set onto steel plate
6. Steel channel
7. Landing in steel plate
8. Steel plate deck
9. RHS box section
10. Balustrade
11. Folded steel plate to form continuous tread and risers
12. One stringer with projecting arms to support treads/risers or two stringer sets near edges of stair



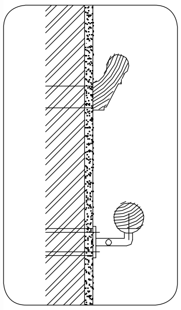
3D view showing underside of folded steel plate stair

3D view showing folded steel plate stair

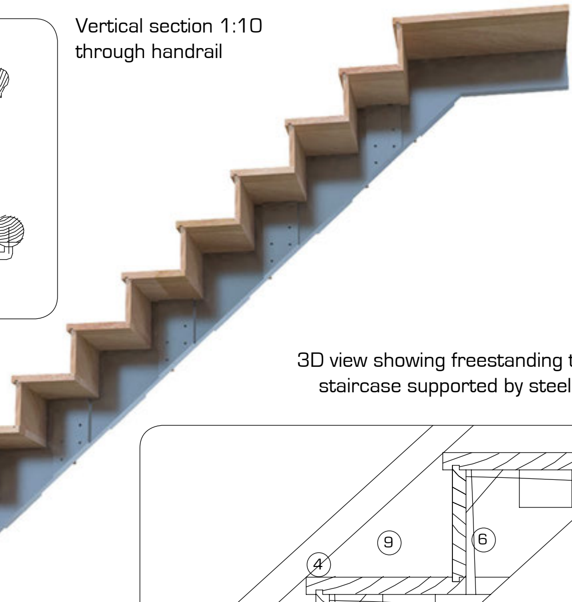




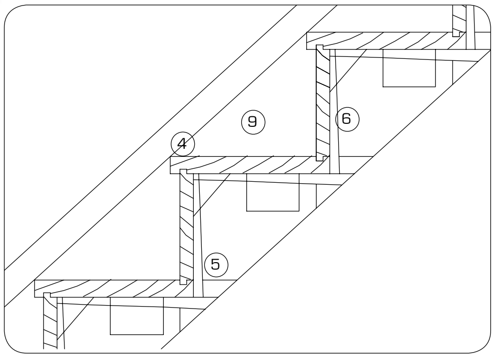
3D view showing timber staircase against in-situ cast concrete wall



Vertical section 1:10 through handrail

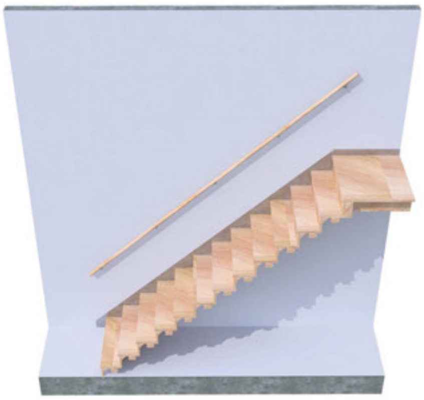


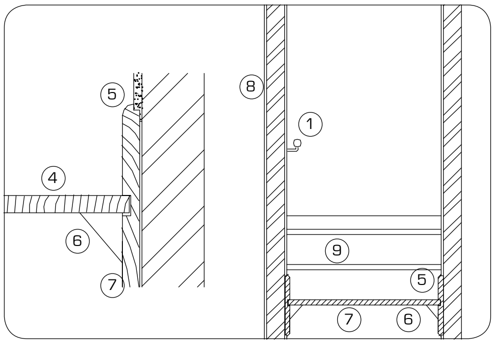
3D view showing freestanding timber staircase supported by steel beam



Vertical section 1:10 & 1:50 through stair

(Below) 3D view showing timber staircase against in-situ cast concrete wall





Vertical section 1:10 through treads

Details

1. Handrail
2. Balustrades
3. Timber beam
4. Tread
5. Carriage
6. Wedge
7. Bracket
8. Wall
9. Riser
10. Newel post
11. Trimmer joist

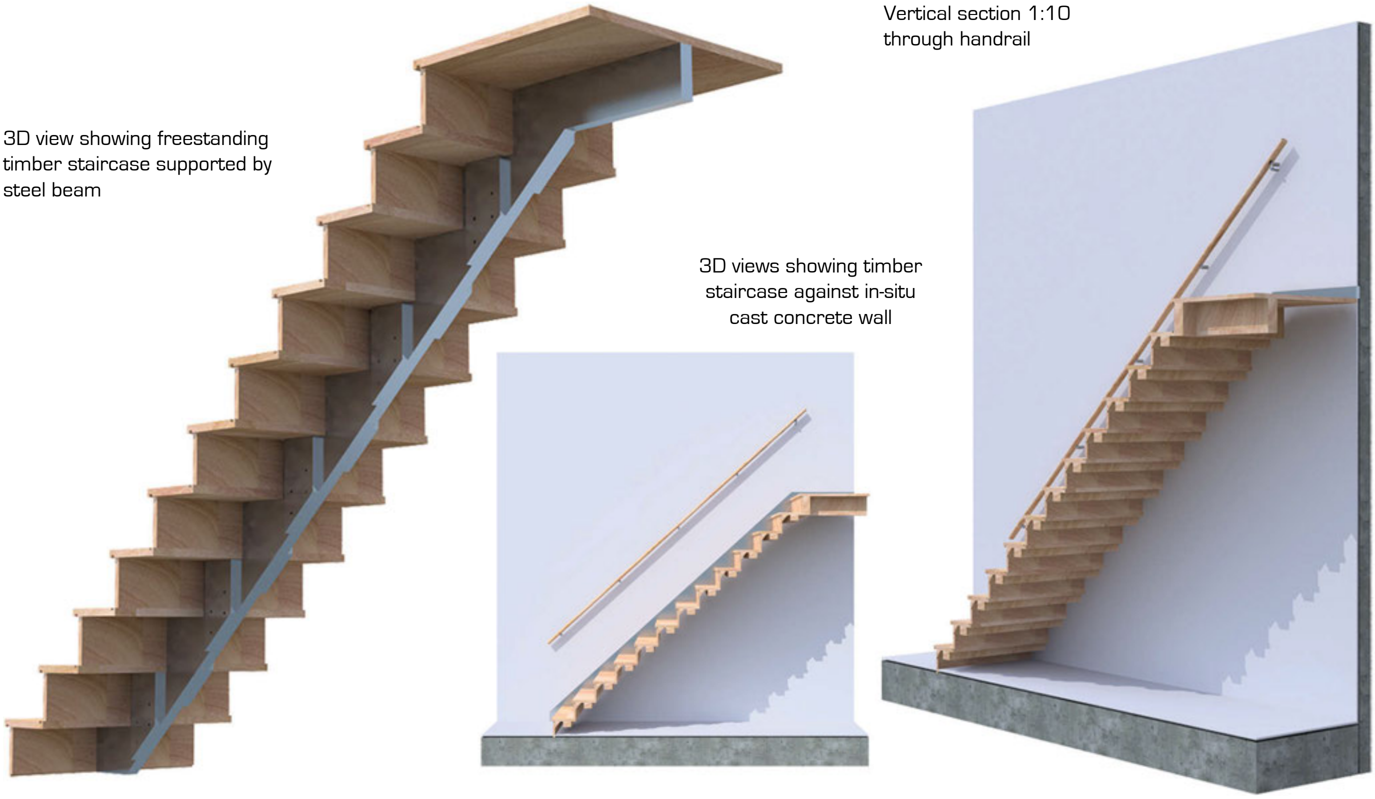
An advantage of timber staircases is that they can be integrated easily into adjacent timber construction and can be modified easily on site in a way that is very difficult to achieve in an equivalent steel or concrete construction. Timber stairs consist of stringers or carriages, which support the stair to which treads and risers are fixed. Several carriages may be positioned between stringers as loading demands. The stair is generally delivered to site as a complete structure secured with timber wedges, avoiding the need for visible fixings. Relatively small pieces of timber are used. The thin timber sections are prone to shrinkage and creep unless they are locked together. Because timber stairs have poor fire resistance, they are often restricted to residential use. Treads and risers are fixed together with tongue-and-groove (or rabbeted) joints that provide a tight fit and avoid creaking when the stair is in use. Both treads and risers are fitted into rebated slots cut into the stringers where they are wedged to provide the correct alignment of treads. Trimmer beams are sometimes added at the top and bottom of the staircase to stabilise it and provide fixing points to the adjacent floors, which are typically also of timber construction.

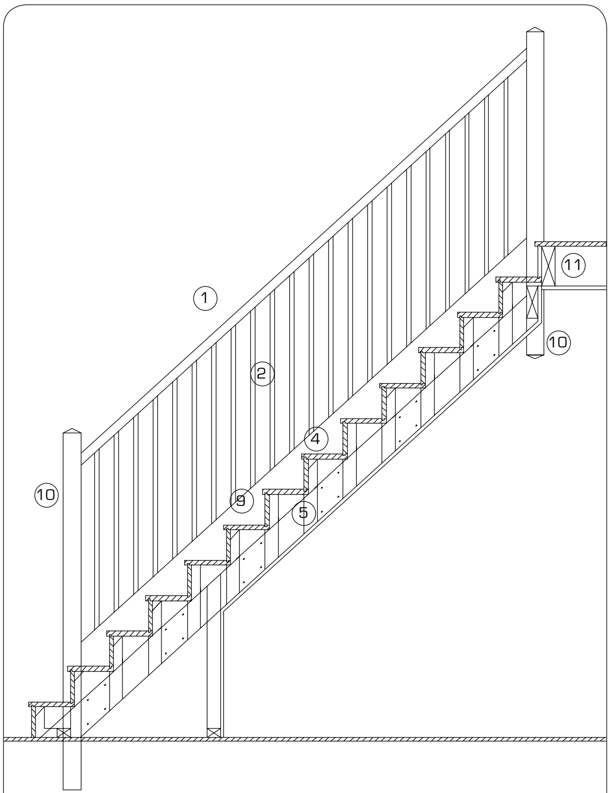
An alternative approach is to use heavy timber sections to form staircases that resemble those in steel. Steel brackets that are bolted into the timber sections connect the stringers and separate treads together. They can easily accommodate steel guardrails which are bolted through the large stringer sections. Timber guardrails follow the traditional use of balusters at close centres, typically set 100mm apart. The lack of large structural members in timber stairs makes the use of balusters at wider centres, as used in steel or concrete construction, less suitable. Timber connections are more fragile than those in steel; they must also accommodate more movement due to moisture. Balusters at close centres allow imposed loads on the guardrail to be spread evenly along the length of the stair stringers.

3D view showing freestanding timber staircase supported by steel beam

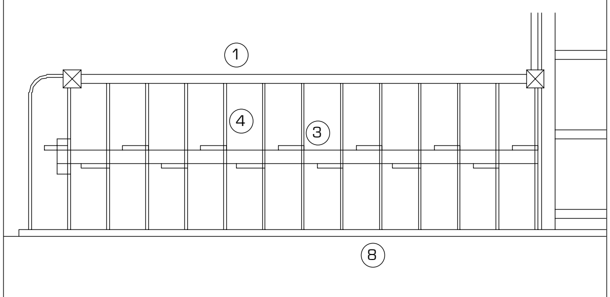
Vertical section 1:10 through handrail

3D views showing timber staircase against in-situ cast concrete wall

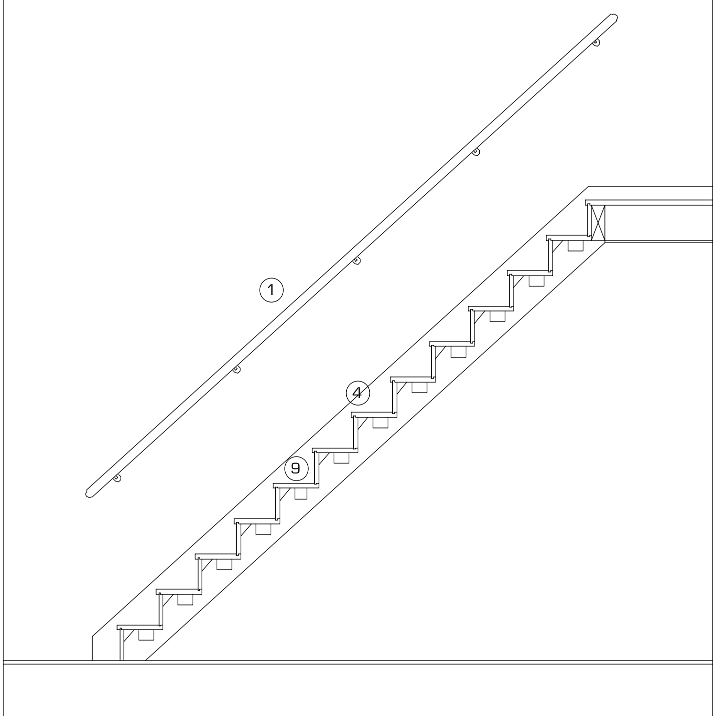




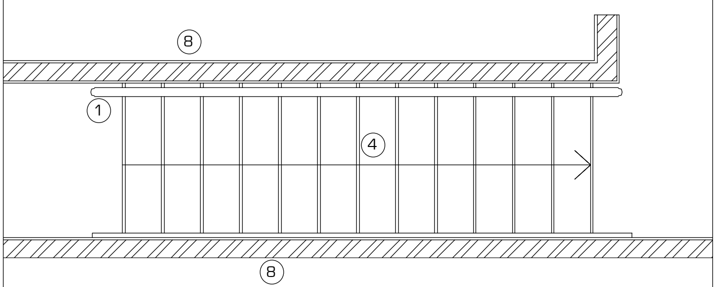
Vertical section



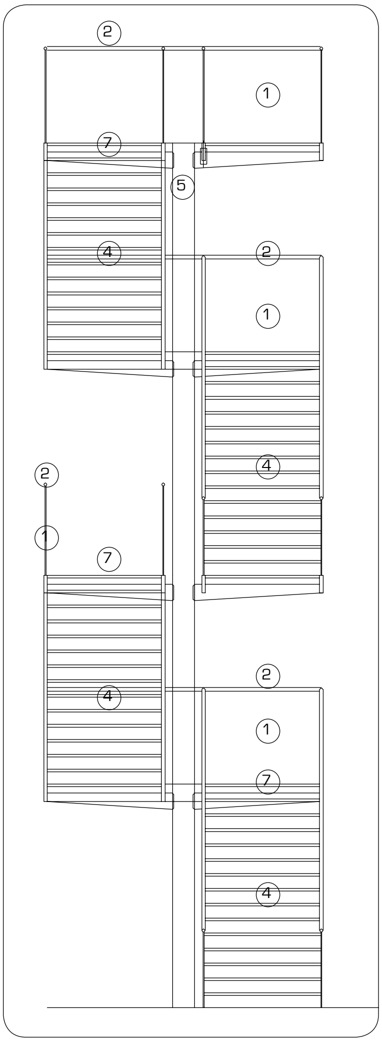
Horizontal section



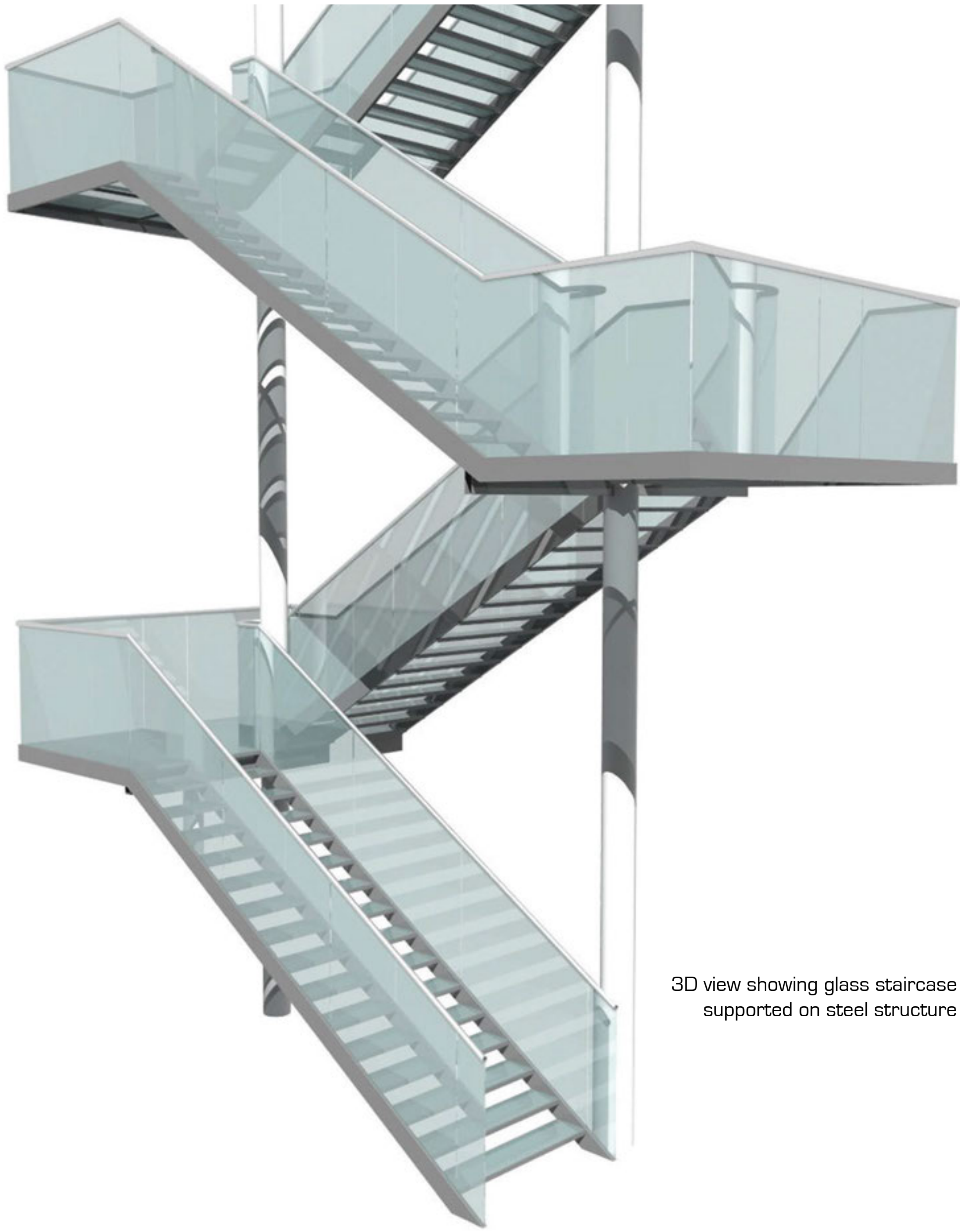
Vertical section



Horizontal section



Vertical section 1:50



3D view showing glass staircase supported on steel structure

Stairs with glass treads have the advantage of transparency, allowing light to penetrate down the stair enclosure. The glass used is usually a thick laminated glass which can be made of two sheets of float glass with a thin interlayer, or toughened glass with a more robust interlayer that stays in place if the two toughened sheets are broken. Glass treads can be supported either within a steel tray which provides support on all edges, or be two-edge supported. An alternative is to bolt-fix the glass using techniques taken from their primary application in glazed walls. This method allows the stair to be suspended from cables, a technique still in the early stages of use. The tread assemblies are then usually supported by steel stringers, though concrete can also be used.

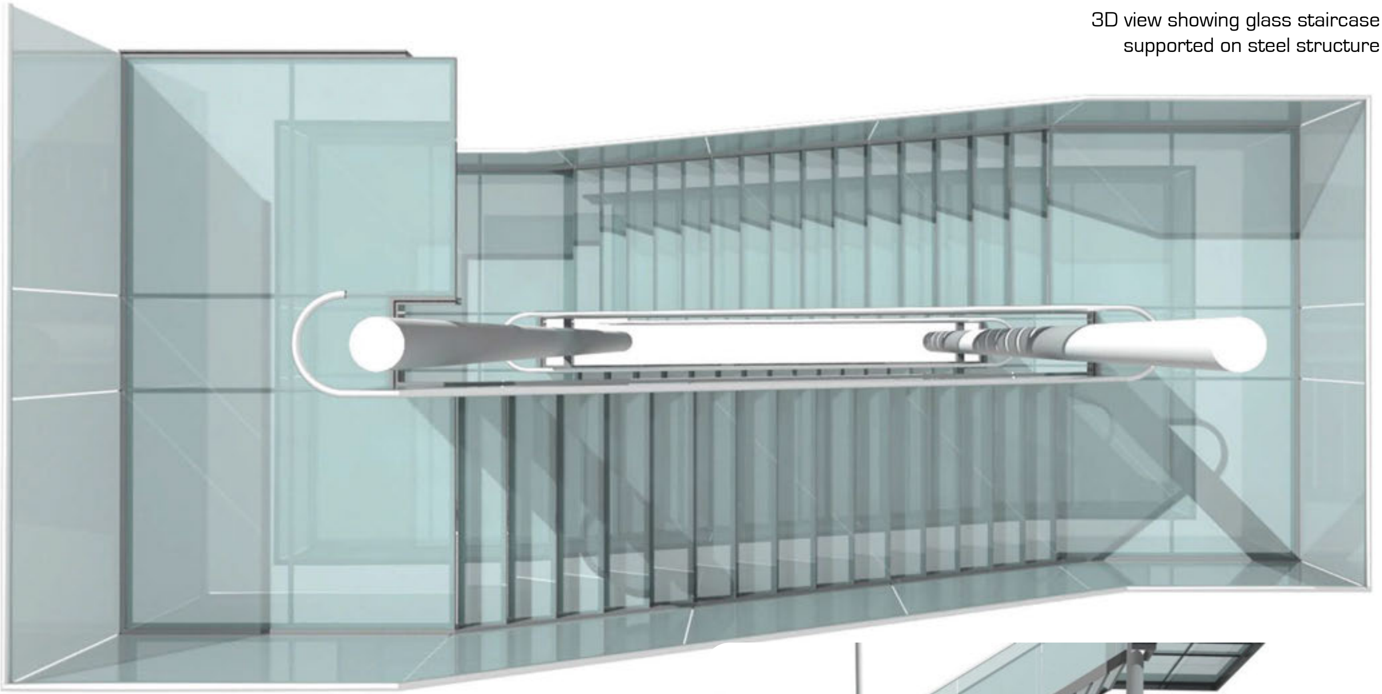
Where glass treads are set within a steel supporting tray, the laminated glass sheet is set directly onto a silicone-based bedding. In addition to holding the glass in place, the bedding provides both a cushion and a method of ensuring that the glass is evenly supported along all the edges and is fixed level. An additional weather seal is used on the sides of the glass between the glass and frame, if the stair is to be used in external conditions.

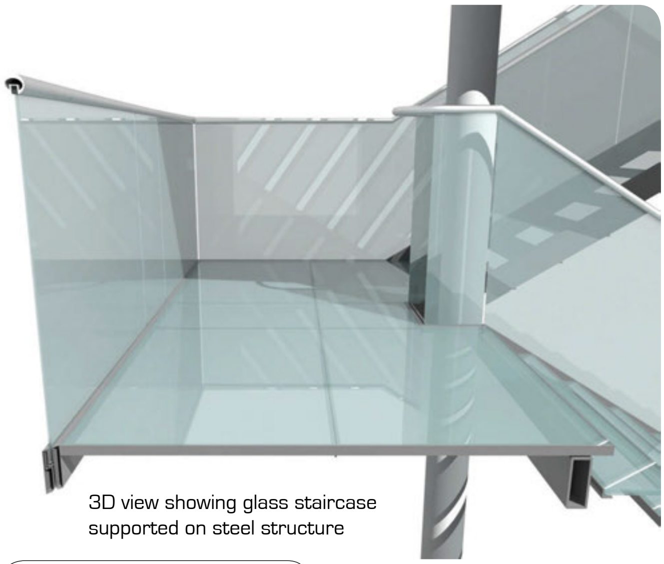
Treads often have a surface treatment to provide slip resistance. Sandblasting, etching or the addition of a carborundum coating, typically in strips, is used for this purpose.

Guardrails

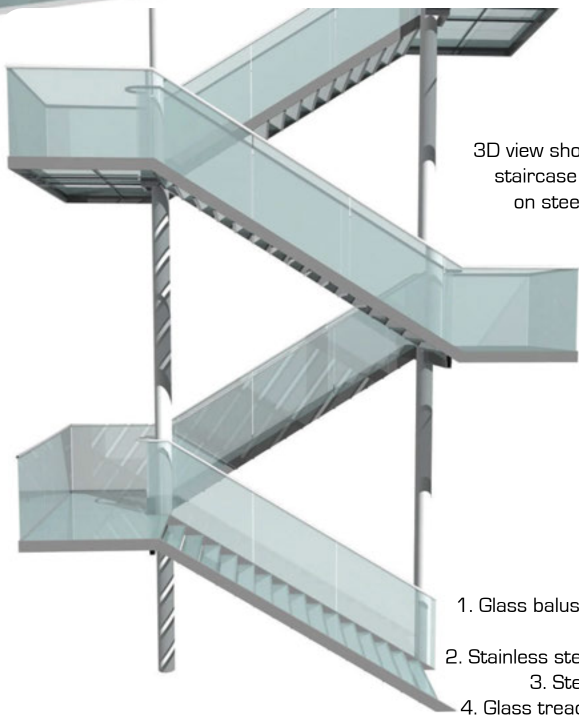
All-glass, or structurally glazed, balustrades can be constructed with sheets of toughened or laminated glass and used with a stair built in another material. They comprise sheets of toughened or laminated glass fixed at floor level with either a clamped plate secured by bolts or by bolt fixings directly through the glass. The glass must be sufficiently strong and rigid to span vertically without additional vertical support. A 12mm thick sheet is typically used. A handrail can be added by introducing a rebate into the handrail section and setting it directly onto the top of the glass guardrail. An alternative method is to form a guardrail from steel posts that support a handrail, with laminated or toughened glass sheets used as infill panels. The glass can be fixed with clamps or be bolt-fixed back to the posts. Glass sheets are set with a vertical gap of around 10mm between them which is filled with a translucent or transparent silicone seal.

3D view showing glass staircase supported on steel structure



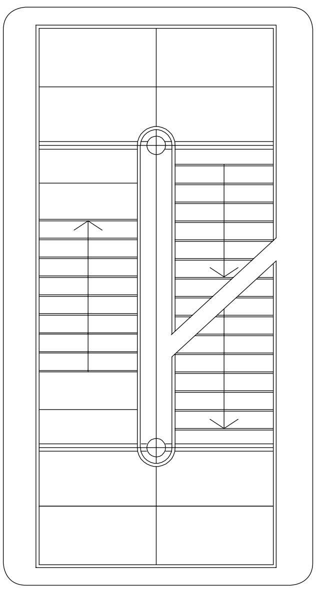


3D view showing glass staircase supported on steel structure

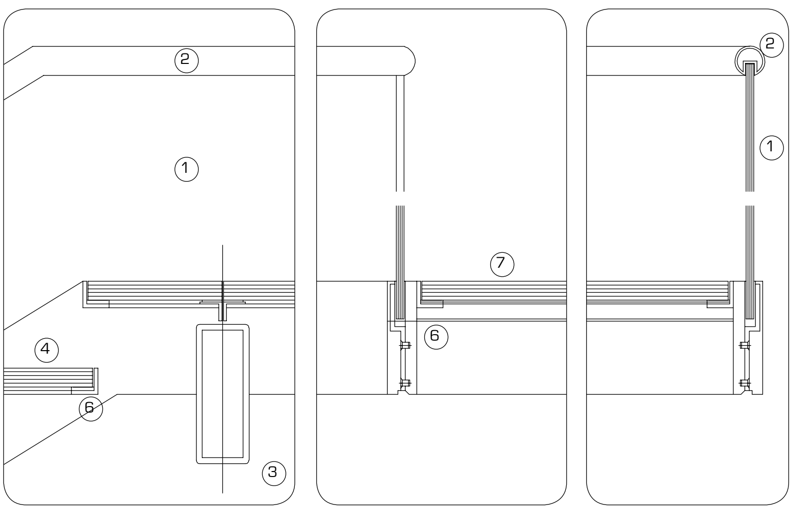


3D view showing glass staircase supported on steel structure

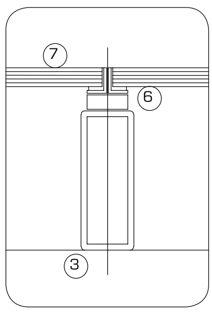
Details
1. Glass balustrade fixed at base
2. Stainless steel handrail
3. Steel stringer
4. Glass treads, typically sandblasted to provide friction
5. Steel tube support frame
6.. Steel angle
7. Glass landing in steel plate



Horizontal Section



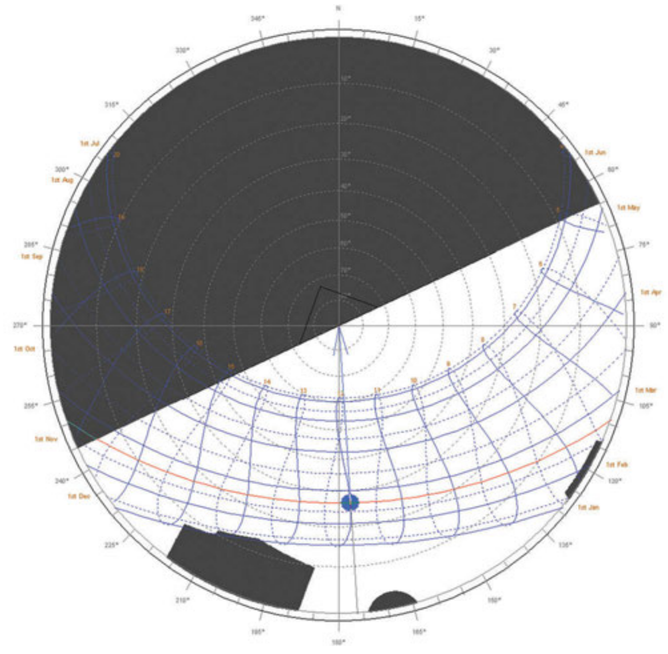
Vertical sections



Horizontal section 1:10

5

ENVIRONMENT



Sunpath diagram for southerly facade

Study of shading design on glazed facade

This chapter discusses environmental design in terms of passive and active methods that can be used to modify environmental conditions within a building. Active controls are provided mostly by mechanical ventilation systems that are used to heat, cool and ventilate spaces. Passive controls can be provided by natural ventilation, solar shading, passive heating and even by the use of the building fabric as a thermal mass to slow down the rate of heating and cooling. A combination of these methods helps to reduce the energy consumed by buildings in use. This chapter also looks at the rise of natural building materials in construction and the reduction of embodied energy within building projects.

In the past, combinations of structure and cladding were generally limited to the use of materials that were constructed either from the same base material (steel, concrete or timber) or from materials having compatible amounts of thermal movement. The expression of structure and construction (particularly of joints) was considered one of the primary architectural intentions in cladding design, however this situation is slowly changing. More buildings are clad externally with insulation and use a rainscreen cladding system to conceal it from view. Rainscreens allow a simplified approach to be taken to movements in the primary supporting structure of the building. A continuous, uninterrupted appearance can be achieved with a consistent gap between panels that extend across movement joints in the building structure. Both movement joints and breaks in the construction need not be 'registered' on the facade. Where they are visible they serve only as a decorative device. These innovations have led to a much wider range of structure/cladding combinations being used in construction which has allowed a greater focus on the use of materials with low embodied energy. It has also allowed buildings to exploit the thermal mass of their structural elements to slow down the rate at which the building heats up and cools down.

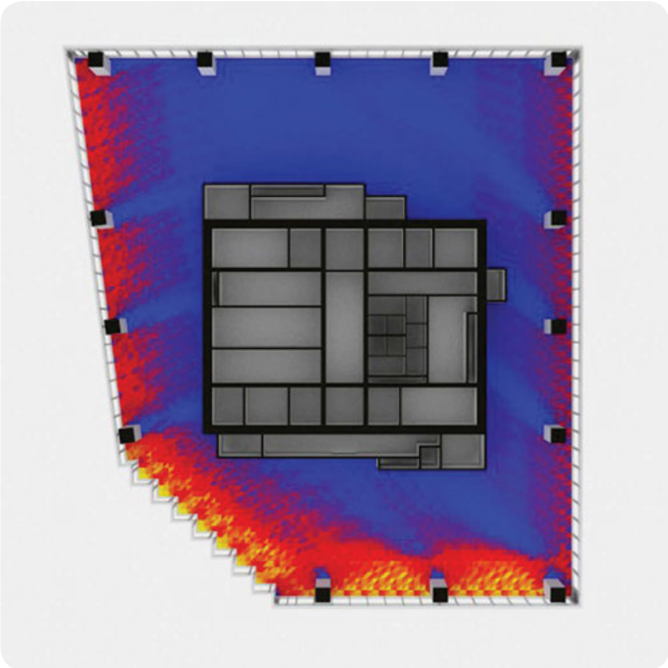
While thermal and structural movement were once the main issues in detailing, the idea of 'energy' is considered important today and detailing has become more complex in response to these changing priorities.

Protection vs comfort.
Over time the concept of the building as a means of protection from natural elements and predators has slowly given way to control and modification of the natural climate to create a comfortable environment for an increasing range of human activities. The challenge for the design team is to develop strategies for creating buildings that create an effective filter between man and his natural environment.

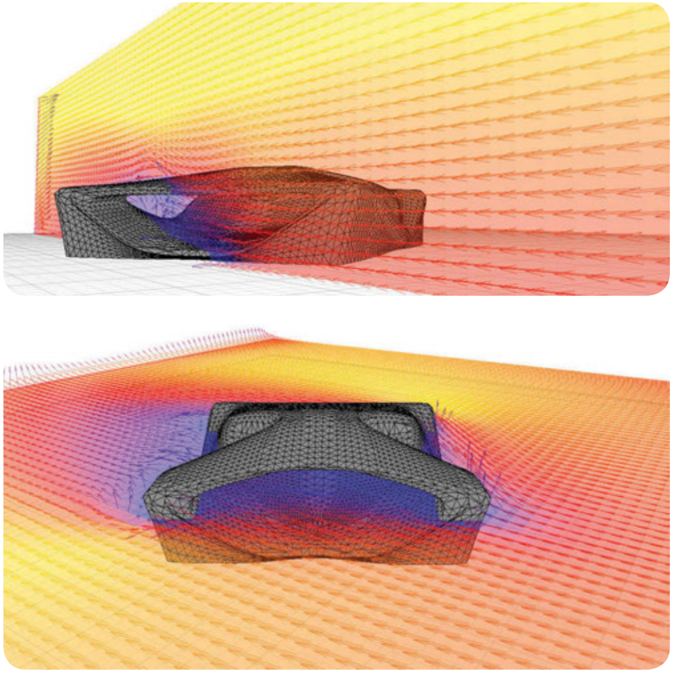
The last century saw a tendency for designers to focus on the problems associated with climate. Their challenge was to develop methods for dealing with the effects of hot or cold climates, mitigating the impact of high solar gain risks or counteracting other inhospitable conditions. This focus resulted in the creation of buildings with increasingly artificial environments and high energy costs in an attempt minimise their interaction with the external climate. As building technology developed, designers could aim for improved comfort conditions in increasingly hostile climates without compromising design philosophies that were often at odds with the local vernacular.

Over recent years there has been a move to reverse this thinking and work instead to exploit the potential benefits that the climate offers. For example, facades with high solar exposure can harness the suns energy through photovoltaic cells to contribute to the energy demands of the building. This shift has seen a change in design emphasis towards buildings that minimise their impact on the environment whilst ensuring they provide acceptable comfort conditions for the occupants.

Since humans spend most of their time inside buildings, the drive for improved comfort standards is important to maintain the health and wellbeing of each individual.



Study of sunlight penetration into office floor plate



CFD analysis of air movement around a building.

Human comfort
The environmental conditions conducive to human comfort are not absolute. They can vary based on the individual's metabolism, the tasks they are trying to accomplish or their perception of the environment they are in. In brief, the definition of comfort can be defined as the absence of discomfort. During the design of most new projects a series of environmental parameters will be presented as a means of providing comfortabel conditions within the building. However comfort is more of a holsitic concept based on the interaction of many factors and the individuals ability to alter those variables. Since everyone has different criteria for comfort it is often measured by the percentage of occupants who report they are satisfied with the conditions. In terms of the built environment this can be categorised into 3 areas:

Thermal comfort – The user experiences discomfort if they are too hot or too cold. This occurs when the temperature, humidity, airflow and radiant sources within a space are not kept within an acceptable range. This exact balance of these factors will vary depending on what activity is occurring within the space and at what intensity, as well as what the occupants are wearing.

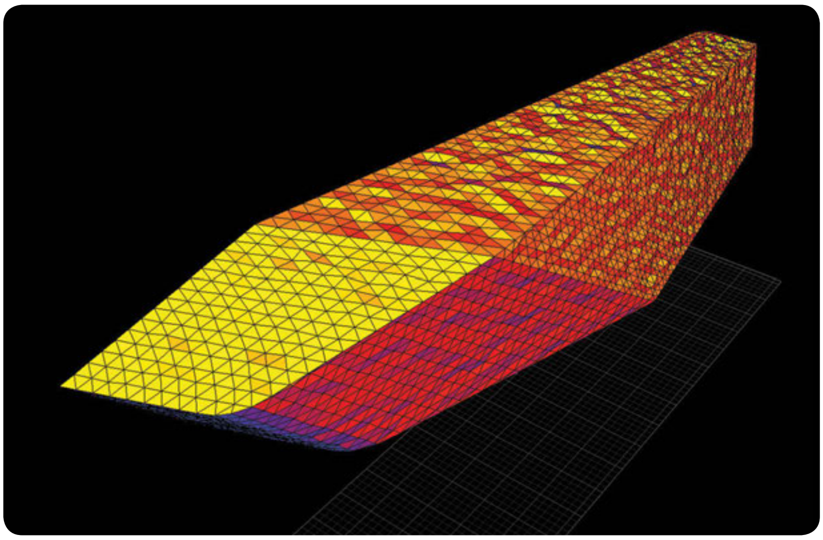
Visual comfort – A space becomes uncomfortable if there is not sufficient light to undertake the task required by the user. This level will vary depending on the activity. Laboratories, for example, will require higher light levels than classrooms to maintain user comfort. Natural light tends to create the most comfortable environments but artificial lighting has the advantage of maintaining a constant illumination. Visual comfort is also based on offering occupants a good view. This gives users a sense of connection with their surroundings and helps promote a sense of wellbeing.

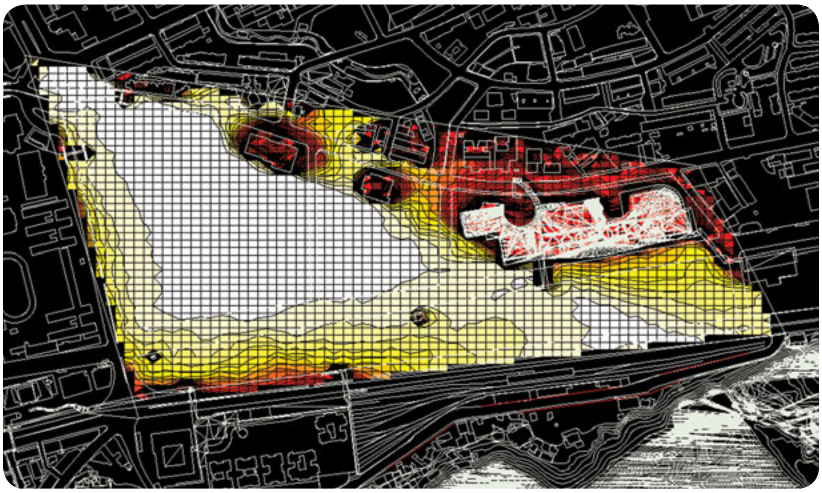
Acoustic comfort – This is achieved by ensuring the user has the right level and quality of noise to use the space as intended. Depending on the environment, control of decibel level, reverberation times and sound reflection can aid user comfort.

Environmental analysis in design
The design team can use environmental analysis throughout the design process to study how a building is likely to perform when in use by predicting how a building affects, and is affected by, its local environment. This allows the designer to respond to, and develop solutions to, potential problems before construction is completed. This analysis can be performed at various stages of the design process through to building use, with equal benefit. At the earliest stage of the project analysis of the local environment can help to inform the project brief, identifying natural climatic factors that can be exploited within the design as well as highlighting potential challenges to occupant comfort.

During the design process itself, proposals can be tested to establish their effectiveness at responding to the challenges of the local climate in order to inform future design development. Once the building is in use it can be assessed to see how it is performing. The results of these assessments can be studied and the lessons learnt can be fed back into the pre planning stage of future projects. Assessment at this stage can also help to develop strategies for improving the comfort of occupants through modifications to the building.

The following pages look at some of the concepts of environmental design focussing on solar control, daylight, thermal performance, wind and natural ventilation. This is followed by case studies which show how these concepts can be applied in the context of building design.





above & top left: solar insolation analysis of complex forms

left: exposure study for urban site

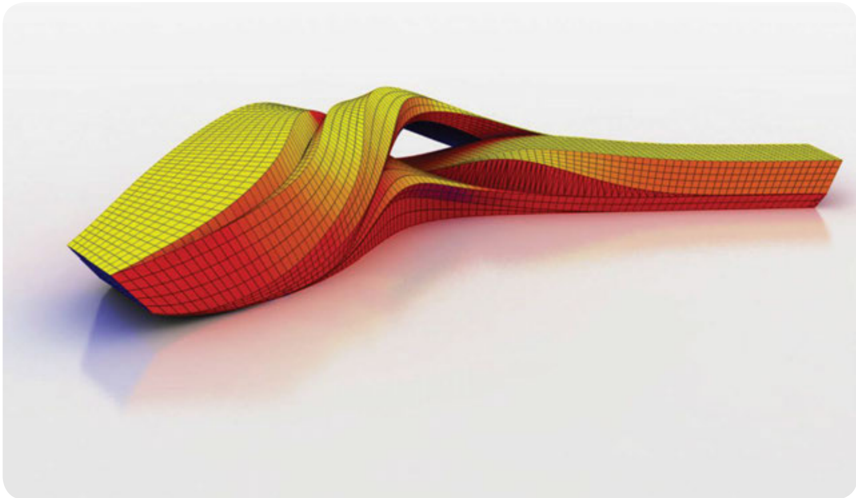
Decisions made early in the design process have considerable influence over the environmental performance of the completed building. Designers need no longer rely on 'rules of thumb' to create energy efficient buildings during the early stages of design. The use of computer software can also allow designers to be more independent of specialist consultants during the early stages of design without ignoring the essential issues of environmental design. Specialist consultants too often become involved in a building design only after the conceptual stage of the design process is complete.

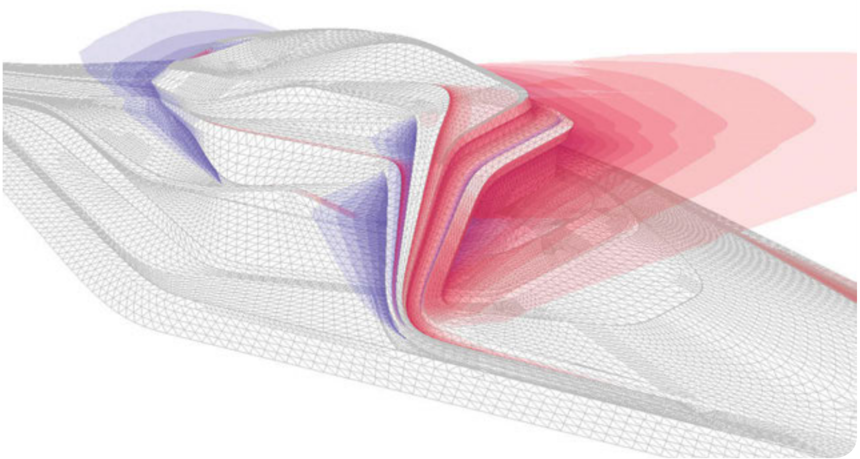
Computer software has developed to the point that many 3D CAD design applications have some form of environmental analysis tools built into them. Most applications will allow the designer to project shadows both onto, and created by, the building being designed. Some more advanced software applications will provide an analysis of solar gain, calculate approximate daylight levels and give information about the thermal properties and embodied energy of construction materials.

If designers both use and respond to these opportunities for analysis, it allows them to keep step with the specific environmental demands of their building. This helps the design team keep the overall project design in balance rather than having to accept 'features' being added to the final design as consultants try to alleviate problems caused by a lack of environmental input at the early stages. Digital analysis also allows the design team to understand the performance of their building without having to invest significantly in mock-ups or time consuming calculations undertaken by hand.

One of the major benefits of computer based analysis is that it can be used to inform design decisions at all stages of the design process. Data is displayed in a graphic manner that is easy to understand and interpret, and also aids discussion with other project consultants. At the earliest stages of a project, environmental analysis can help inform decisions about the orientation and specific geometry of the external envelope. Analysis can be carried out on a digital model of the 'empty' site to help the designers build up a picture of the microclimate they are dealing with and ensure that appropriate design responses are formulated at the earliest stages of the project. Information about annual sunpaths, temperature ranges, humidity and prevailing winds can be used to identify key issues that need to be addressed during schematic design.

This analysis becomes even more important when dealing with projects in parts of the world unfamiliar to some in the design team, and will help identify how design solutions which are considered to be 'standard' may need to be modified to meet specific environmental conditions. As the design process develops and more information can be input into the software





above & top right: solar insolation analysis of complex forms

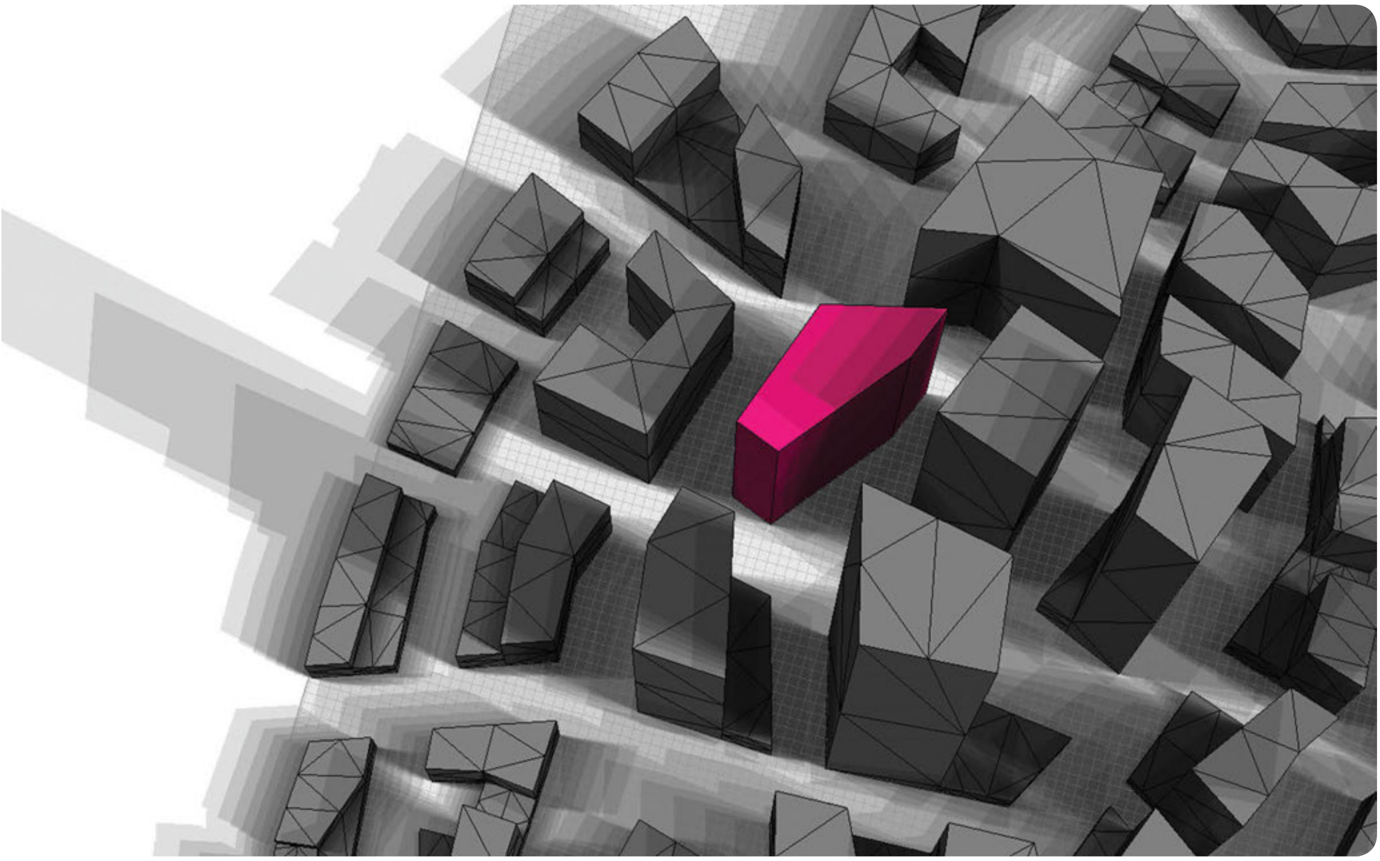
right: cumulative shadow projection for a complex form

programme, more detailed environmental analysis can be carried out on the project. This analysis can help inform decisions about geometry optimisation, window placement and shading design. Throughout the design process the impact of design decisions can be analysed and their consequences evaluated. This process is conducive to an iterative design process where many options are proposed, analysed, modified and analysed again. Because the resulting data is displayed in such a graphical way it is easy to compare the results and identify the most successful solutions to the design brief.

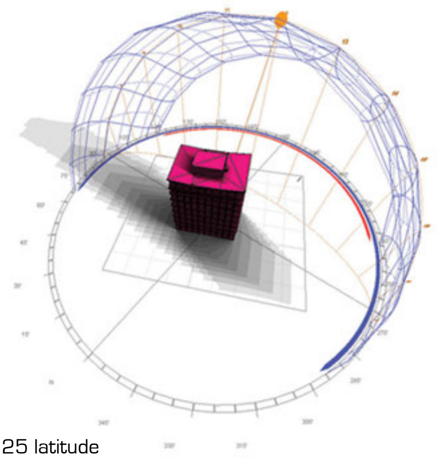
Over recent years digital tools have made the design and construction of complex forms more achievable. Conventional rules of thumb regarding environmental design become harder to implement once the building geometry deviates from traditional shapes and with complex geometry it can be difficult to know where to focus the attention of environmental design since the worst case conditions are not always obvious. Environmental analysis software can harness a computer's ability to carry out complex calculations in an iterative manner to allow the evaluation of the whole building in a relatively short period of time. This can help the designer to identify areas of the building that require further development, for example areas of a facade that are subject to particularly high levels of incident radiation or whether the building will cast unwelcome shadows over its surroundings at a particular time of the year.

As computers become more powerful and software algorithms more efficient, the use of real-time analysis will become more prevalent in building design. The ability to change parameters such as window size and location within a facade and receive instant feedback on the impact on daylight levels or solar gain will allow design teams to see the consequences of design changes as soon as they are made. The ability to embed this parametric interactivity within a shared 3d model will allow designers from all disciplines to see the impact of design changes on the performance of the building as a whole.

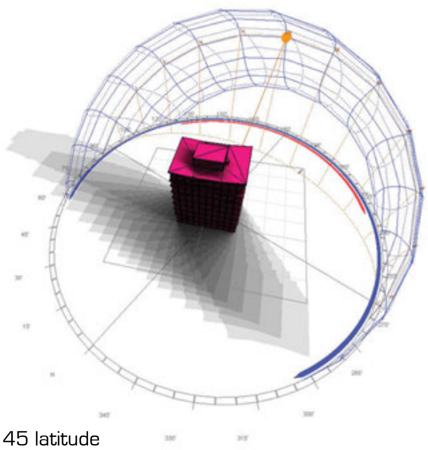
As with all analysis tools a certain understanding of the subject is required to interpret the results effectively. The risk with digital analysis is that the wealth of data available can overwhelm the design team. Similarly, the software will only present the results of analysis in relation to its inputs. The user is still required to evaluate the results and decide on their relevance to the design process.



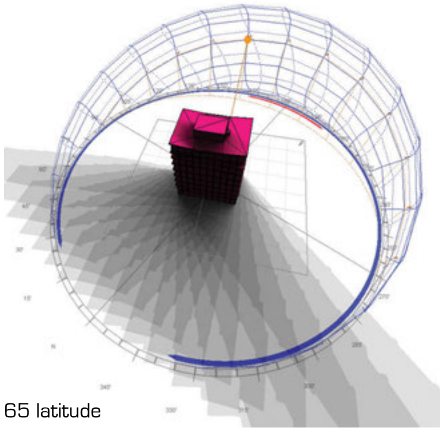
Overlaying shadow projections for one day helps evaluate how the building's shadow tracks across the site.



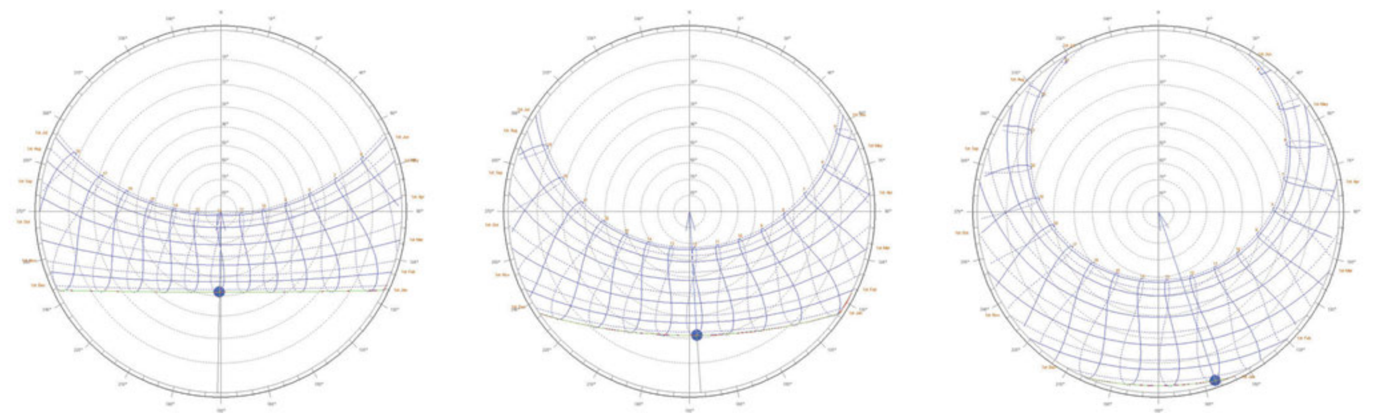
25 latitude



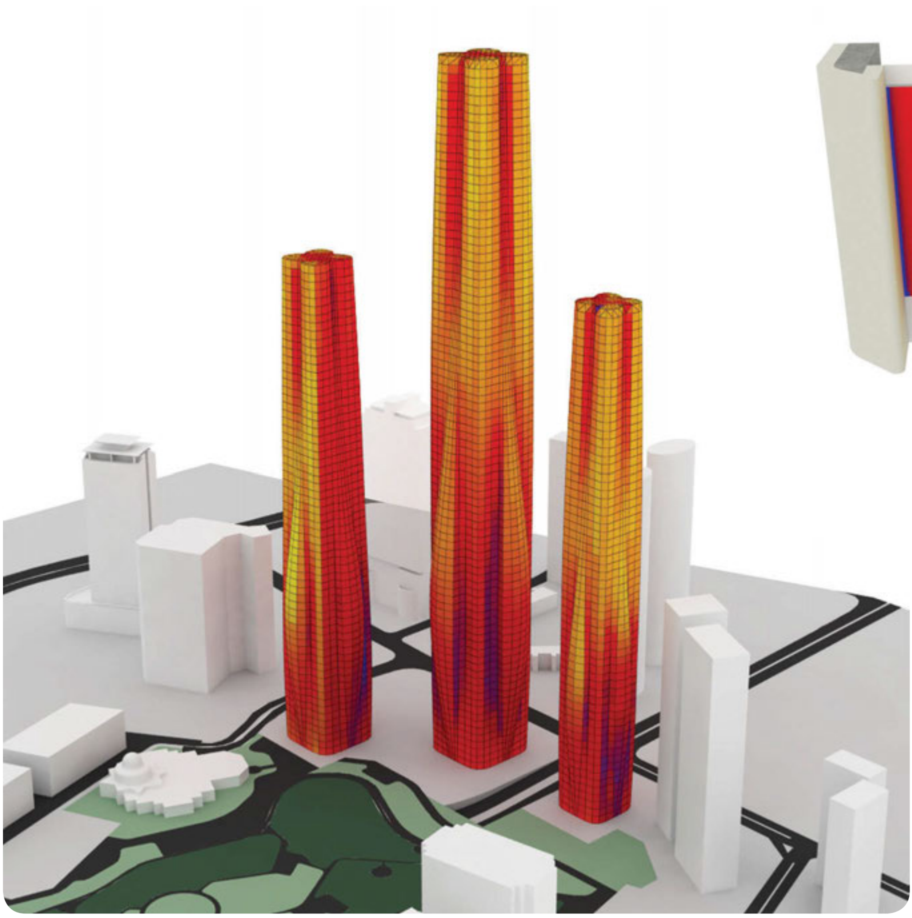
45 latitude

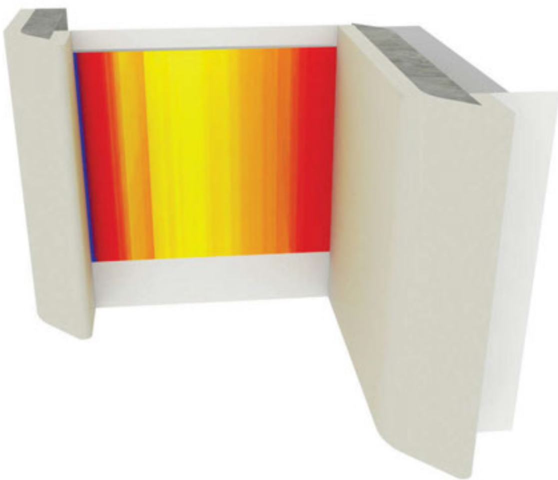


65 latitude



Comparison of sunpaths at different global latitudes and the effect on shadow projections





above: analysis of the overshadowing effect of a building's exoskeletal structure on the facade glazing. Here the west facing glazing is partially shaded by the stepped facade geometry

left: analysis of the overshadowing effect of surrounding buildings on a proposed facade volume. Areas of the facade closest to the ground are subject to much less direct sunlight due to overshadowing from surrounding buildings

Sunpath
An awareness of how the sun moves around a building at different times of the year can assist with the design of solar shading for a building. In most situations the specific design aim would be to exclude some of the effects of the sun during the summer months, when solar gain is at its most intense, but potentially to allow some spaces behind the facade to enjoy the effects of solar gain during the winter to take advantage of its warmth.
Sunpath diagrams offer the most visual way of assisting this understanding and most 3D CAD design software will allow the user to evaluate the sun's position in real time for any time of day at any location in the world.

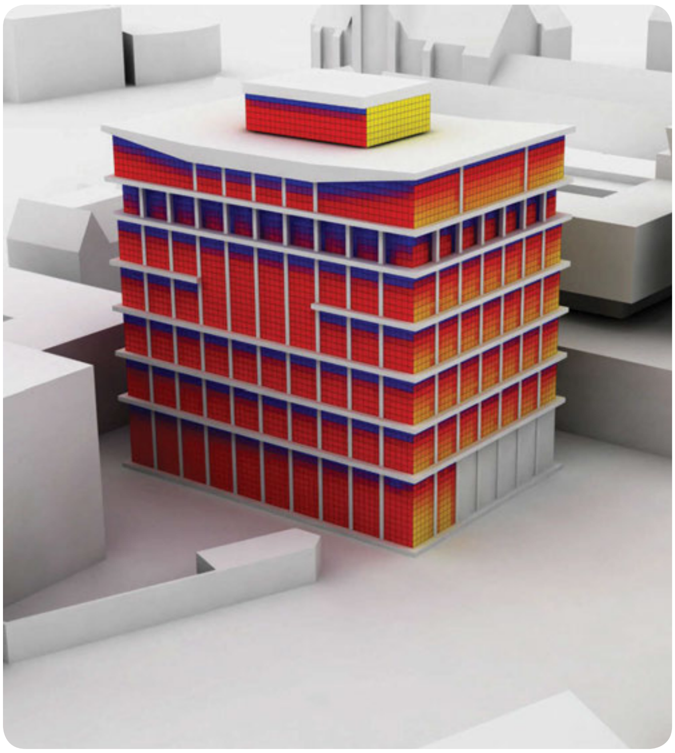
Shadow projection
The sunpath features in 3D CAD design software also enable the user to evaluate shadows falling across the model. This allows real time analysis of the sun's penetration into buildings, aiding the designers with the placement of windows as well as the design of the electrical lighting. This analysis also allows the designer to visualise the overshadowing effect of surrounding buildings, as well as the extent to which the proposed building will, in turn, overshadow its neighbours. This is particularly important for urban sites where maintaining rights of light may be a significant aspect influencing the building's design.

Mapping how building shadows track across the site throughout the day helps with the design of outside space. Cafe terraces can be sited in areas which attract the sun and external landscape features can be positioned based on their planting requirements.

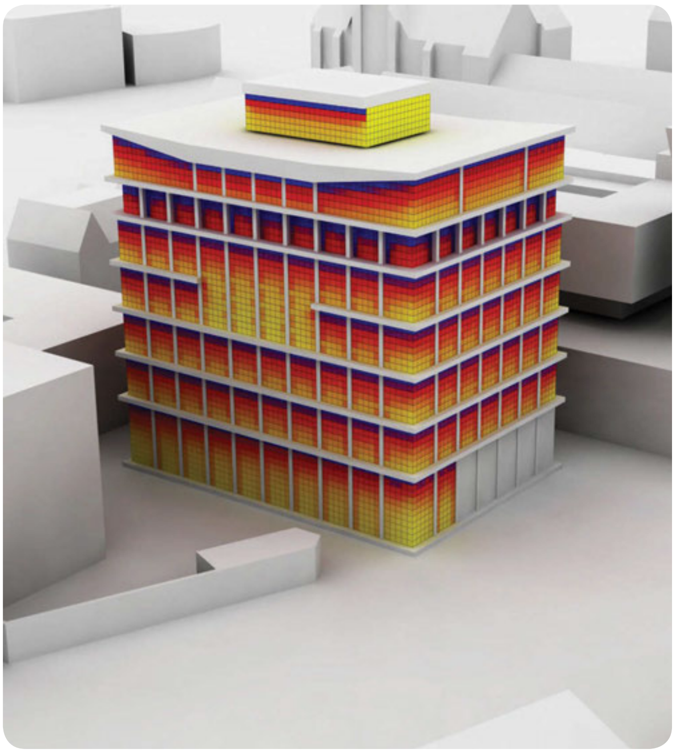
Sun path analysis can help to identify problems with reflections from the building's facade. This is more of a problem in built up areas since the glare from the sun on occupants of surrounding buildings can cause significant discomfort. Digital analysis can help to alleviate these concerns by projecting the path of building reflections throughout the year.

Overshadowing
In urban areas, the effect of overshadowing from adjacent buildings may have a significant impact on certain aspects of design. Areas of the facade that are in shadow for most of the day will not require the same shading design as areas that are more exposed. Traditional analysis techniques would treat all areas of a facade in the same manner, based on 'worst case' environmental conditions. Digital analysis allows the designer to take overshadowing into account to produce optimised shading solutions. This type of analysis can also be applied to smaller facade modules to assess whether overhangs, projections or other envelope details will have an overshadowing effect.

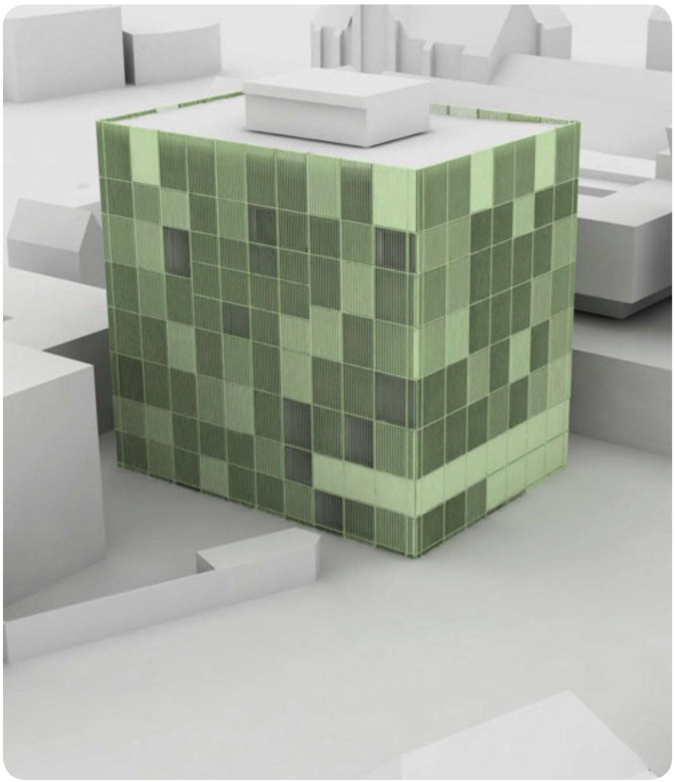
Solar exposure
Digital environmental analysis can help to identify areas of high solar exposure over a building and assist with the placement of solar panels on the facade. With more detailed analysis it is possible to calculate how much energy these solar panels can generate over the course of a year.



Study of cumulative solar radiation incident on a building facade over the course of 1 year



Study of peak solar radiation incident on a building facade over the course of 1 year



Based on the solar radiation analysis, along with a study of internal program requirements, a louvred facade shading system helps to keep internal comfort levels within an acceptable range by minimise solar gains and sunlight penetration.

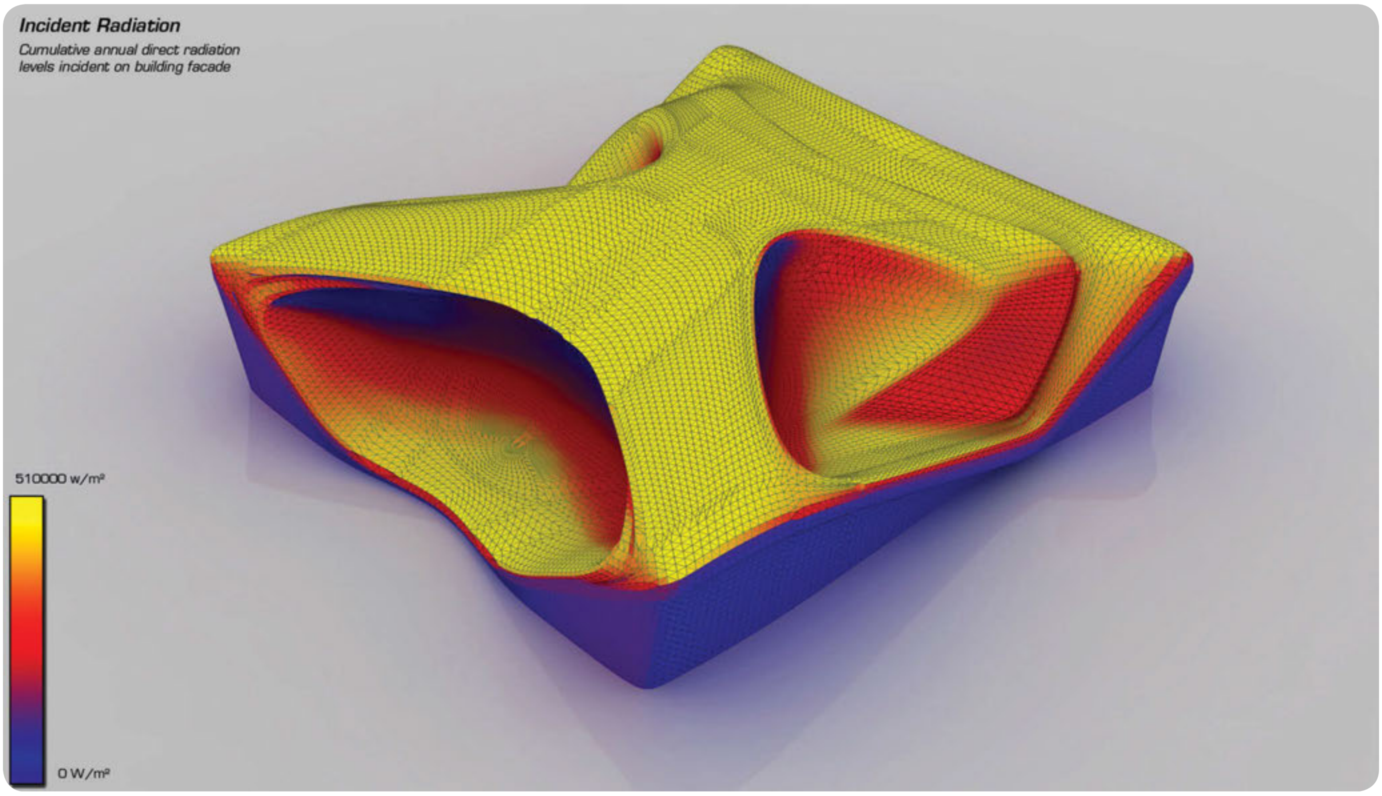
Solar gain

Solar gain can be defined as the increase in temperature of an internal space due to the absorption of the sun's energy by the building fabric. In most situations it is necessary to minimise solar gains, especially during the summer, though in cooler climates solar gain is sometimes encouraged as a means of reducing internal heating loads. In buildings where natural ventilation systems are being considered it is important to ensure that solar gains match natural cooling capacity to ensure that spaces in the building do not overheat.

The sun is at its strongest towards the middle of the day when it is also at its highest. At this point the sun is incident on vertical facades at quite a steep angle, depending on the time of year and geographical location, so the proportion of heat energy transferred is relatively low. Roofs and atria, which face the sun more directly, are particularly vulnerable to solar gain during this period of the day. Either side of its peak the sun's strength reduces but is incident on the facade at a more direct angle, transferring a high proportion of its energy to the cladding.

Environmental digital modelling can help to indicate the distribution of solar radiation across the facades of a building and build up a picture of which areas inside the building are particularly at risk from overheating. This information can be used to help inform decisions about window placement and material systems.

There are a number of ways of controlling the effects of solar gain. Solar control glazing can help to reduce the amount of solar transmittance through windows and glazed facades. Shading systems are an effective means of controlling solar gain since they limit the amount of solar radiation that penetrates



Analysis of incident radiation on complex building form to assess areas which are at highest risk of problems from solar gain.

the facade. External shading is far more efficient at controlling solar gain than internal shading, but requires cleaning and maintenance, as well as being able to be removed in the event of facade components being replaced. Careful choice of other cladding materials will also help minimise heat transmittance through the facade.

In hot climates it may not always be possible to control solar gain by passive means. In this case mechanical ventilation systems will be needed to provide additional cooling inside the building. By analysing the peak annual radiation values for the facades it is possible to design mechanical systems to cope with the effects of overheating. In this situation it is still beneficial to use passive solar control systems as this will reduce the average energy use of the mechanical systems

Sunlight penetration
Solar exposure analysis identifies the number of hours facade elements are in direct sun. When read in conjunction with an analysis of solar radiation distribution, solar exposure analysis can help create a more complete picture of how the sun is impacting on solar gain across the facades.

Solar exposure analysis can also be carried out for the landscape surrounding buildings in order to inform decisions about hard landscape design, planting schemes and irrigation requirements.

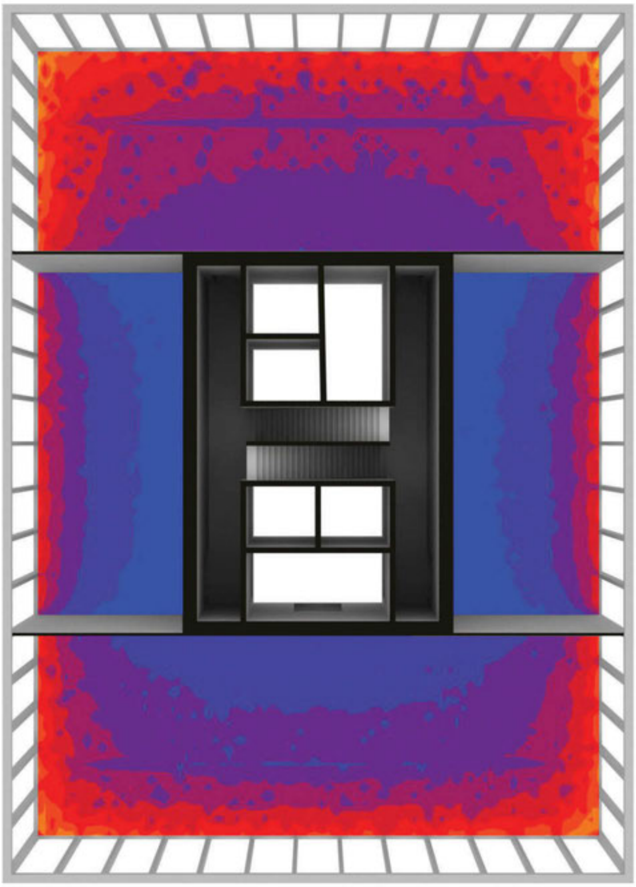
Within buildings, solar exposure analysis can help to understand how sunlight will penetrate through facades. It provides a more quantitative measure of solar access which may be of use when designing internal fit outs, helping to identify areas where computer screens or sensitive equipment should be placed, for example. In conjunction with computer software generated renders the study can help to build up a more complete picture of how sunlight penetrates the building.

Shading design
The use of external shading can significantly reduce the amount of energy needed to cool buildings in summer months in either temperate climates or hot climates. External shading prevents solar energy from passing through a facade by absorbing, then radiating and convecting solar energy outside the building envelope. In contrast, internal shading has much less effect in controlling solar gain since the solar energy has already passed through the facade and is radiated and convected back into the room having been absorbed by the internal shades.

In the northern hemisphere typical guidelines suggest horizontal shading devices are generally effective on south facing facades to deal with high angle sun, whilst vertically set systems on the east and west facades are generally efficient at dealing with low angle sun.

In the design of buildings it is not always possible to follow these guidelines, but detailed digital analysis can help designers derive more specific systems suited to both the building's geometry and location.

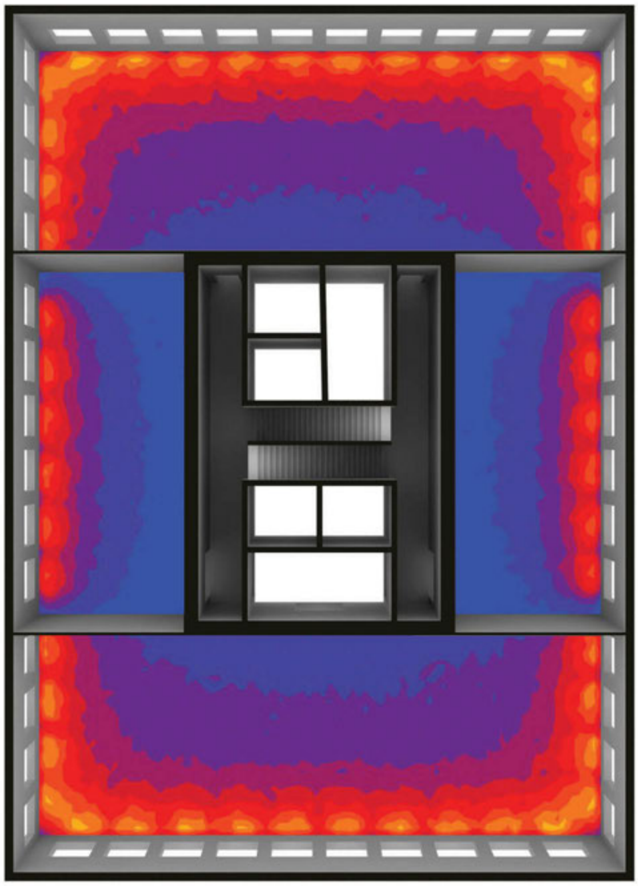
Iterative design techniques help to assess the effectiveness of different shading systems. This allows shading systems that may be considered to be more visually unconventional, but very effective, to be developed with confidence that they will function effectively.



Scale
(Daylight factor)

0%	6%	12%	18%	24%	32%	38%	44%	50%

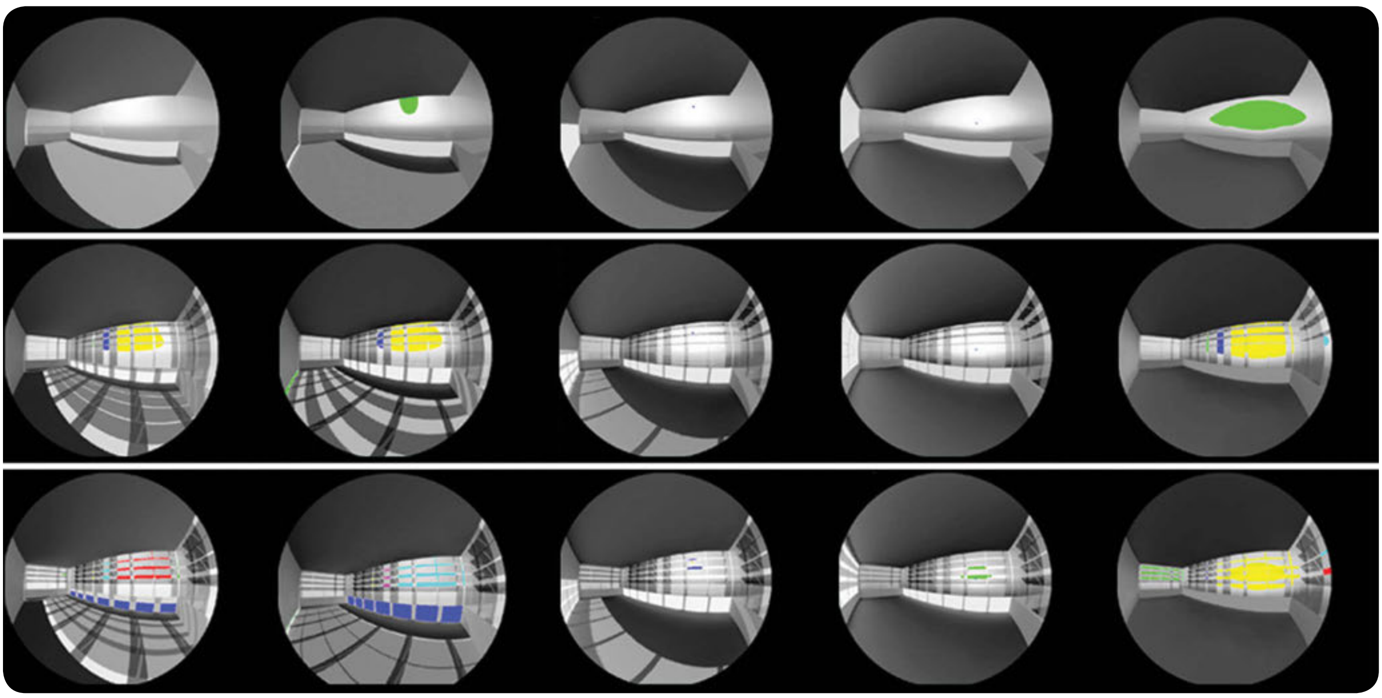
A fully glazed curtain wall facade results in high levels of daylight penetrating the office zones. Since the entire wall is glazed, an even spread of daylight is achieved in the space. Highest light levels occur at the corners of rooms where light is allowed to enter from 2 sides. In these areas, glare may cause discomfort for the user,



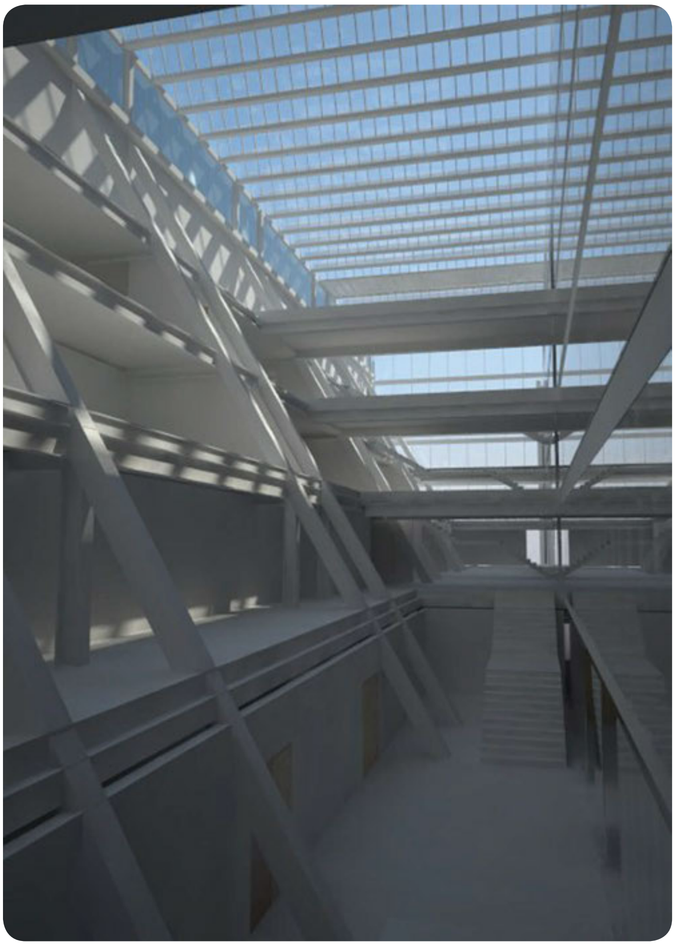
Scale
(Daylight factor)

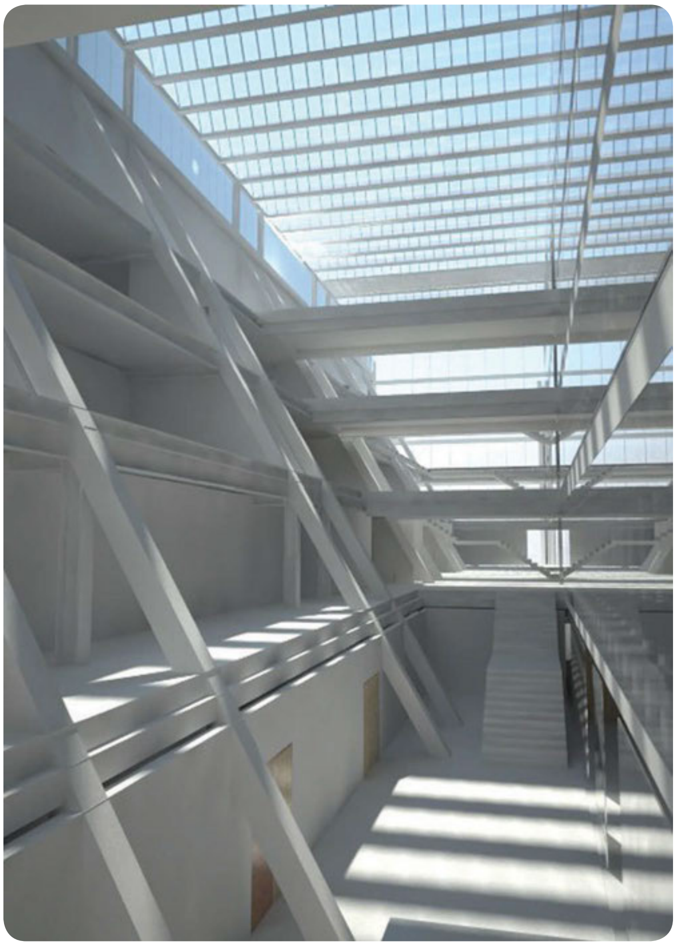
0%	2%	4%	6%	8%	10%	12%	14%	16%

A solid facade with punched windows results in significantly reduced light levels within the office zones. Higher light levels occur close to windows however the distribution through the rest of the space is still fairly even. Although the back of the office areas may experience low daylight factors, they may still be within an acceptable range for the tasks undertaken within the space.



Glare studies of a room highlight areas of high contrast between daylight levels inside in the room and at the window for a series of shading designs





By comparing rendered views it is possible to build up a picture of how light levels fluctuate throughout the day.

Levels of daylighting in buildings have increased in recent years in building types that consume a high level of energy in electrical lighting, mainly office buildings. An increase in daylighting, accompanied by a control of glare and solar energy from external shading has led to a reduction in the energy used in electrical lighting, particularly near the glazed walls.

Daylighting levels are expressed as a daylight transmission factor, measured in terms of the percentage of daylight passing through the glazed facade. Daylight transmission factors of 70% to 80% are common in double glazed units. For daylighting levels in buildings and their accompanying levels of electrical light to either supplement this or provide electrical lighting during hours of darkness, the amount of light required is defined for different tasks. Lighting levels are expressed in terms of lux, with office spaces having 250 lux, depending on how detailed the work needs to be, and how the lighting is distributed between general lighting from the ceiling, and task lighting usually provided on desks, which can give up to 400 lux.

Analysis method

The calculation of internal daylight levels requires considerable data input to achieve accurate results. Changes in minor elements of the design such as internal finishes can have a significant effect on the daylight factor within a given space.

Computer rendering can be used as a simpler alternative to digital analysis if quantative results are not important. Care must be taken when treating rendered images as accurate representations of actual lighting conditions as what appears dark in a given image may actually be adequate in a working environment. When used in comparative analysis, rendered images can help to assess the quality of light within a space over the course of a year.

If quantative daylight analysis is undertaken, it is essential to construct the digital model as accurately as possible with regard to window openings, floor and ceiling profiles and proposed furniture.

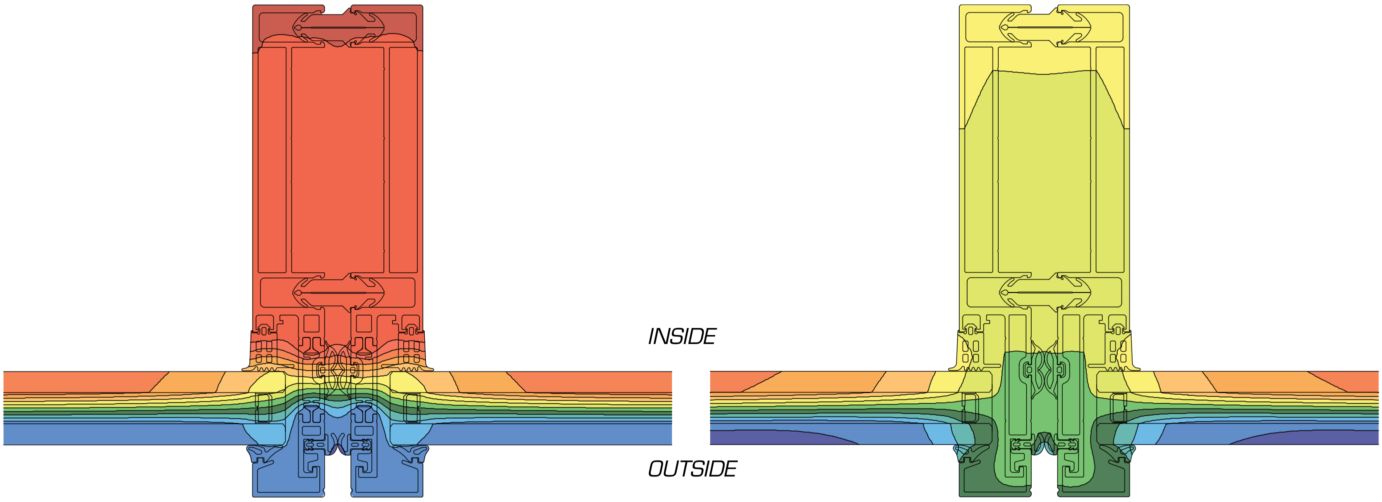
Analysis is typically carried out on the working plane of the room, typically 700mm above floor level, as this is where light levels have most impact on the occupants. Analysing a space in section is also beneficial as it can highlight areas of particularly high contrast between light and dark spaces.

Daylight vs solar gain

An environmental study can investigate what daylighting levels are provided by a facade and suggest ways of modifying the design to balance daylight with heat gains and energy losses.

When designing shading systems, a balance needs to be struck between providing an appropriate shading response and maintaining natural light levels within the building.

In climates where light levels outside the building are particularly high it is necessary to reduce the amount of open area on the facade to reduce glare and create comfortable working conditions for the occupants. In this situation shading elements can help to reduce the overall transparency of the facade.



The diagrams above show the difference in thermal performance between a unitised curtain wall mullion with an integrated thermal break (left) and a system without a thermal break (right). Isotherms show areas of equal temperature within the mullion in a design case that specifies an exterior temperature of -18°C and and interior temperature of 24°C.

Whilst the temperature differential across the glazing units is similar, the low conductivity of the thermal break component reduces the heat transfer between the outside and inside. The result is that the inside temperature of the thermally broken mullion is around 15°C whilst the interior temperature of the non thermally broken mullion is closer to 0°C.

Controlling the rate at which heat energy is exchanged with its surroundings is an important factor in maintaining a constant temperature within a building. Keeping heat inside buildings in cold climates reduces the energy demand for mechanical heating in cold climates. In warmer climates keeping heat out of buildings will help to reduce the energy costs associated with mechanical cooling. Another benefit of good thermal insulation is the reduced risk of surface condensation which is unsightly and can damage the building envelope.

A thermal insulator is a material which opposes the transfer of heat between areas of different temperature. Thermal conductivity (λ) is the rate at which heat is conducted through a particular material and is a measurement that allows the comparison of how well different materials conduct heat. It is measured as the heat flow in watts across a thickness of 1m of material for a temperature difference of 1 degree Kelvin and a surface area if 1m². The unit is W/mK. Resistivity is an alternative method of defining the conduction of materials and is expressed as 1/λ with the unit mK/W. Values for the thermal conductivity of common materials can be easily found in manufacturers data tables.

U-values

A U-value is the measure of the overall rate of heat transfer through a particular section of the building envelope. Each layer of material will conduct heat in at different rates depending on its resistivity, whilst cavities will allow heat transfer through conduction and convection. In addition, the inside and outside surfaces of the wall or roof will radiate heat to their surroundings. The U-value is regarded as an combined thermal transmittance coefficient and is measured as the rate of heat flow in watts through 1m² of a structure where there is a temperature difference across the structure of 1 degree (Kelvin or °C). It is expressed in W/m²K

U-values are calculated from the thermal resistance of the parts making up the envelope construction. Each element of the wall or roof will oppose the transmission of heat by varying amounts depending on their material. This is referred to as its thermal resistance or R-value. Thermal resistance falls into 3 catagories:

Material Resistances – The thermal resistance of each layer of material depends on its conductivity and its thickness. It can be calculated using the following formula:

$$R=d/\lambda$$

Where

R = thermal resistance of element (m²K/W)
D = thickness of material (m)
λ = thermal conductivity of material (W/mK)

Surface Resistances – At the surface of the building envelope the air in contact with the building skin forms a stationary layer that opposes the flow of heat. Surface resistances can be obtained from tables of design standards.

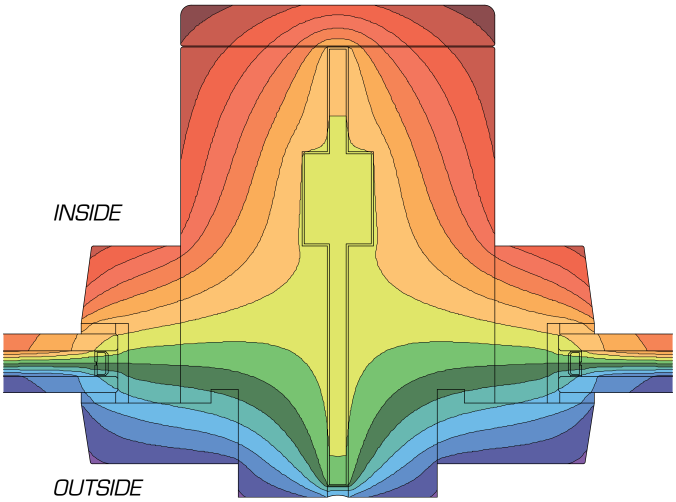
Airspace Resistances – The thermal resistance of an airspace or cavity depends on the nature of conduction, convection and radiation within. These can vary depending on the thickness of the airspace or the flow of air through it. Typical values can be found by consulting published standard values.
The total thermal resistance can be calculated as the sum of the thermal resistances the external surface, of each compenent, including air cavities, plus the internal surface and air cavities.

$$R_T = R_{SO} + R_1 + R_2 + R_3 \ldots + R_n + R_{SI}$$

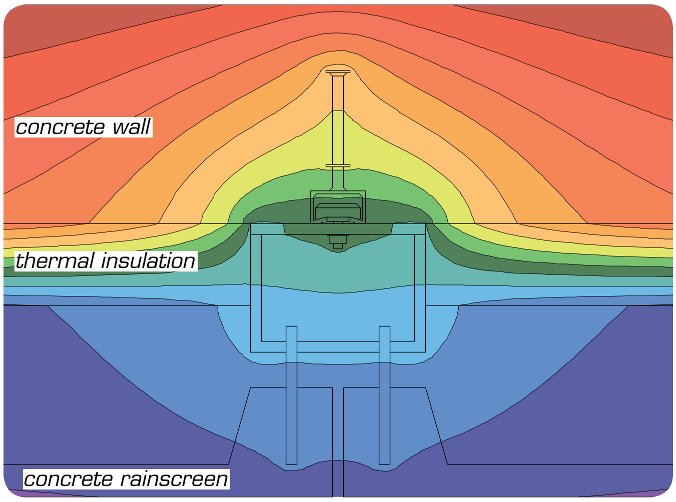
The U-value is expressed as the reciprocal of the total thermal resistance:

$$U=1/R_T$$

Typical U-values for solid wall and roof build ups are around 0.2 - 0.35 W/m²K. For glazed assemblies an overall U-value of around 0.15 W/m²K can be achieved although the glass unit itself may have a U-value of up to 1.0 W/m²K.



A timber framed window has a thermal performance comparable to a thermally broken aluminium system. The resistivity of timber reduces heat transfer through the profile and despite the presence of a steel insert between the frames the interior temperature of the frame is around 15°C



In rainscreen cladding systems thermal insulation is used to limit the transfer of heat from inside to outside. The weak link of the system is the fixing bracket and the diagram above shows how the temperature levels distort around the cladding support

Where a particular part of the building envelope contains more than one construction system, for example a window in a wall, the overall U-value can be calculated by assessing the relative areas of each construction and relating their specific U-value to each proportion:

$U_{average}$= $(A_1 U_1+A_2 U_2+...) / (A_1+A_2+...)$

Where A_1, A_2 etc are the areas of each construction and U_1, U_2 etc are the U-values associated with each component.

Air temperatures within buildings are kept at between around 18°C and 25°C, with the surface temperature of facades being a few degrees either side of this temperature for the internal face. Isotherm diagrams are used to investigate and check variations of temperature across facade systems, and these also serve to detect and check thermal bridges across facades. Isotherm diagrams are also used in conjunction with thermal calculations or thermal models of a building, including its facade. The diagrams above show isotherm projections for a number of different facade systems in a cold climate. Poorly performing systems result in cold surfaces on the interior surfaces of the facade which will in turn affect how the interior temperature of the building is maintained.

Humidity levels are significant in the transition from inside to outside, particularly when linked to extremes of air temperature. The relative humidity inside buildings is set in the region of between 30% and 70% depending on the internal air temperature. Dew point diagrams are used to determine where condensation will occur for the most demanding or extreme conditions experienced by the facade. This might be done in summer when, for example, it is hot and humid at 45º outside, while internal conditions are air-conditioned at 18º. It is essential to know where the dew point will occur to see if condensation forming at the dew point will cause any damage to the construction, and whether vapour barriers are needed in particular locations, or whether it is better to allow parts of the construction to be ventilated to either the inside or the outside.

While data for established forms of construction is usually easily available, and is used by manufacturers, unusual designs or significant variations from established facade systems will need to be checked from first principles.

Thermal properties of glass

In glazed areas the U-value of the construction must be evaluated in conjunction with the potential for heat transfer through solar gain to understand its overall thermal performance. The performance data for glazed assemblies often refer to the following properties:

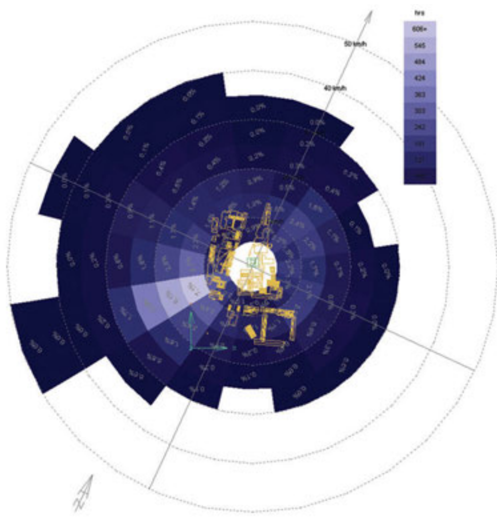
G-value – the coefficient used to measure the solar energy transmittance of glass. It is expressed as a value between 0 and 1 where low values represent low thermal transmittance. The g-value is sometime referred to as the Solar Factor and is expressed as a percentage. (for example a g-value of 0.35 is equivalent to a Solar Factor of 35%)

Solar Heat Gain Coefficient (SHGC) – the solar energy transmittance of a complete glazing assembly including glass, frame, opaque inserts and external shading.

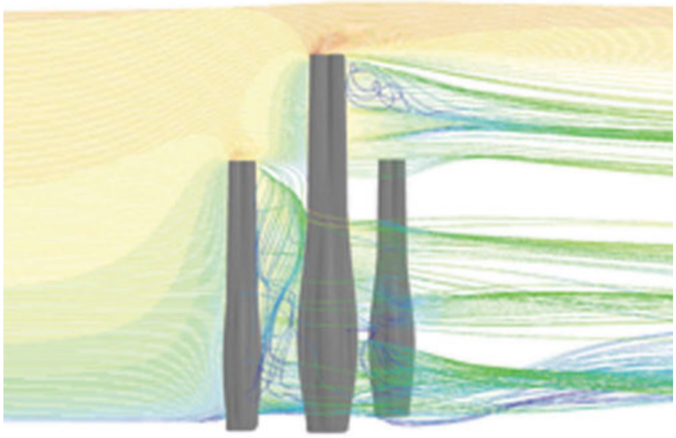
Shading Coefficient - The ratio of the solar energy transmitted by a particular glass combination to that transmitted by a reference glass, usually 3 mm or 4 mm thick clear glass.

Light Transmission – The percentage of light that passes from the outside of the glass assembly to the inside. It is often expressed as a percentage with lower values representing lower levels of light transmission.

When calculating U-values of glazed assemblies it is important to consider to take an averaged value that takes into account the thermal transmittance of each element. An averaged U-value of a glazed assembly would include the individual values for the glass, the frame and any insulated spandrel panels that may be present.



Wind rose for U.K. site



CFD analysis of air movement around a collection of tall buildings

Airflow in and around buildings can have a large impact on their design and the way people experience it. At a large scale it is important to understand how prevailing wind conditions will affect building performance and in turn how it will impact its surroundings. Loads imparted on the building will affect the design of the structure, cladding and weathertightness which means that an understanding of the prevailing conditions will allow the design team to minimise potential problems during the design process. The size and form of a new building development will have an impact on wind paths which could cause problems for neighbouring structures and reduce pedestrian comfort.

Airflow studies within building can help to assess the effectiveness of ventilation systems, identify areas of stagnant air within buildings and even predict the spread of heat and smoke should a fire break out in certain locations. All of these factors will have an impact on the levels of comfort experienced by the users and identifying potential problems early in the design process will save costly remedial work at a later stage.

Wind and the urban environment

In built-up areas wind speeds are often accelerated at pedestrian level due to the particular aerodynamic configurations associated with buildings. This is particularly problematic with tall buildings which can induce downdraughts at their base due to the pressure differences created by velocity differences at the top and bottom of the building. It is direct exposure to the wind rather than the height of the building that causes the problem of downdraughts which means that they will only induce high wind speeds at lower levels, if a significant part of them is exposed to direct wind flows. If a building is significantly taller than its surroundings, this effect can be exaggerated further.

Where buildings are positioned adjacent to one another the channelling of wind flows between them can induce horizontally accelerated airflows at ground level. Similarly, openings through the base of buildings can induce high wind speeds due to the difference in pressure between the front and back of the building. To the average person these accelerated wind speeds are no more than a discomfort but in extreme conditions they can affect pedestrian safety.

During the design process pedestrian comfort studies can help to understand wind conditions at street level. For each test location a wind speed is established and evaluated to determine whether it is considered comfortable. The definition of comfort depends on the activity that the space is designed for. These fall into 3 main catagories:

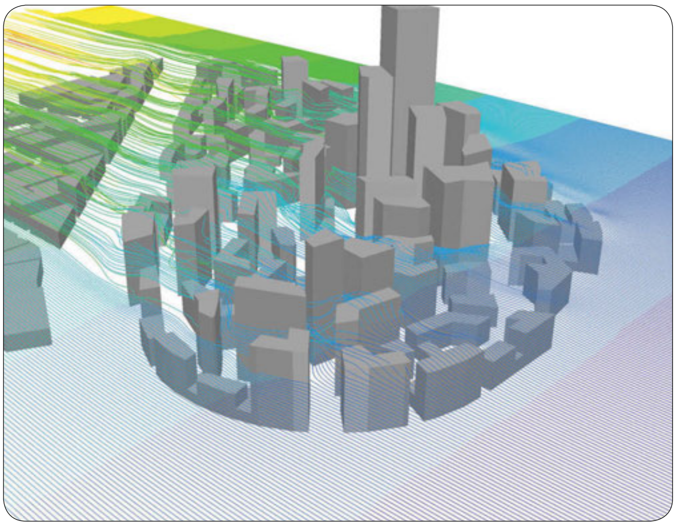
Long stationary – areas where a person will spend more than 10 minutes in a stationary activity such as sitting. In these areas wind speeds up to 10m/s are considered comfortable during which a person can read a newspaper without it blowing away. This is recommended for outdoor seating areas and other areas that promote long-term sitting.

Short stationary – areas where a person may spend no more than 10 minutes in a stationary activity such as queuing or waiting. Examples include building entrances or bus stops where people will linger but not sit for prolonged periods. Wind speeds up to 14m/s are considered comfortable for these locations, a level that will rustle leaves.

Recreational motion - areas where the average person will be walking at slow speeds or involved in recreational activities such as frisbee. Wind speeds of up to 19km/h are considered comfortable for these locations, a level that would lift leaves and disturb loose clothing.

Transitory motion – areas where the average person will be active and receptive to some degree of wind movement. Examples include pavements, playing fields or plazas. Wind speeds of up to 25m/s are considered comfortable for these locations, a level that would lift loose paper

The criteria above include both average wind speeds and peak wind speeds which take into account the fact that there will always be a few days in the year when wind speeds are particularly high. Wind conditions are considered comfortable if they are within the specified range for at least 80% of the time. The exact values may change depending on local climate and the expectations of the potential user groups.



Study of windflow in an urban environment

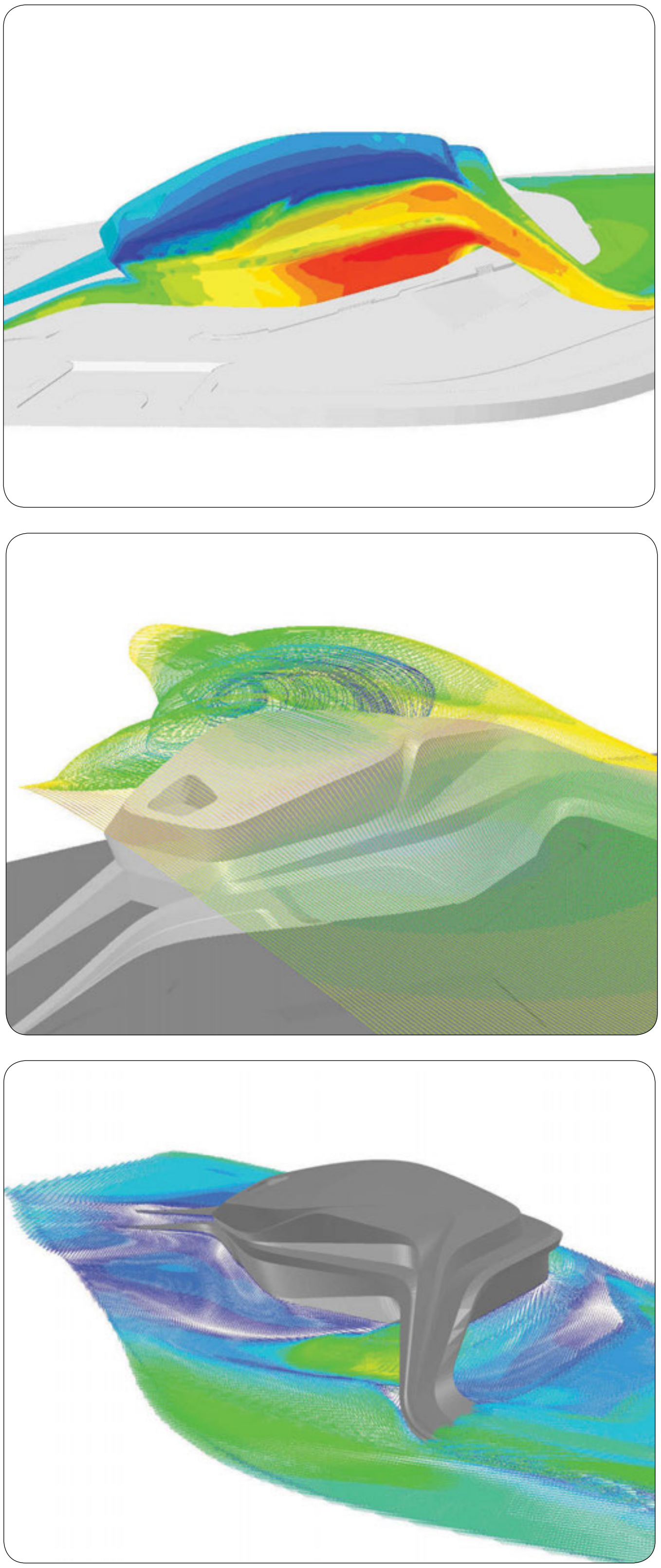
Wind speeds above 25m/s are considered uncomfortable in most situations. The effects vary from small trees swaying to walking becoming an inconvenience. Gusts of wind above 88 km/h are considered dangerous if they occur regularly. Gusts of this speed can significantly affect pedestrian balance and cause slight structural damage to buildings.

Once potential problems have been identified, modifications to the building's design can help to reduce their impact. Curved buildings, for example, generally promote lateral airflows and behave much better than angular buildings in terms of pedestrian level winds. Canopies or skirts at the base of tall buildings can prevent downdraughts from reaching ground level, whilst balconies or alcoves in the building facade can diminish downdraught effects at pedestrian level. In each case, however, such measures may simply transfer the problem to another part of the building or across the street.

Testing methods

Pedestrian comfort studies have traditionally been performed using wind tunnels. In these tests a scale model is used to assess the impacts of wind from different angles and at different speeds. Sensors record wind speeds at critical areas to give accurate and reliable predictions of the building performance. Since measurements can only be taken at discrete points on the model it is not possible to form a complete 3d view of wind flow around the building. More sensors will result in more accurate analysis: however, this has added expense and increases the risk of the sensors themselves interfering with wind flows and corrupting the data.

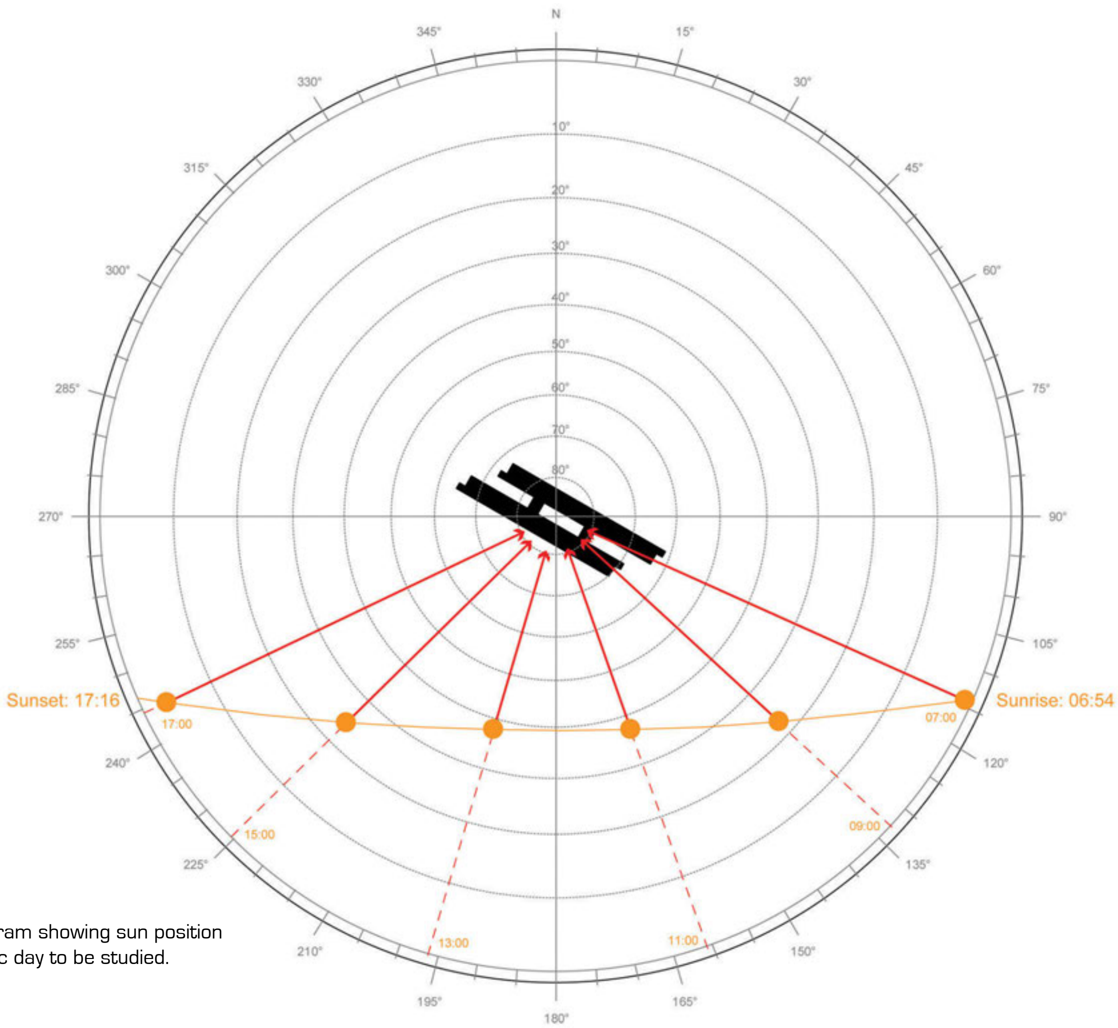
Advances in computer power and digital technology have allowed for an alternative approach called Computational Fluid Dynamics (CFD) to become a viable alternative to wind tunnel testing. CFD analysis allows designers to investigate the whole modelling domain to build up a detailed picture of airflows, velocities and pressures which can be presented in easy to understand graphical form.



CFD studies looking at the effect of local topography on the proposed building. Wind from different directions has different effects on the cladding pressures due to the overshadowing effect of the hillside.

The analysis also highlighted the accelerating effect of the tail component geometry especially at ground level which could compromise pedestrian comfort.

This analysis helped to develop structural and environmental responses during the design process.



Sunpath diagram showing sun position on the specific day to be studied.

The relative position of the sun is a major factor in the heat gain of buildings and understanding how the sun moves across the sky is crucial in preventing unwanted solar gain through building facades. The term ‘sunpath’ relates to the apparent positional changes of the sun as the earth rotates and orbits the sun. The position of the sun in the sky changes continually through the day and is also subject to seasonal variation. Sun position is very location dependant and the latitude and longitude of the site is required before accurate sunpath data can be produced.

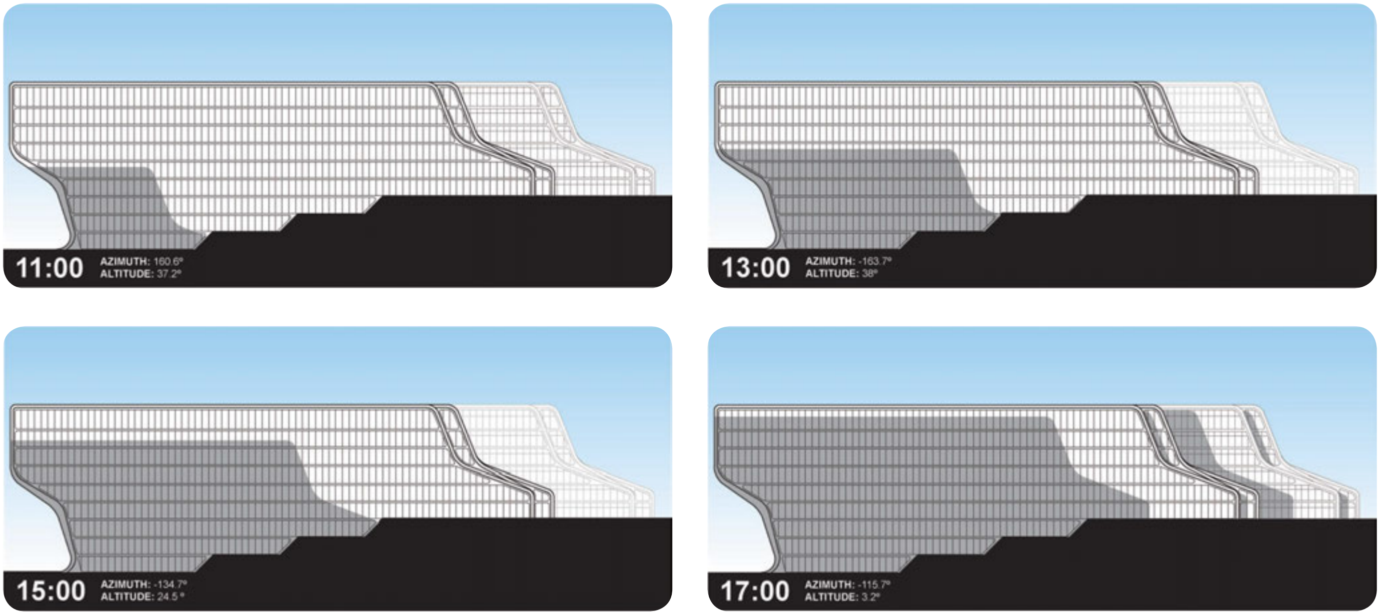
A sunpath diagram, such as the one shown above, is a method of displaying the annual changes in sun position in an easy to interpret 2D diagram. For any given time of the year data for the azimuth (horizontal sun angle relative to north) and altitude (vertical sun angle relative to horizontal ground plane) can be evaluated and used to develop effective shading systems.

The diagram above shows the sunpath for a single day and highlights the sun position at regular intervals as well as showing the times of sunrise and sunset for the specific site location. The sun is at its highest between 11am and 1pm when it reaches an angle of 50°.

The amount of radiation incident on the building facade is governed by the Lambert cosine law which states that the relative intensity of radiation on a surface is equal to the cosine of the angle of incidence, and that the relative area over which it is distributed is equal to the inverse of this value. Therefore high angle sun, whilst stronger, imparts only a fraction of its energy on a vertical facade, whilst low angle sun imparts a greater percentage of its energy. For this reason, horizontal facades in equatorial climates where sun angles are high are more prone to solar gain than vertical facades.

Within a building the effect of sunlight penetration can have a dramatic effect on user comfort. This is affected by a number of factors such as the occupancy of the space and the tasks that the users are undertaking, for example direct sunlight in an atrium or circulation space may be desirable, whereas in an office environment it may become problematic. Similarly sunlight entering a building early in the morning before the building is in use may not be considered a problem.

Shadow studies on the interior of the building can help to build up a picture of how direct sunlight enters the building over time. These can be used to analyse the impact of shading devices or overshadowing elements of the surrounding site and identify the need for additional shading systems such as blinds or screens to block sunlight completely.



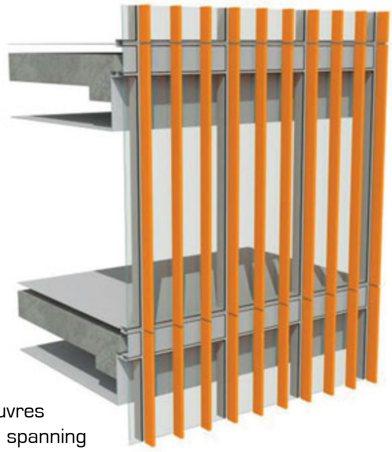
Shadow projection of surrounding buildings on the glazed office facade at different times of the day.

Study of sunlight penetration into the office space throughout the day to assess the impact on internal working conditions.

Unshaded condition:
Floor to floor glazing with
opaque spandrel panel.

Shading option 1:
Small horizontal louvres
equally spaced over full
extent of glazing

Shading option 2:
Single, large louvre
positioned at spandrel level



Shading option 3:
Vertical shading louvres
equally spaced and spanning
floor to floor.

The need to control the amount of sunlight that penetrates the building facade is based on a number of design considerations. In warm, sunny climates excess solar gain may result in high cooling consumption to keep the internal temperature at a comfortable level. In cold climates winter sun entering the building can contribute to passive solar heating and help reduce the winter energy consumption. Sunlight penetration into buildings can also have a detrimental effect on human comfort as the impact of glare can easily make a space unsuitable to carry out certain tasks. For this reason shading devices can also be used to improve user's visual comfort by controlling glare and reducing contrast ratios.

The design of any shading device will depend greatly on the path of the sun through the sky for the building's location as well as the orientation of a particular building facade. Thus a shading system developed for a building in Europe may not be suitable for an equivalent building in the Middle East. The following concepts hold true for most shading applications:

Horizontal shading – protects from high angle sun and is typically used on facades that are equator facing. For locations with high sun angles a single louvre at floor level can shade a whole storey of glazing. A more dense shading arrangement may be required in locations with lower sun angles.

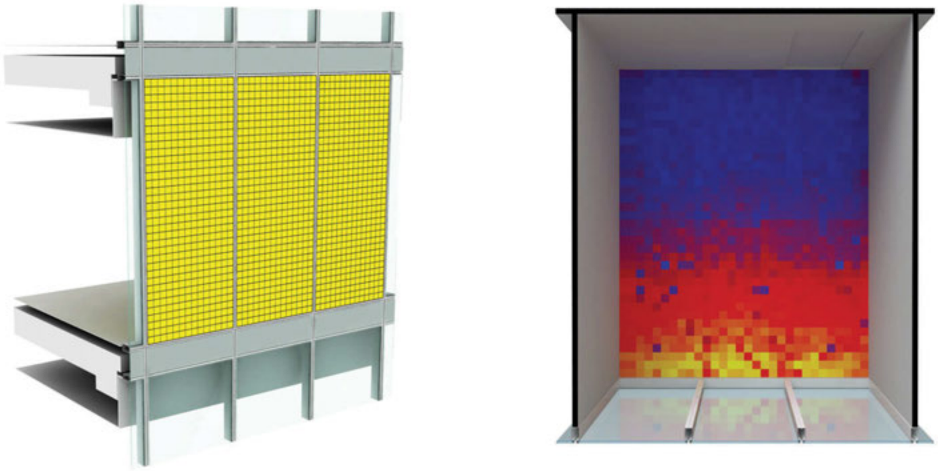
Vertical shading – Generally used on east and west facing facades to protect against glancing sun angles. Vertical shades are also useful on pole facing facades to protect against low angle sun in the early morning and late evening.

Shading screens – Perforated screens on the outside of the building reduce the amount of direct sunlight that hits the facade. The effectiveness of shading screens is dependent on their opacity and has a significant impact on the amount of daylight entering the building.

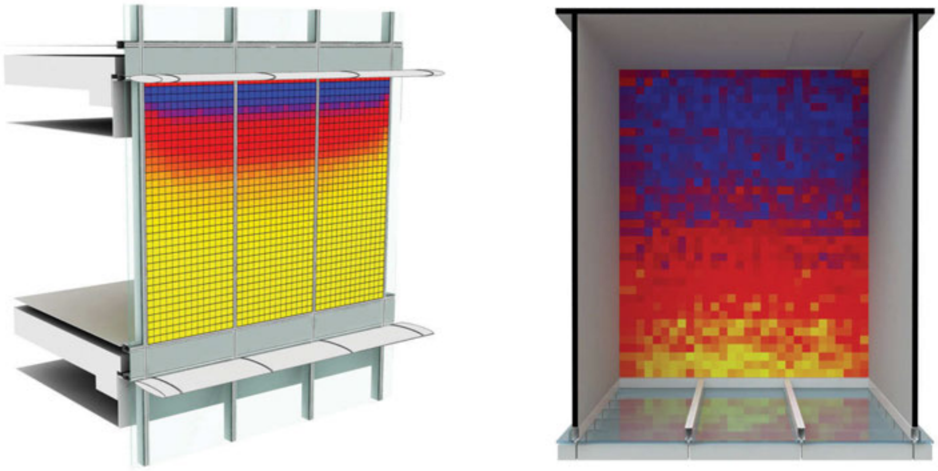
Interior devices – Blinds, curtains and other interior shading devices have limited ability to control solar gain; however they can help to control the penetration of low angle sun into the building as well as reducing the impact of glare. Interior devices tend to be controlled by the user which gives occupants a sense of control of their environment.

The development of high performance glazing products with low shading coefficients has led to buildings being less reliant on shading systems; however they allow significantly less light to enter the building. External shading systems allow more transparent glass to be used without compromising the overall performance of the facade.

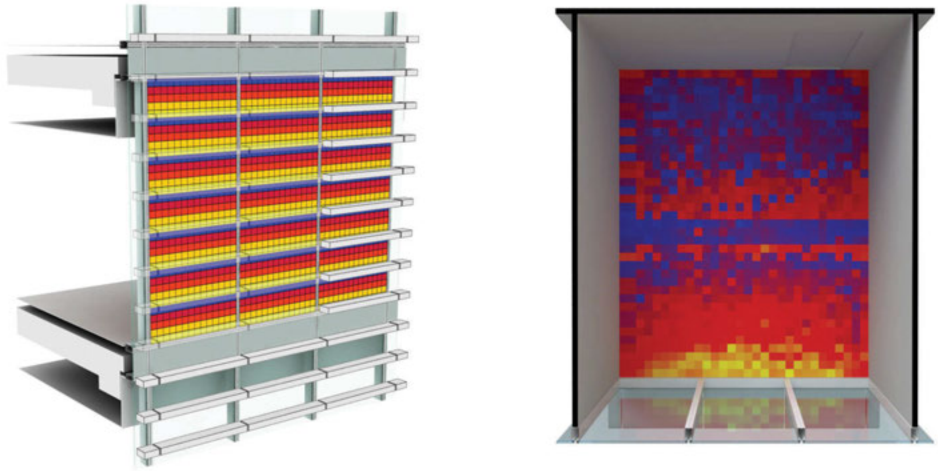
The studies on this page show a comparison of the shading performance of different louvre configurations alongside their impact on daylight levels within the building. An unshaded, glazing bay is used to provide a reference case for the shading systems to be compared against.



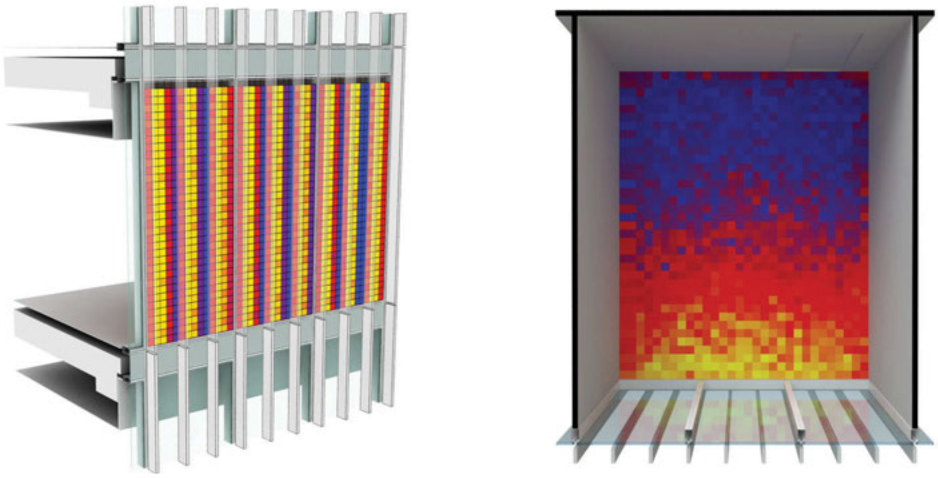
The unshaded facade sets the benchmark for exposure levels. This configuration allows high levels of daylight to penetrate the space.



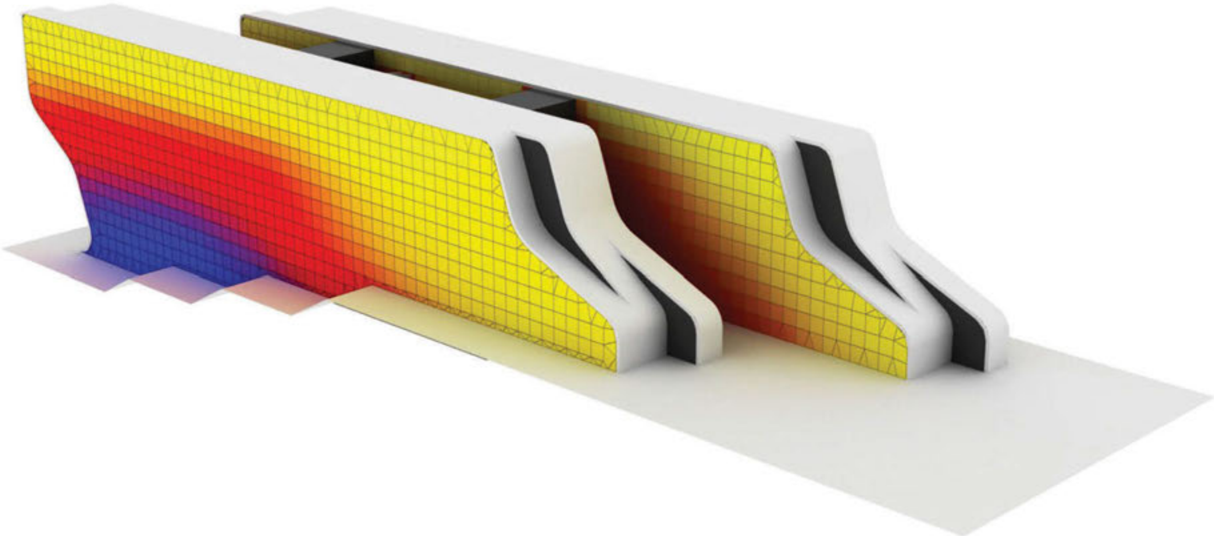
A single horizontal shade stops high level sun from hitting the facade. It has little effect on daylight levels and in some cases it may even increase daylight penetration as a result of reflecting light into the space

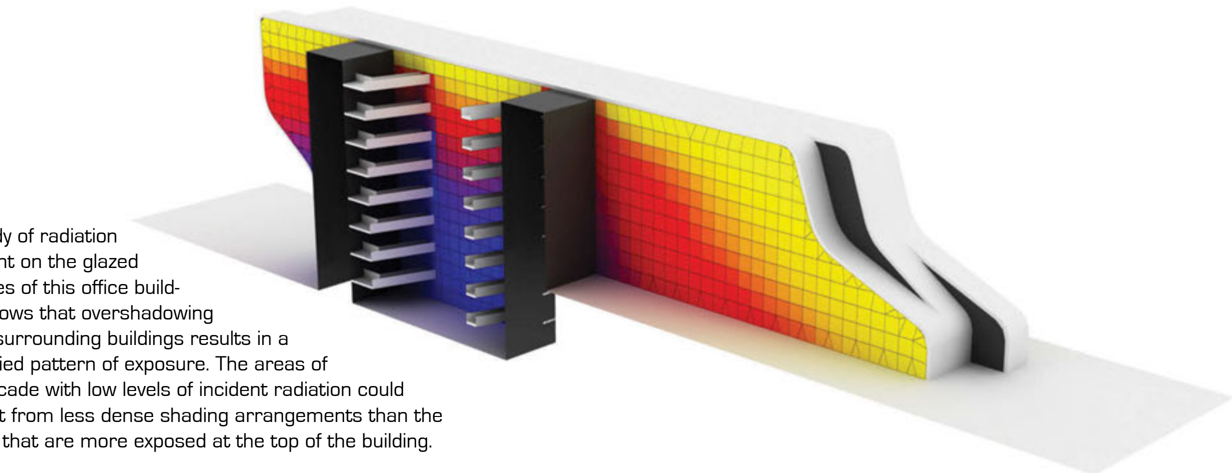


Evenly spaced horizontal louvres have a greater shading effect but result in lower daylight levels inside the space.



Vertical louvres protect against low angle sun hitting the facade at glancing angles but have little effect on high angle sun. Daylight levels are similar to the horizontal layout.





A study of radiation incident on the glazed facades of this office building shows that overshadowing from surrounding buildings results in a stratified pattern of exposure. The areas of the facade with low levels of incident radiation could benefit from less dense shading arrangements than the areas that are more exposed at the top of the building.

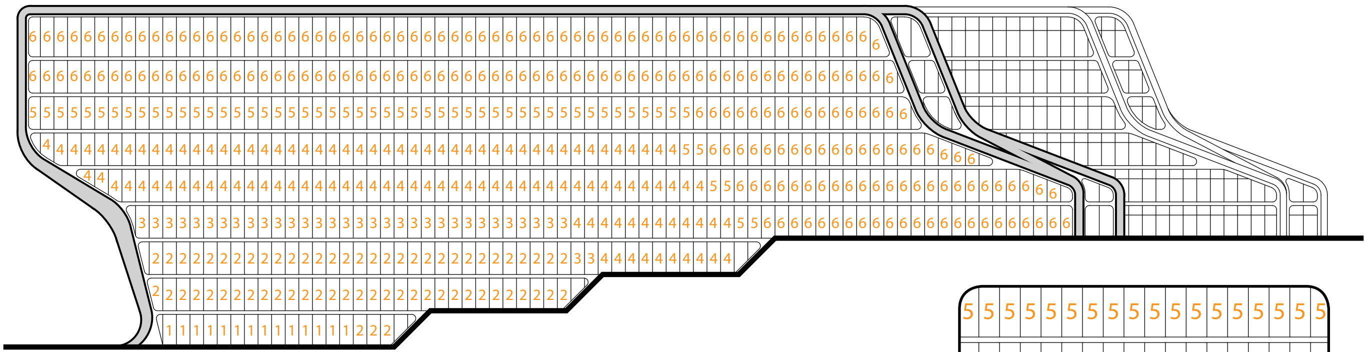
Shading devices can have a dramatic impact on building appearance and the earlier they are considered in the design process the more likely they are to become a well integrated part of the project. With the increased use of digital analysis software there has been a trend in recent years to develop whole building shading strategies that assess the shading demands of each part of the facade and develop specific solutions. This strategy allows the shading effects of the building geometry, the surrounding buildings and environmental features such as trees or hedges to be taken into account when defining shading requirements of the building.

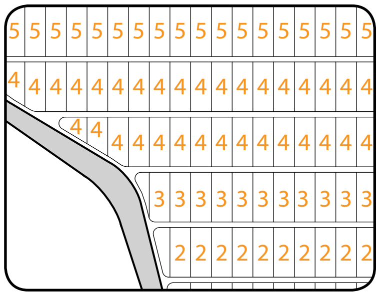
One of the many advantages of this philosophy is an improved relationship between the external climate and the internal space. Designers can consider the shading requirements of the space based not only on its orientation but also its function and shading solutions can be developed that meet the building's specific needs. Location specific shading solutions help to maintain visual comfort levels for users by allowing improved views out of the building whilst also ensuring higher levels of natural daylighting inside the space. Bespoke shading solutions also allow designers to differentiate building facades from one another, adding interest and human scale to even the most functional of buildings.

The case study on this page shows the development of a whole building shading system for an office building in Egypt. There was a need to design a shading system for the building to prevent the office spaces from overheating due to solar gain, but there was a desire to take advantage of the overshadowing effect of the building's geometry to limit the amount of shading louvers.

A digital analysis of the facade's exposure to direct sunlight identified that the upper floors of the building were in direct sunlight for large parts of the year, whilst the lower floors were less exposed. The design team was keen to avoid designing a shading system to the 'worst case' scenario and applying it uniformly across the facade. Instead there was a desire to express the stratification of the exposure analysis and a decision was made to use a shading system that could be adapted to give many shading densities.

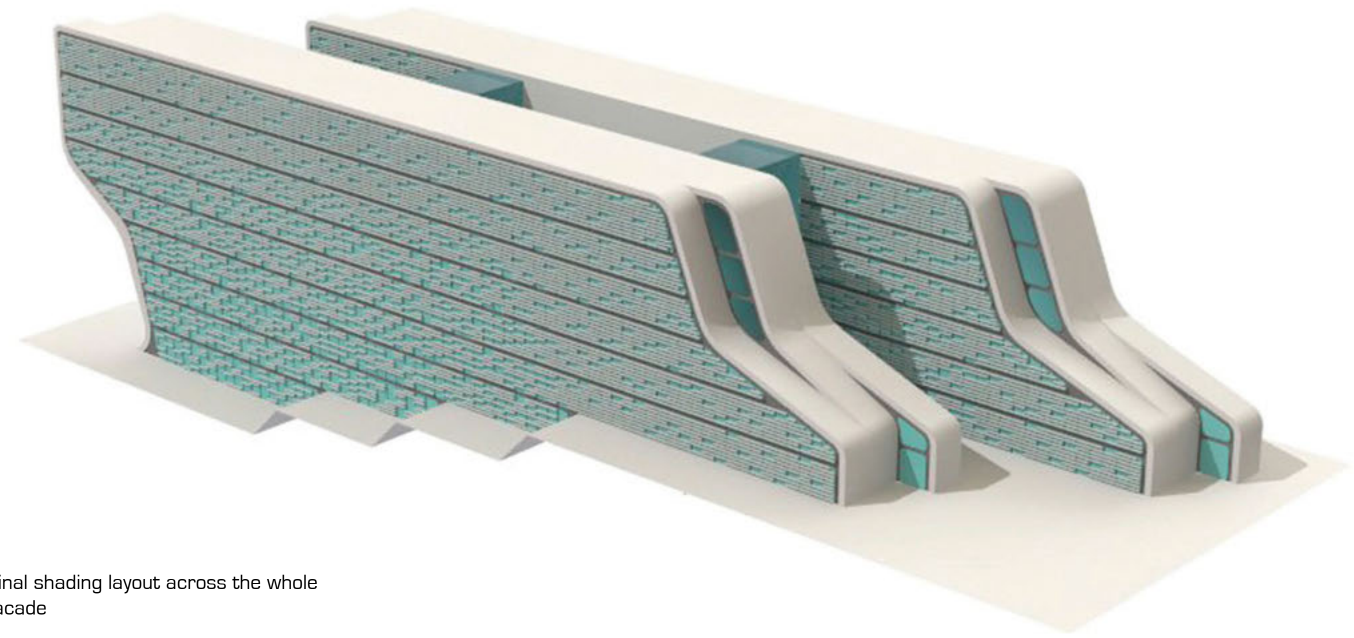
The digital study was mapped onto the facade so that each glazing bay was given a numeric value to represent the level of shading required to prevent the space behind from overheating. Earlier studies had identified that horizontal louvers were the best performing system for the climate and a series of louvre layouts were generated and mapped to the facade based on this shading level required. The result was a gradual increase of shading density across the facade which not only protected the interior from unwanted solar gain but also maximised the amount of daylight entering the ground level spaces.



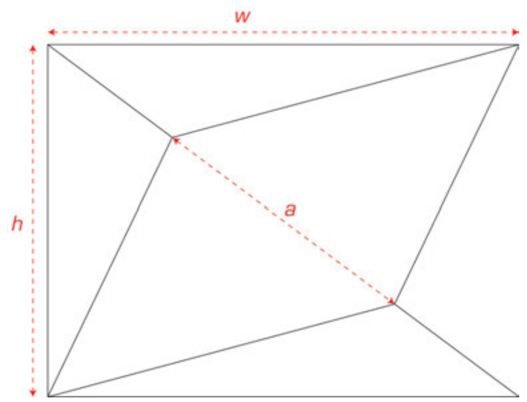


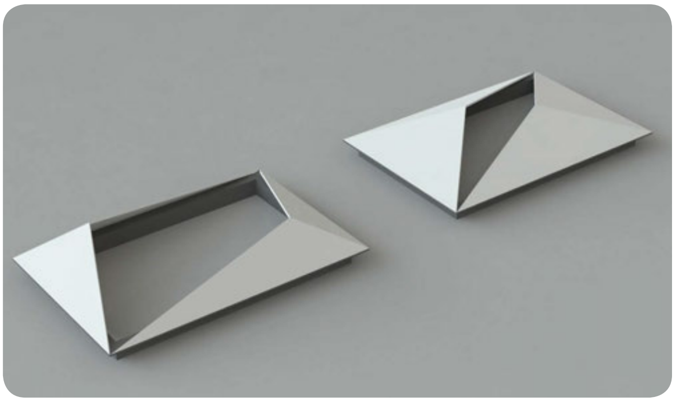
Each glazing bay is given a code based on its exposure. This code relates to a shading density.

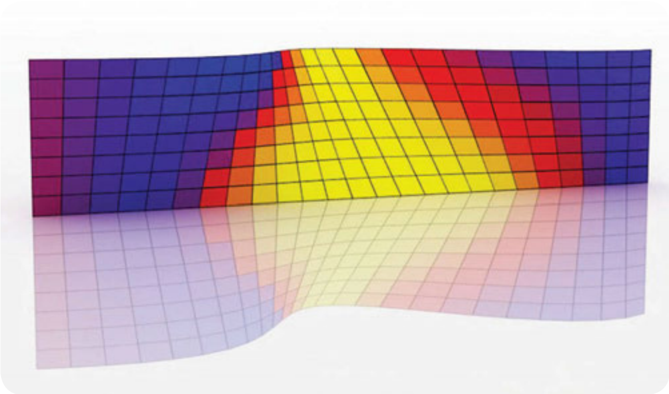
Different shading layouts of varying densi-ties are set up.

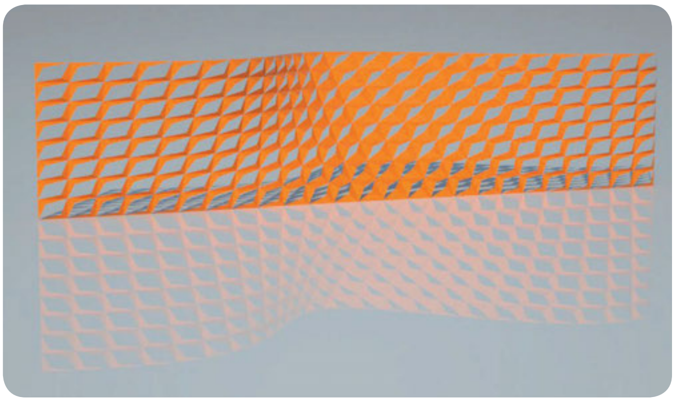


Final shading layout across the whole facade









A shading component can be designed to have a variable aperture with the opening sized in relation to the amount of radiation incident on the facade at each particular location. In this case, distance 'a' is linked to the exposure value from an environmental study of a curved facade resulting in small apertures in highly exposed locations and larger apertures in locations with lower exposure.

Well-designed shading systems will protect a facade from the worst effects of solar gain and keep internal conditions at a comfortable level but their static nature means they will never be able to protect against all sunlight conditions. In recent years there has been a rise in the deployment of adaptive shading systems which change their shading performance based on their location on a building facade. Adaptive shading systems fall into two main catagories, static systems and kinetic systems.

Static systems

These use fixed elements that have been shaped to suit the particular shading requirements of their location. The example above shows a component of a set width and height with a geometry that creates an aperture at the centre. The size of the aperture (a) can vary to restrict the amount of sunlight that can penetrate, with small apertures used where facade exposure is high. A digital exposure analysis of the facade identifies exposure levels which can be used to size the aperture. The result is a shading system that relates directly to the site conditions.

Kinetic systems

These systems use moveable elements which allow building facades to respond to a number of changing factors:

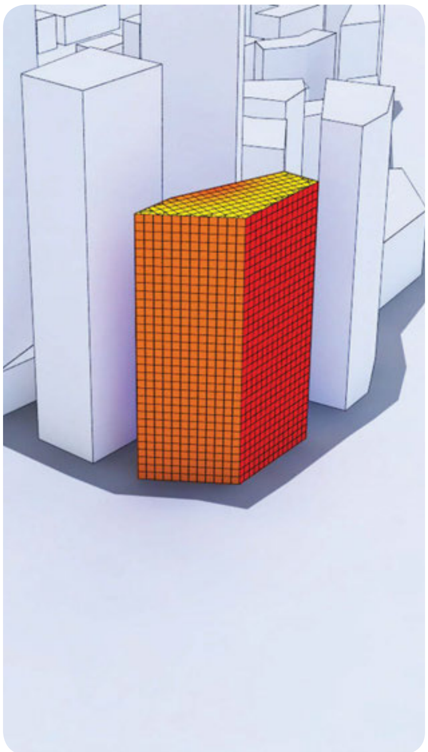
Sun position – shading elements move based on the movement of the sun providing shading when needed and when out of use can move to a position that maximises daylight into the building and provides unobstructed views out.

Context – constant urban renewal means that the nature of the buildings surrounding a new development may change over its lifetime. The overshadowing potential of neighbouring structures cannot be relied on to be present for the lifetime of the building and moveable systems allow the shading potential to alter over the life of the facade.

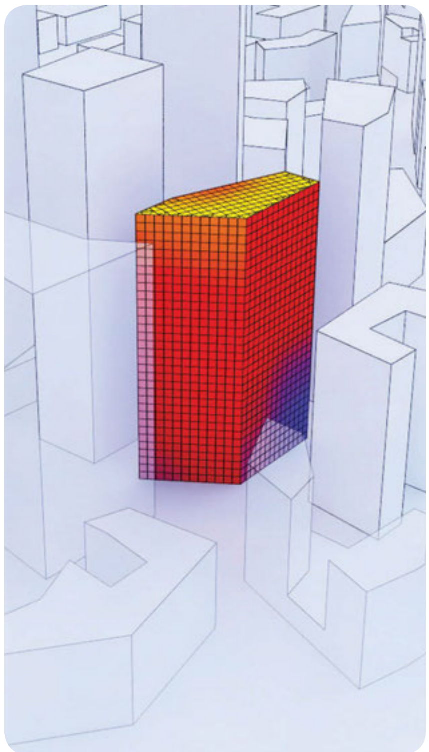
Function – the change in function of a building, or parts of buildings, may require changes in shading performance over the lifetime of the building. Moveable systems allow the shading components to be reconfigured based on the changing demands of the building.

The example opposite shows a tower built as part of a master plan in the Middle East. The building was on the edge of the first phase of the development and the south facade was exposed to direct sunlight for much of the day. The latter phases included further development to the south with new towers overshadowing the facades of existing towers. A shading system was proposed with the potential for change over the lifetime of the building as the site developed. At the beginning of the building's life the shading system would be working at its hardest to prevent solar gain from the south facade. As new buildings are constructed on the neighbouring plots the moveable parts of the shading system reconfigure themselves to allow more daylight into the building with the overshadowing from surrounding buildings helping to control solar gain.

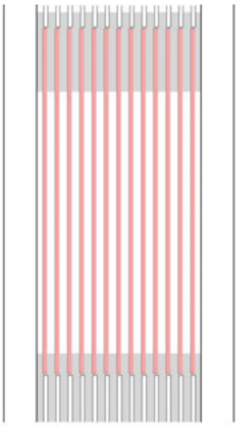
Development Phase 1
Development Phase 2
Development Phase 3
Building Study

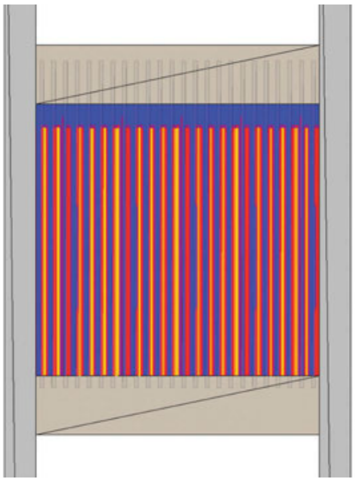


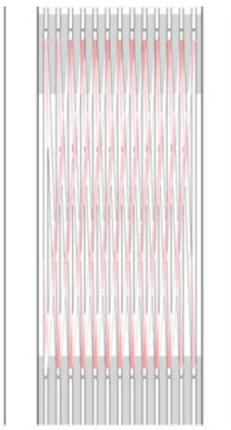
Facade exposure after completion of Phase 1. South facade is highly exposed to direct sunlight

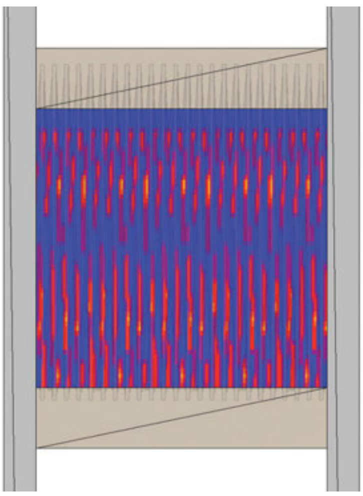


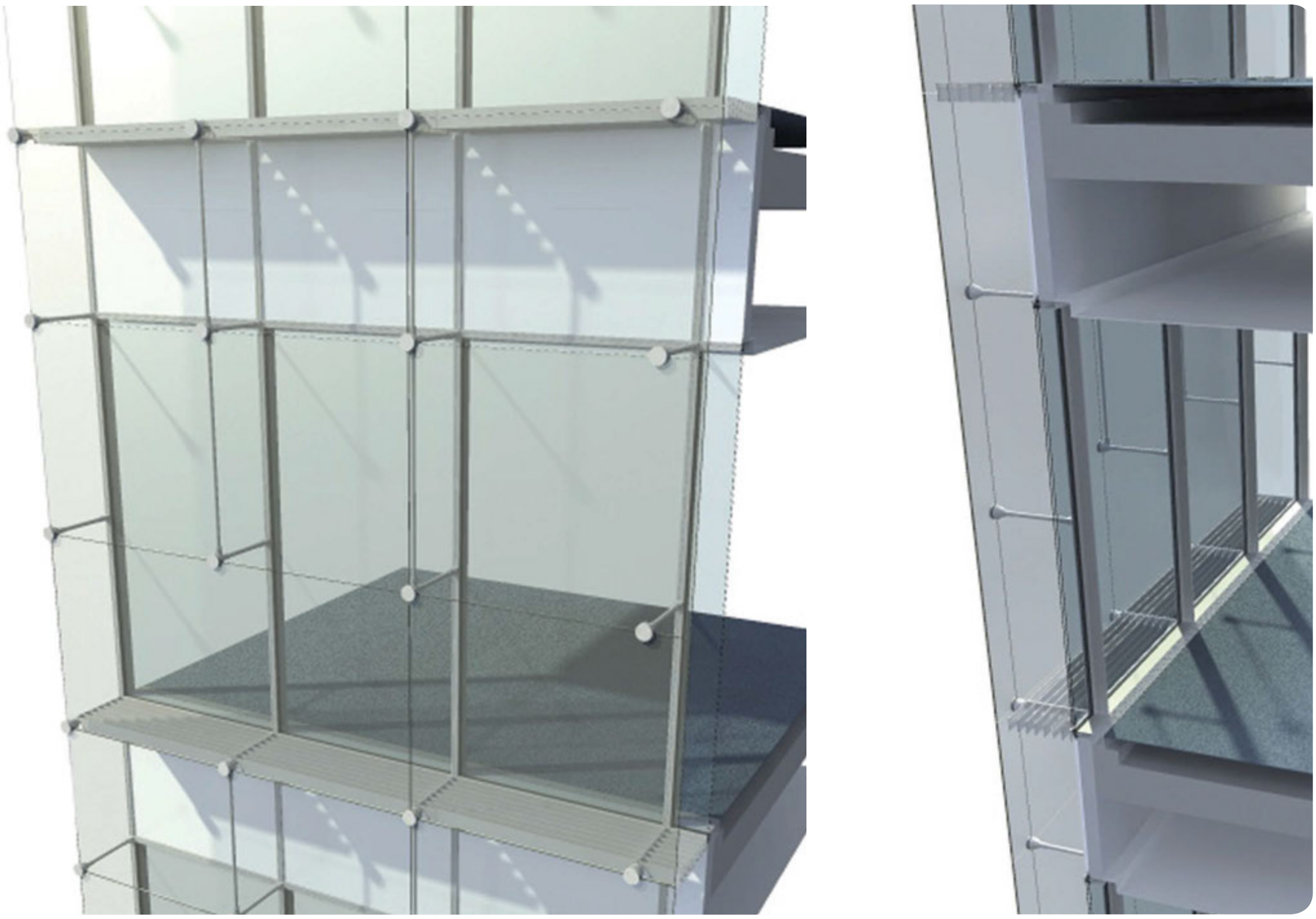
Facade exposure after completion of Phase 2. Surrounding buildings offer a degree of shading to the lower floors on the south facade











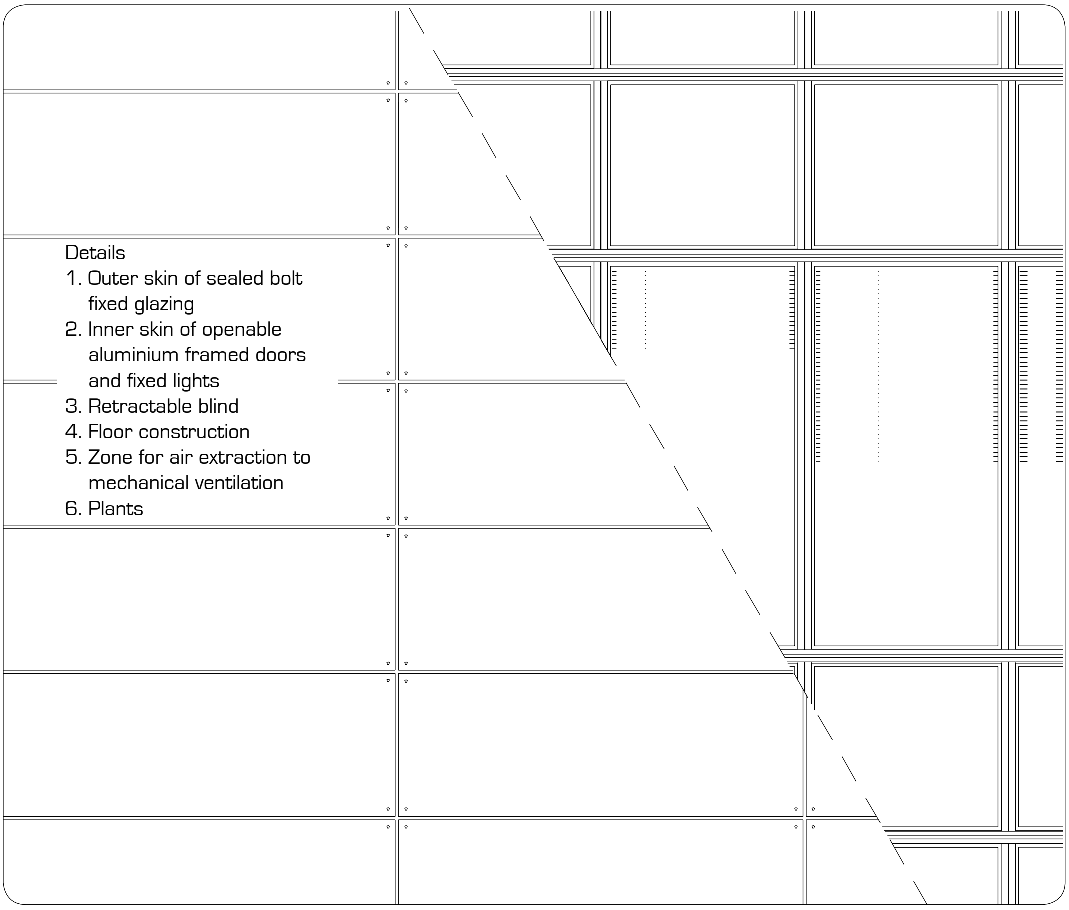
3D view of corner clamped double skinned facade system

Double skin facades

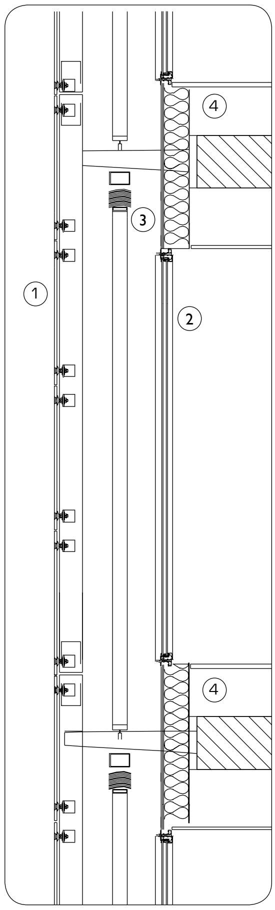
A recent development in facade technology has been the introduction of double skin facades, which present a solution to increasing requirements for natural ventilation, increasing daylighting and the use of thermal mass for night time cooling. The use of double skin facades can provide energy savings of up to 50% in the mechanical ventilation of a building. External shading is useful in buildings with single skin glazed facades where there is a risk of high solar gain, resulting in overheating inside the building. When located externally, fixed shading systems are considerably cheaper than those with moveable screens or louvres, but they are unable to respond to the changing angle of the sun during the day, and through the year. Internal shading does not perform as well, as mentioned in the following sections. However, in double skin facades the solar shading is installed in the void between inner and outer skins, where the blinds are better protected. Conventional single layer glazed walls tend to introduce conflicting performance requirements into a single layer. Solar control films or layers have the effect of reducing the transparency of external walls, which increases the amount of electrical lighting required internally. Layered facades separate out functions of waterproofing, solar control and ventilation in different configurations. In double wall facades these have become two generic types: thick walls and thin walls.

Thick walls

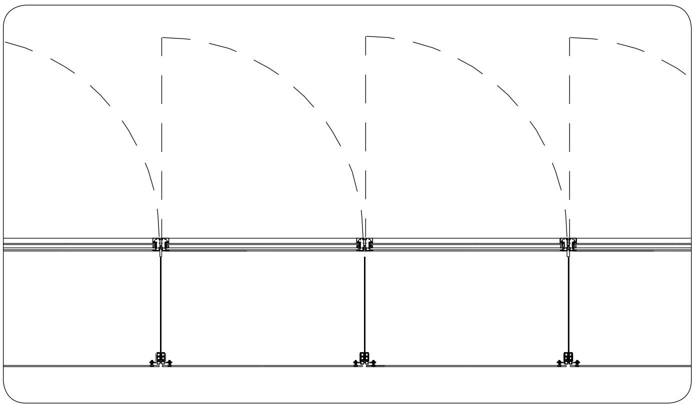
In thick double skin walls, an outer layer comprises a single skin of glass, typically a single glazed bolt fixed glazed wall. This is separated from the inner wall by a gap of between 750mm and 1000mm. The wide cavity is required primarily for maintenance access. The inner skin is typically a standard double glazed curtain wall system using either stick or unitised systems, with opening windows. Because the outer wall is protecting the inner wall from windblown rain, materials other than metal and glass can be used to form the inner wall. Fresh air is allowed to pass through the outer wall into the zone between the two skins. This is achieved either by having open jointed, or partially open joints in the outer glazed wall, or alternatively metal flaps or louvres at floor level that are operated mechanically to admit air at different times of day and at different times of year. This latter method provides a more controlled method of regulating air intake into the void between the two skins, but is considerably more expensive than the open joint method. Once air has entered the void its wind speed drops dramatically, allowing the inner glazed wall to have opening windows to introduce fresh air. This method is particularly useful in taller buildings over three storeys, where the wind speed is often too high to allow windows to be opened safely, particularly in office buildings and public buildings. A walkway is set into the void, usually at the same level as the internal floor to provide easy access to it and ensure that the walkway does not obscure views out of the building. The walkway allows the glass surfaces facing into the void to be cleaned and maintained easily. Depending on the height of the facade, the natural ventilation provided by this configuration uses external wind pressure to provide fresh air into the void. It uses the stack effect to allow the heat gained within the void, in



Elevation 1:25



Vertical section 1:25

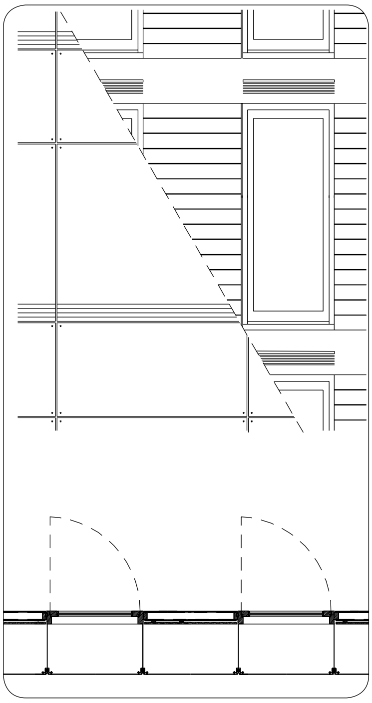


Plan 1:25

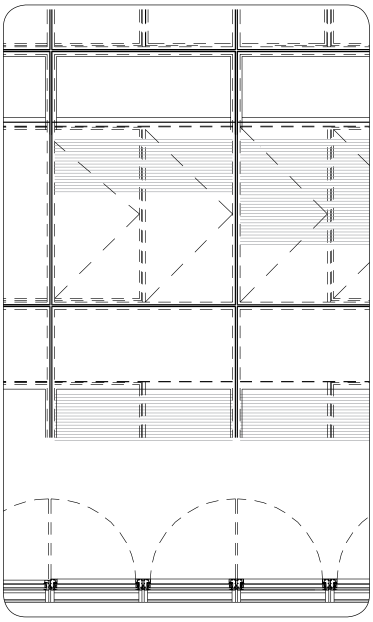
3D view of twin wall from inside

3D view of twin wall cavity

View of vertical section through stepped twin wall facade system



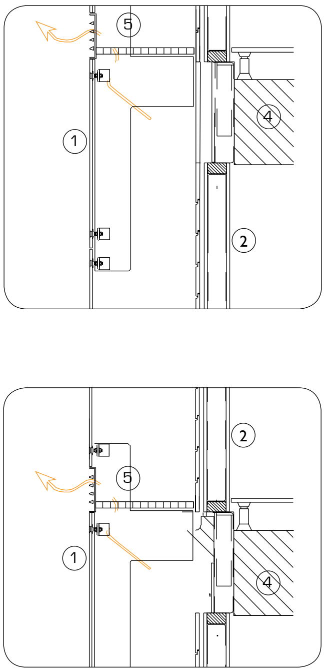
1:50 Plans and elevations : Thick wall with ventilated outer screen



1:50 Plans and elevation : Thin wall with out sealed glazed unit

3D section cut through double skin system with openable screen

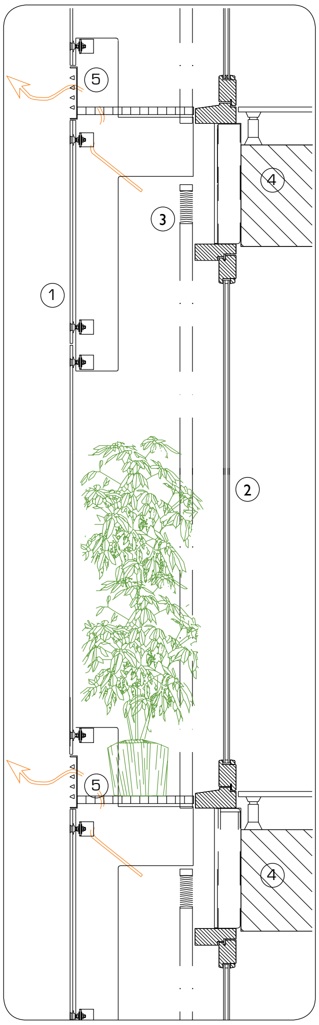
Plan view of twin wall with openable screen



Vertical section 1:25 through thick twin wall system

Details
1. Outer skin of sealed bolt fixed glazing
2. Inner skin of openable aluminium framed doors and fixed lights
3. Retractable blind
4. Floor construction
5. Zone for air extraction to mechanical ventilation
6. Plants

Vertical section 1:20 and 3D views through double skinned facade with plant in cavity

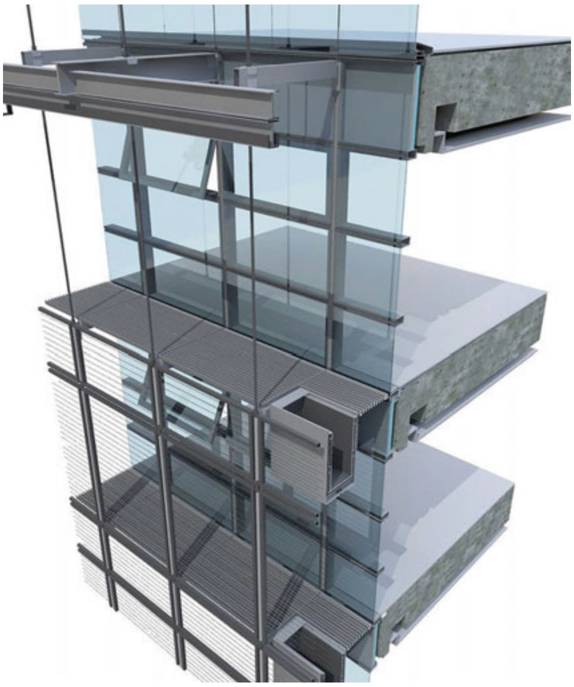


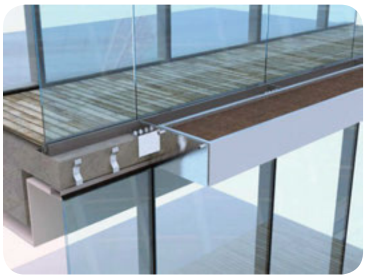
warm weather, to escape to the outside. In winter, where solar gain is a much less significant issue, in open jointed methods of ventilation the outer skin can suffer from cold air being allowed to enter the void, which can act as a winter 'buffer zone'. The method of using metal flaps and louvres allows the quantity and frequency of fresh air entering the void to be more closely controlled. This helps to regulate the temperature of air passing through the inner wall, by ventilation or by opening windows. Air in the void between the two skins will be warmed in winter by heat transmitted through the facade as well as any incident solar gains. The cavity within a double skinned facade acts in a similar way to that of a greenhouse. This area becomes ideal for the growth of many plants. The plants can not only enhance the appearance of the facade but also enhance the environmental benefits of the double skin system. Double skins help insulate the building, absorbing the heat of the sun during summer and retaining warmth during winter. Plants, it has been shown, are more efficient in controlling these environments than traditional blinds and other solar devices and can provide very efficient shading to interior spaces. In addition to this they can provide sound attenuation as well as providing potential crops or food growing areas in buildings.

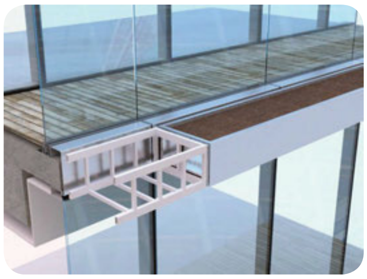
Thin walls

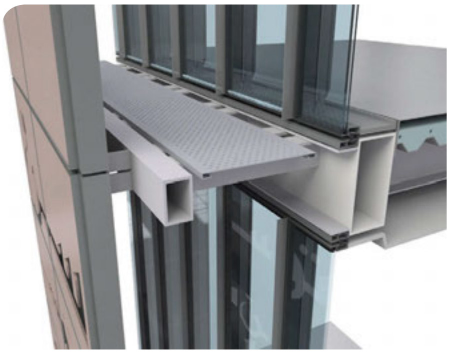
Thin wall facades comprise two skins of glass set closely together, with a cavity in the region of 100mm wide. The cavity is mechanically ventilated, allowing it to be considerably smaller in depth than the naturally ventilated thick wall design. Air can be drawn up through the cavity from outside or from inside. Air drawn from outside needs to be relatively free of dust and pollution, since this makes the cavity dirty quite quickly. In this system, the air drawn through the facade is separate from the mechanical ventilation for the building. The inner skin has a series of opening doors to allow access into the cavity for cleaning and maintenance. Blinds are usually set into the void in order to provide solar shading. Solar energy absorbed by the blinds is radiated into the cavity where it is drawn away by air rising in the cavity. The warmed air is then ejected at the top of the panel.

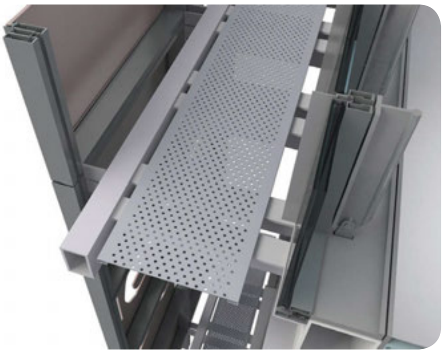
In winter, warm air extracted from the inside of the building is drawn through into the facade at floor level or in the void below floor level and is drawn up through the external wall to reduce the amount of heat loss through it. When air is drawn through the facade from inside the building, the wall becomes an integral part of the mechanical ventilation system for the building. The air is drawn through a heat exchanger to be used in heating the space in cooler months, or is ejected from the building through the mechanical ventilation system. In summer, air drawn up the cavity from inside the building passes over the solar shading blinds, which are dropped down in place to provide solar shading. The heat from the blinds, as a result of the solar energy, is drawn away and is ejected from the building through the mechanical ventilation system. When the air into the cavity is provided from inside, the facade is completely sealed, and requires only occasional access to the void for cleaning and maintenance.







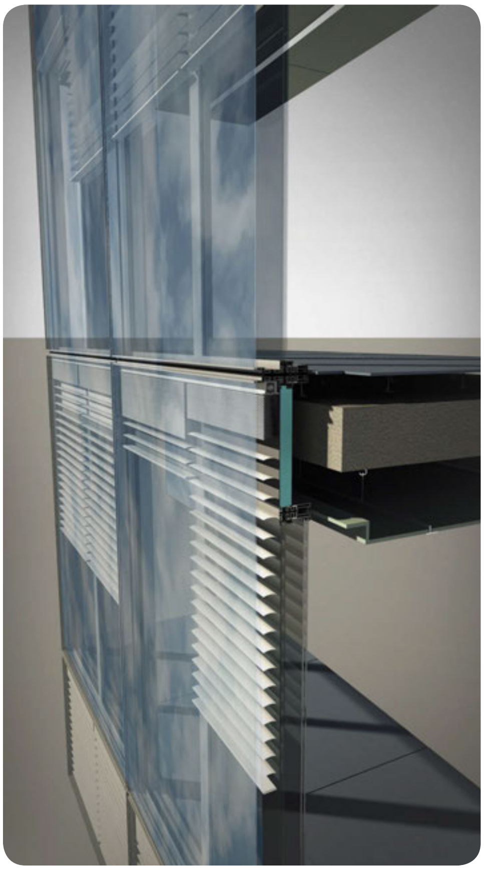




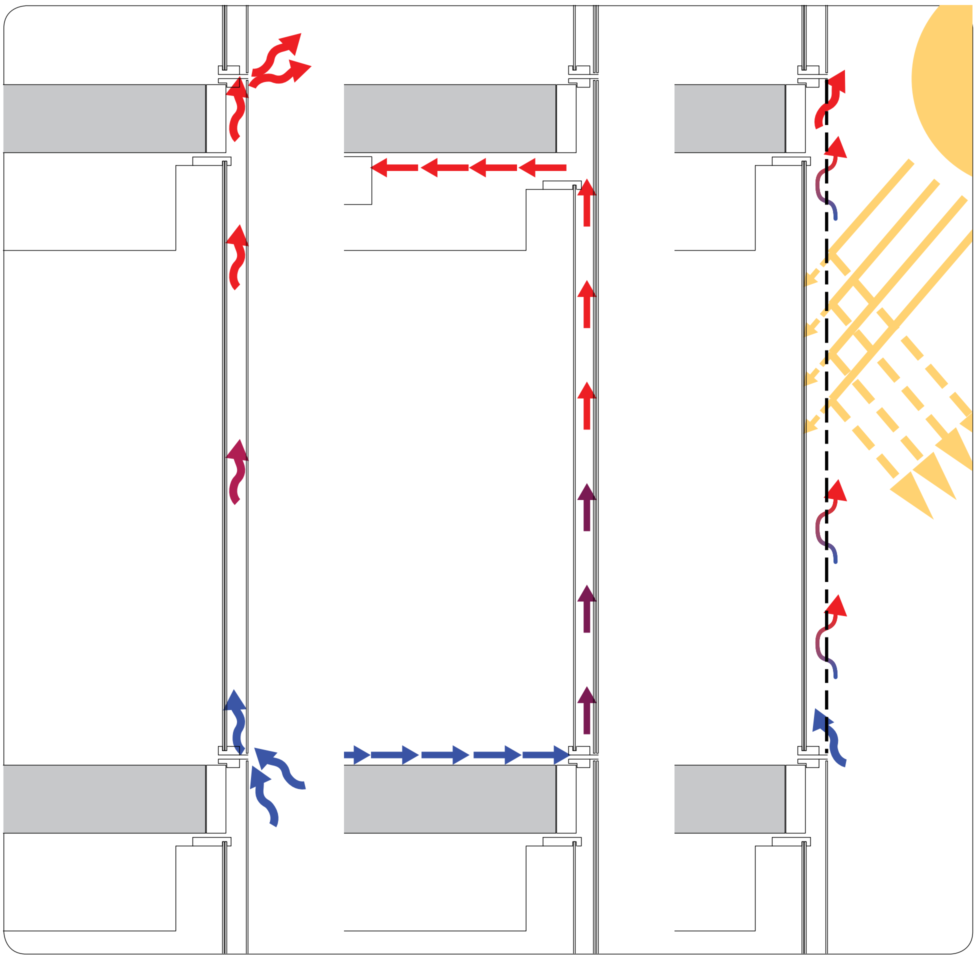
Thin double skin walls, formed as unitised (prefabricated) panels, comprise two skins of glass set apart, forming cavity in the region of 100mm to 300mm wide. Panels are either ventilated from the outside with fresh air, or are internally ventilated by the mechanical ventilation system. The construction of the panel is based usually on unitised glazing, where each panel, usually from 1500mm to 3000mm wide. In contrast, wide double skin walls can be constructed as two stick built facades, or as a mixture of stick and unitised glazing. Combined systems of ventilating from both the outside and the inside are not used to date due to the conflicting requirements of the position of the double glazed units which need to be one side of the panel (either inside face or outside face) to suit either internal ventilation or external ventilation. The cavity can be either mechanically ventilated or naturally ventilated to suit performance requirements. Air is drawn up through the cavity either from outside or from inside and is expelled at the top of the panel, typically at each floor level.

Thin double skin panel ventilated to the outside has a single glazed outer skin and a double glazed inner skin. The inner skin is openable from inside, as opening doors, in order to access the cavity for cleaning and maintenance. Fresh air is introduced from outside at the base of the panel, admitted through slots at the bottom and expelled at the top. The solar shading blind is fixed at ceiling level, where it is usually left visible when in the closed position. The void above the blind, in the floor / ceiling zone, is closed off by a metal faced spandrel panel on the inside skin. Air is drawn up to the top of the cavity, which helps to avoid heat build-up in the void which is highly insulated at this point.

Thin double skin panels ventilated on the inside are formed with a double glazed unit on the outside and a single glazed panel on the inside face, with the inner panels opening for cleaning and maintenance. Tempered air from inside the building is drawn into the void of the facade panel at floor level, or in the void below floor level, and is drawn up through the cavity to provide a thermal buffer. The air is extracted internally and drawn through a heat exchanger to be used in heating the space in cooler months, or is ejected from the building through the mechanical ventilation system. In summer, air drawn up the cavity from inside the building passes over the solar shading blinds, which are dropped down in place to provide solar shading. The heat from the blinds, as a result of the solar energy, is drawn away and passed through the mechanical ventilation system. When the air into the cavity is provided from inside, the external skin of the facade is sealed, while the inner skin is openable. The cavity between the glass skins requires cleaning from the dust drawn into the cavity between the two glass skins. The set of doors on the inner skin provides access for cleaning the two faces of the cavity, but the external face of the wall of both types requires cleaning from outside, typically from a cleaning cradle. An advantage of the blinds being in a cavity rather than on the outside is that they can be made to be moveable without the need to have motorised equipment outside, where it is more vulnerable to deterioration in the external environment.



Details
1. Metal cladding to exoskeleton structure
2. Unitised double skin facade panel
3. Outer glazed wall
4. Inner glazed wall
5. Perimeter frame to panel
6. Intermediate horizontal framing member
7. Floor finish
8. Floor slab
9. Ceiling finish
10. Structural column



Externally ventilated

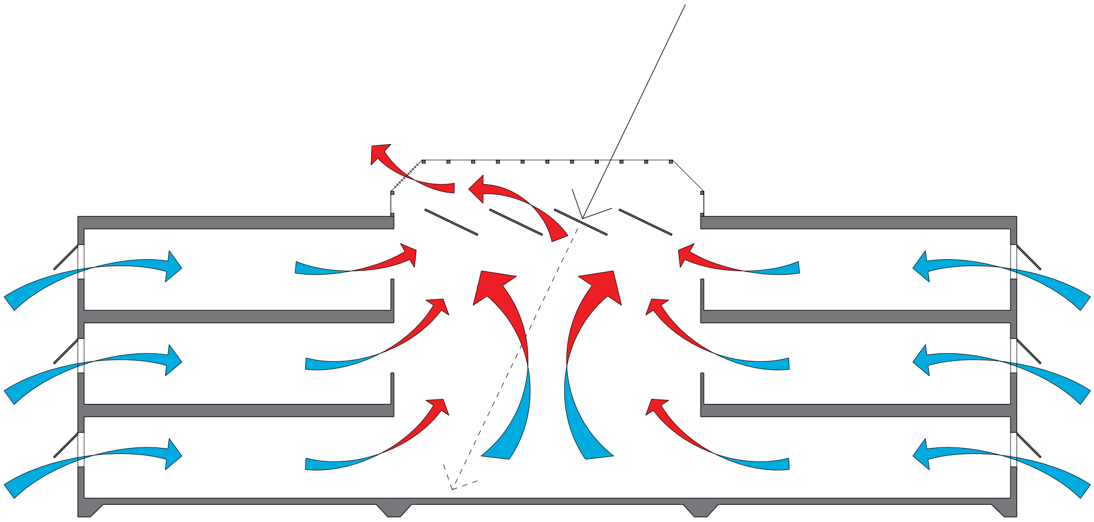
Internal double glazed unit with single glazed external skin.
Cavity ventilated with outside air by buoyancy.
Cavity needs to be of adequate dimensions to optimise stack effect.
System can be mechanically driven to increase effectiveness during thermal peaks.

Internally ventilated

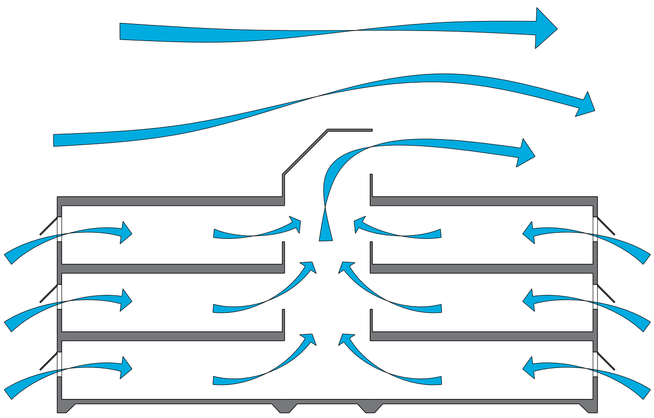
External double glazed unit with single glazed internal skin.
Cavity is ventilated with return room air which is extracted from the room at floor. level and returned to the air handling unit.
Shading devices in cavity absorb solar radiation which is then expelled via the moving air.

Externally shaded (screen)

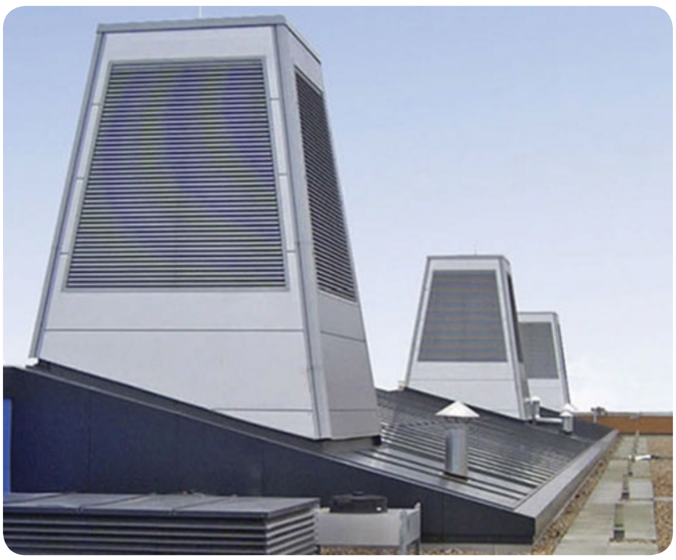
External perforated metal or mesh screen with double glazed internal skin.
Outer screen acts as shading element for inner skin in addition to benefits of externally ventilated approach.
Cavity ventilated with outside air by buoyancy.
Cavity needs to be of adequate dimensions to optimise stack effect.



Stack effect ventilation: As sunlight heats the atrium space the air temperature increases. Hot air rises to the top of the atrium pulling air from the office spaces. The resulting pressure change draws cool air into the building from outside.



Wind driven ventilation: Wind flowing over a chimney creates areas of low presure which draw air from the shaft below. This in turn draws air into the building from outside.

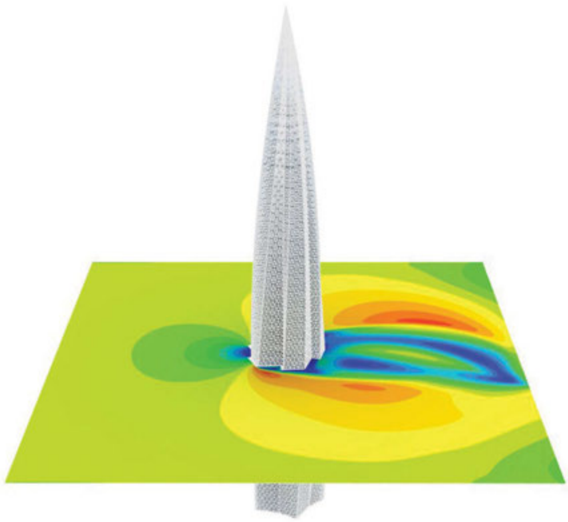


Ventilation chimneys on the Ionica building in Cambridge, U.K.

The return to natural ventilation in buildings, and away from dependency on mechanical ventilation (including air conditioning), has gathered momentum in recent years. This has come about from the desire to reduce both the energy consumption in buildings and the wider issue of carbon dioxide (CO_2) emissions from the primary energy generation through to building use. The link between global warming and the build-up of greenhouse gases has yet to be conclusively proven, but the circumstantial evidence seems convincing. Nearly half of CO_2 emissions generated in the U.K. alone arise from energy consumed within buildings. The reduction of energy consumed in buildings has a huge benefit for future generations. The decline in the supremacy of air conditioning can also be linked to 'sick building syndrome' due mainly to systems dependant on the re-circulation of used air in buildings.

This has resulted in the increased use of opening panels and window systems. Previously, building types other than housing were often designed as hermetically sealed boxes which aimed to provide a constant temperature and steady rate of ventilation. In addition, air conditioning systems would control humidity as well as temperature. This high degree of environmental control led to very high energy consumption from running the equipment. In urban areas, the use of operable windows to provide natural ventilation is often considered inappropriate due to high levels of noise and atmospheric pollution. This has led to the development of 'layered' systems in which functions of sound insulation, weatherproofing and air infiltration are separated.

Natural ventilation in buildings is generated either by wind or by a 'stack effect'. In most buildings a combination of both occurs. As air flows across a building, a difference in air pressure will occur as a result of varying wind pressure. This difference in pressure causes the air in the area of higher pressure to flow towards the area of lower pressure. Provided openings are appropriately located in these pressure regions, the movement of air creates a natural ventilation flow through the building. 'Stack effect' ventilation is caused by a difference in density of air due to internal heat input from casual and solar gains to the ventilating outdoor air. The temperature, and consequently den-



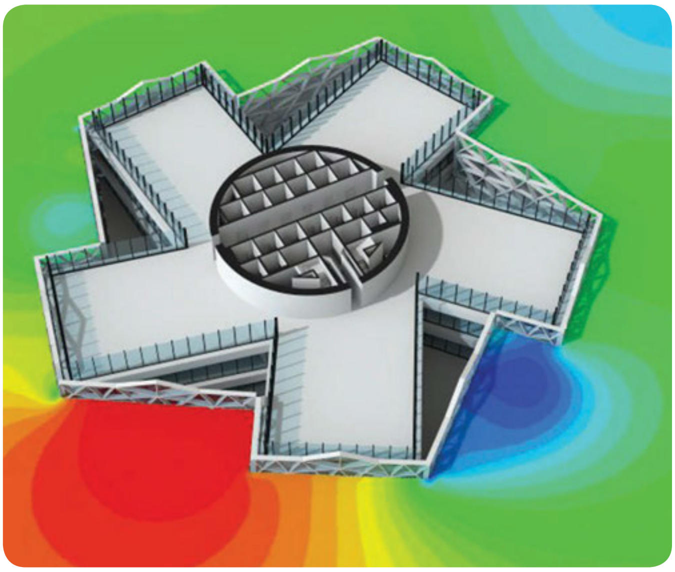
The CFD study above shows the variations in wind speed around a tower and the impact that the complex geometry has on the design of the framing that supports the glazed panels.

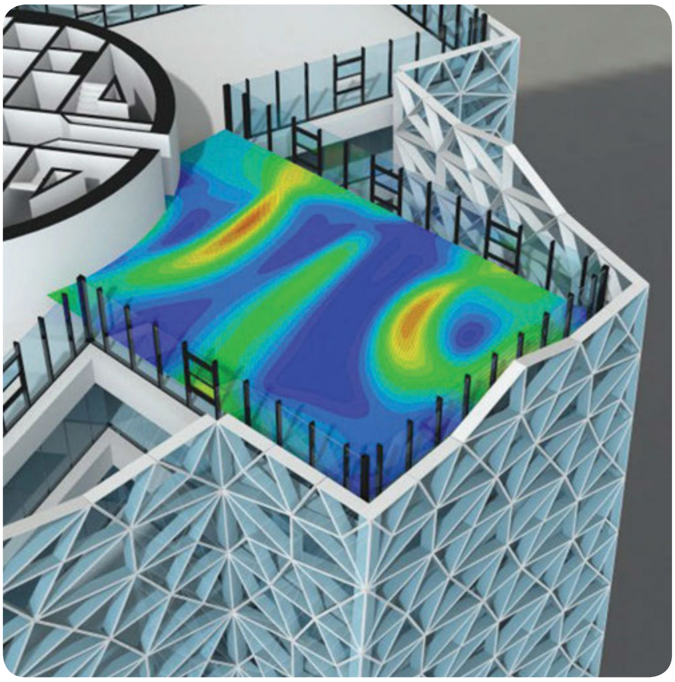
sity difference between indoor and low level supplied outdoor air results in an upward flow (buoyancy). Air moves from low level to high level in a building with a higher temperature than that outside, whilst the reverse will occur if the air in the building is cooler than that outside.

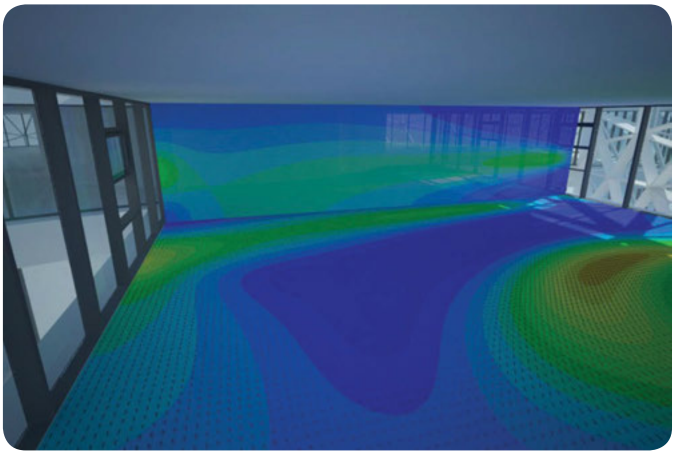
There are a number of advantages to using natural ventilation strategies over mechanical systems. Perhaps the most significant is the reduced energy consumption of the building during its operation which in turn helps to reduce the operational costs of the building during its lifetime. Since there are fewer ducts, filters, pumps and other mechanical equipment, maintenance costs for the building are also reduced. The reduction in mechanical equipment has the added benefit of reducing celing zones in commercial buildings which can allow additional floors to be added to multi-storey buildings without compromising ceiling heights.

Most natural ventilation systems require some manual operation which offers a psychological benefit to users since occupants are able to control their own environment. The air entering the building is also regarded as healthier as it has not passed through ducts and filters which could potentially harbour diseases.

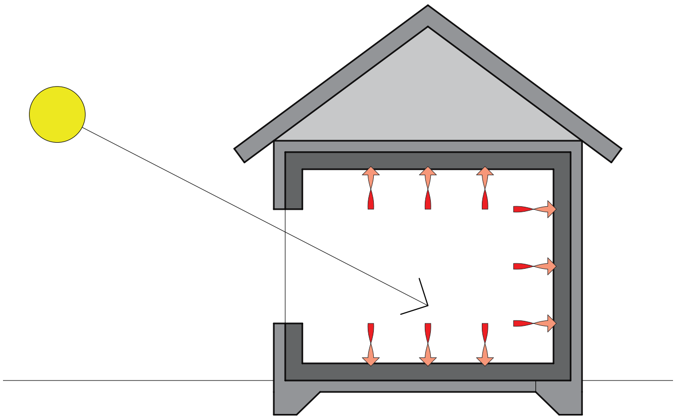
There are a number of potential problems with implementing natural ventilation strategies, in particular noise control. The requirement for large openings and open plan spaces may conflict with accoustic separation between spaces and may not be suitable to particularly noisy locations. It is also important to ensure that the air flow patterns within the building as a result of natural ventilation do not create areas of stagnant air or air that moves too fast to be comfortable. This is particularly problematic in tall buildings where double skin facades are often used to provide a cavity to extract air from rather than pulling air directly from outside.



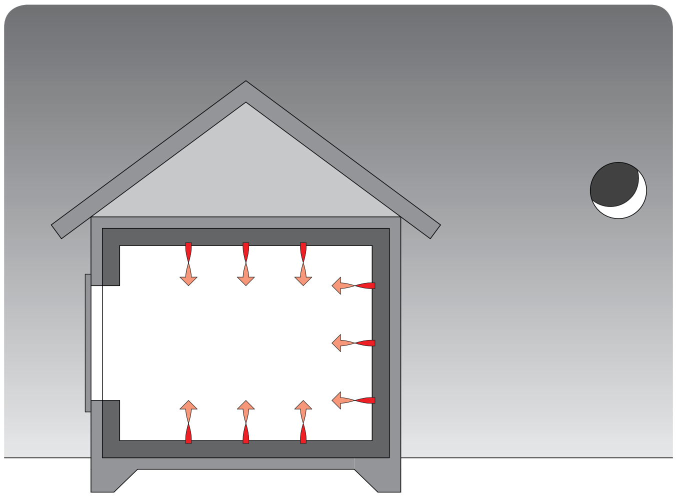




Pressure differences across the facade create ideal conditions for a pressure driven natural ventilation strategy. In this building inlets in the outer skin create areas of varying pressures in the atrium spaces which drives cross ventilation of the office floor plates.



During the day, exposed thermal mass within the building absorbs heat resulting from solar gain which helps to keep the room at a comfortable temperature.



At night, the heat energy stored within the thermal mass radiates back into the room, helping to maintain a comfortable temperature and reducing the need for nightime heating.

Thermal mass is a term used to describe the ability of the building fabric to absorb excess heat. Materials with a high thermal mass are able to absorb heat, store it and then release it at a later time. Since these materials take a long time to heat up and cool down they can be effective at regulating temperature fluctuations within a building and help to keep the internal temperature at a comfortable level throughout the year.

Heavyweight materials such as concrete and brickwork store a large amount of heat and can be regarded as having high thermal mass. Lightweight materials such as timber and metal do not have the capacity to store a great deal of heat and therefore have a low thermal mass. A table of the heat capacity of typical building materials can be found below:

Material	Heat Capacity (kj/m³°C)	Specific heat (kj/kg°C)
Fibreboard	300	1.0
Hardwood	900	1.23
Gypsum plaster	1050	1.10
Lightweight concrete	1000	1.0
Brick	1360	0.80
Dense concrete	1760	0.84
Stone (marble)	1500	0.88
Water	4200	4.2
Air	1.2	1.0

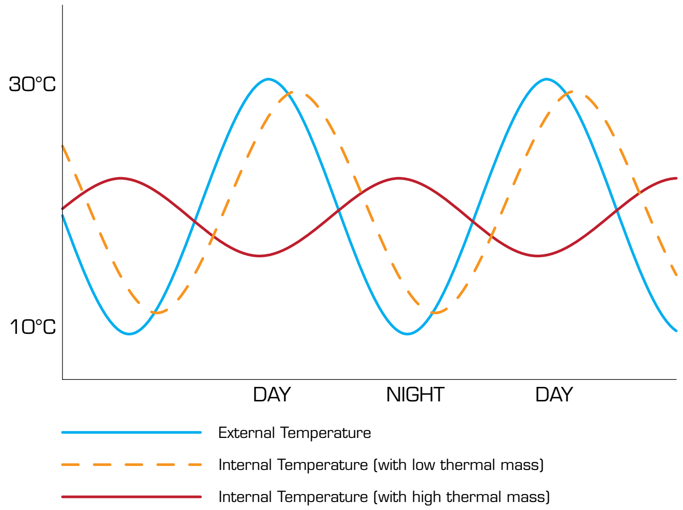
When used in conjunction with an effective passive solar design strategy, thermal mass can help to reduce energy use in mechanical heating and cooling systems, reducing the running costs of the building. Large thermal mass can be a disadvantage in winter, if the building is not in constant use or has intermittent heating as it will take a long time to heat the building up.

Cimate and thermal mass
The application of thermal mass in construction is dependent on the local climate. In cold or temperate climates thermal mass can be used to absorb heat energy from low angle winter sun which is then released back into the space at night. In the summer thermal mass within a building can absorb excess heat as a result of solar gain and occupancy, limiting the temperature rise within the room. At night cool air from outside is allowed into the building and flows across the surfaces that have absorbed the heat during the day, purging that energy and allowing the process to start again the next day.

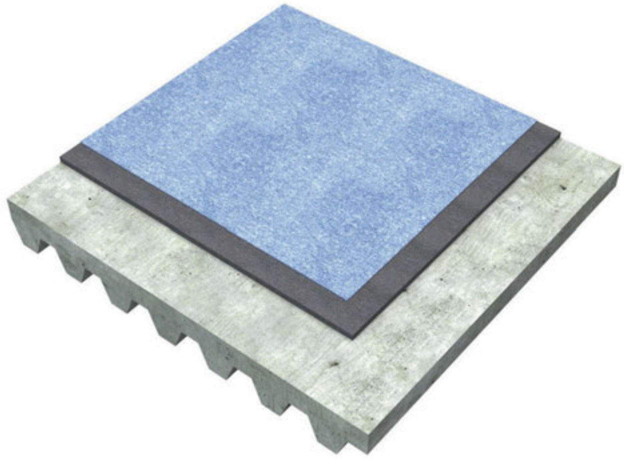
In hot climates thermal mass is used to regulate the high diurnal temperature variation. The building fabric absorbs heat during the day keeping the internal temperature at a comfortable level. At night when temperatures drop significantly, this heat is then re-radiated back into the room.

Thermal mass in offices
Office and commercial buildings which have specific occupancy periods can make use of thermal mass to control internal temperatures during the day. The thermal mass is typically provided by concrete floor slabs with either an exposed soffit or underfloor ventilation system. The slab acts as a heat sink which absorbs excess heat generated from electrical lighting, equipment loads, occupancy loads and solar gain and since the material has a relatively low radiant temperature, a comfortable internal temperature can be maintained. As well as reducing the peak internal temperature a building with high thermal mass is able to delay the temperature peak by up to six hours. In an office environment this will typically occur in late afternoon, after the occupants have left. At night cool air is allowed to enter the building to remove the heat stored in the slabs in preparation for the process to begin the following day.

Floor slab configurations
Exposed slab – The quickest and simplest way of providing a high degree of thermal mass in a building. When used in conjunction with natural ventilation this form of construction can provide around 15-20 W/m² of cooling. Profiled or coffered



Graph showing impact of thermal mass of internal temperature. With high thermal mass the temperature fluctuations are less extreme and the peak temperature is delayed by up to six hours.



Exposed slab: Underside of slab is exposed and absorbs heat from roof below. Night purging uses cool air from outside to remove heat.

slabs have an increased surface area which improves convective heat transfer and improves thermal performance. Profiled slabs have a cooling capacity of around 20-25W/m².

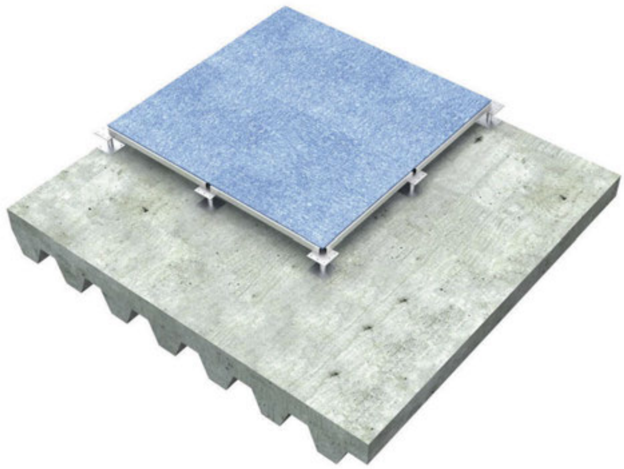
Exposed slab with underfloor ventilation – Raised floors are common in office environments with the primary function of routing power and communication cables. This configuration system can also be used to provide ventilation via floor outlets via a mechanical system or through natural cross flow. Since air is in contact with both the upper and lower surfaces of the slab, the thermal mass of the whole slab can be exploited and can provide an overall cooling capacity of around 25-35 W/m².

Exposed hollowcore slab – Precast hollowcore slabs have tubular voids extending through their length. Air is passed through these voids at low velocities allowing it to be in contact with the concrete for a prolonged period and increasing the transfer of heat to the slab. A cooling capacity of up to 40W/m² can be achieved with this system.

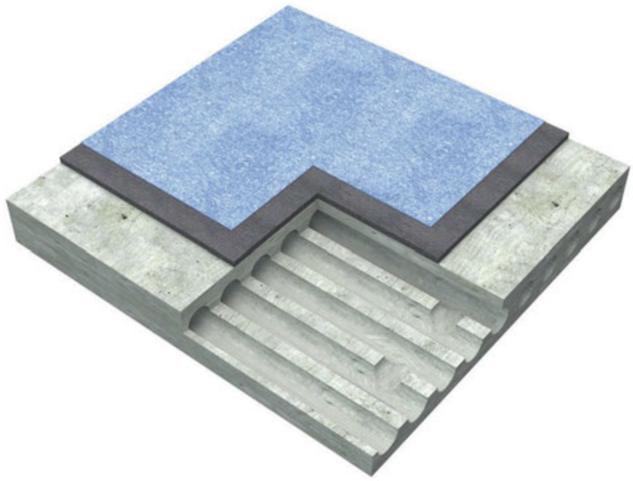
Exposed slab with water cooling – The use of water rather than air to cool floor slabs enables higher cooling capacities to be achieved by increasing the rate of heat transfer. Typical systems use a plastic tube embedded within the concrete slab through which water is circulated. This application is particularly suited to buildings whose occupancy patterns or local climate do not allow for night-time cooling as a constant flow can be maintined if necessary. A cooling capacity of around 60-80 W/m² can be achieved with this system and it is equally suited to providing winter heating solutions by running warm water through the slab.

Locating thermal mass

For maximum effect, thermal mass should be located inside a building and insulated from external temperatures. Brick walls offer little thermal mass benefit as the brick material is on the outside of an insulated cavity. Similarly thermal mass within a building loses its effectiveness if it is isolated by lightweight finishes such as dry linings or suspended ceilings.



Raised floor: Both faces of the floor slab are exposed to the air which increases the transfer of heat. Cool air can be circulated beneath the floor to cool the slab at night.



Hollowcire slab: Cool air is passed through voids in the slab to remove heat either at night or during occupancy.

An introduction to embodied energy

The energy consumed in the manufacturing of construction material, its transport, its installation and ultimate renovation or demolition is almost always in the form of non-renewable fossil fuel which produces carbon dioxide (CO_2) emissions as a result of these processes. Atmospheric emission levels are widely regarded as one of the most significant considerations associated with the production of building material and, particularly the emission of CO_2 as the chief contributor towards climate change.

The energy embodied in a building material can be considered to be the sum of the energy used in the manufacture of its components, transportation, assembly on site, together with its ultimate demolition and associated recycling. This embodied energy must be seen in relation to the overall amount of energy expended by a building during its lifetime. The total energy consumption of a building can be considered to be the sum of its embodied energy and its operational energy consumed in using the building during its lifetime. Embodied energy currently accounts for only around 10% of the lifetime energy expenditure of a building, based on a 50-year period. However, levels of the operational energy component are set to reduce significantly. This will be done by improving thermal insulation and by a mixture of passive and active controls that control ventilation heat loss and solar heat gain. This would make the embodied energy component in a building even more significant.

Since reductions in the operational energy component are currently being researched, the relationship between embodied energy and operational energy is not discussed here. Instead, this text focuses on how typical forms of construction might best be combined to create buildings of low embodied energy, regardless of the individual levels of embodied energy in the materials used.

Embodied energy values

The figures for embodied energy used in this chapter are those quoted by The Institution of Structural Engineers of the United Kingdom in their publication "Building For A Sustainable Future: Construction Without Depletion", which lists the total embodied energy for seventy-one materials including transportation but excluding demolition or recycling. These figures are consistent with an earlier U.K. Steel Construction Institute's publication, "A Comparative Environmental Life Cycle Assessment of Modern Office Buildings" by K J Eaton and A Amato. Precision in measuring embodied energy is difficult when the amount of energy used in the production, transportation to site and installation of the material varies between locations.

Levels of embodied energy in building materials

Current research has focused on levels of embodied energy in individual materials used in buildings rather than in specific types of construction, which use a combination of materials. The body of research reveals that natural materials such as stone have low embodied energy. Reinforced concrete, bricks, concrete blocks, timber elements and other wood products such as laminated timber and plywood have higher EE values. Timber, excluding transportation, has a very low embodied energy, but much of the timber used in highly industrialised countries is imported, which forms a relatively high proportion of the total embodied energy level of this material. The embodied energy of steel is higher still, with aluminium having by far the most embodied energy of the common building materials. These findings have led to an assumption that natural materials are more sustainable.

Comparisons of embodied energy in typical forms of building construction

In order to compare levels of embodied energy, two worked examples have been taken for comparison. The first example is a set of options for the structural frame of an office building. Similar spans and loadings are used for a wide range of buildings in the U.K., from offices to educational buildings and hospitals. The structural frames investigated use either steel or reinforced concrete. Timber was not considered as it is not economical for large spans with high loadings. The second example comprises a set of options for wall cladding in different materials. The two sets of examples could be used as part of the same building. Either a steel or concrete frame could be used with any of the cladding options.

An example of a building designed with an emphasis on low embodied energy materials: The Centre for Alternative Technology, Wales, U.K.

The examples were intended to be used to find out how materials for both structure and external wall might best be used both separately and together to achieve low levels of embodied energy in their construction. Examples of roofs were not used since they would have broadened the scope of investigation too widely into comparisons of construction methods for pitched and flat roofs in various configurations.

The effect of thermal insulation on levels of embodied energy in the wall cladding options was investigated as a separate exercise. Since most forms of thermal insulation can be used with most forms of building construction, a comparison was made between the use of a material with very high levels of embodied energy (expanded polystyrene) and one with very low levels of embodied energy (mineral fibre insulation). Taking the 3x3 metre bay with a 1x1 metre window used in the cladding options, it was found that expanded polystyrene accounted on average for 15% of the overall embodied energy of the wall panel. Mineral fibre insulation accounted for on average less than 1% of the overall embodied energy. Since the type of insulation used with a particular form of construction has such a large effect on the level of embodied energy, it was decided to omit thermal insulation from the following worked examples.

Example 1: options for an office-building frame

The level of embodied energy in a 6000 mm wide x 16000 mm long bay with intermediate columns was calculated for each option. Four options were examined: in-situ concrete flat slab with concrete columns; prestressed precast concrete hollowcore (wide plank) deck on a steel frame; light gauge steel floor cassette on a steel frame; composite concrete steel deck on a steel frame. The structural options are based on alternative designs for a typical office building. For each option the weight of structural components was multiplied by the embodied energy (GJ/m^2). Embodied energy levels for each material were then added together to find the overall value for the complete structural assembly. Fire protection was added to the steel options to make them as closely comparable as possible. For each option, the total embodied energy was derived from the summation of the calculated embodied energy for each component. In all options an alternative has been calculated using multi-cycle steel (steel that will be recycled at the end of the building's life) and recycled steel reinforcement bars (recycled from an Electric Arc Furnace as is common practice) from figures published in The Steel Construction Institute's "A Comparative Environmental Life Cycle Assessment of Modern Office Buildings". Crushed concrete can replace up to 20% of aggregates in structural concrete, but the embodied energy would not change substantially as aggregates have a low embodied energy, therefore this option was not considered. The columns in all options have been omitted, as their contribution is deemed insubstantial.

The results are as follows:

1a) In-situ concrete flat slab (virgin steel reinforcement) 1.73 GJ/m^2

1b) In-situ concrete flat slab (recycled steel reinforcement) 1.41 GJ/m^2

2a) Precast concrete hollowcore floor / steel beams (virgin steel) 1.27 GJ/m^2

2b) Precast concrete hollowcore floor / steel beams (multi-cycle steel) 1.05 GJ/m^2

3a) Light gauge steel floor cassette / steel beams (virgin steel) 1.46 GJ/m^2

3b) Light gauge steel floor cassette / steel beams (multi-cycle steel) 1.20 GJ/m^2

4a) Composite concrete steel deck / steel beams (virgin steel) 2.28 GJ/m^2

4b) Composite concrete steel deck / steel beams (multi-cycle steel) 1.78 GJ/m^2

It is clear from this information that the construction technique with the highest embodied energy is the composite concrete steel deck. The lowest figure was for the prestressed precast concrete hollowcore floor supported off a steel frame, closely followed by the light gauge steel floor cassette supported off a steel frame. The embodied energy for the composite concrete steel deck solution is 80% greater than the prestressed precast hollowcore solution and 56% greater than the light gauge steel cassette solution. The four options were re-examined using multi-cycle structural steel and recycled reinforcement bars. The results remained similar with the exception that the embodied energy for the light gauge steel cassette solution was only


very marginally greater than the precast concrete hollowcore solution. In conclusion, the options with the greatest degree of material efficiency and prefabrication resulted in solutions with the least embodied energy. The present popularity of pre-assembled modular construction appears to be in tune with sustainable construction.

Example 2: options for wall cladding
The level of embodied energy (EE) in a 3000 x 3000 mm (10ft x 10 ft) bay of a facade was calculated for each option. Since thermal insulation has been omitted from the calculations, the U-value of each construction is not considered here. For each cladding panel option, it was assumed that each panel would be supported by a floor slab/perimeter beam both top and bottom. Components within each panel were sized accordingly. Like the structural options, levels of embodied energy were calculated based on the weight of each material used in the assembly multiplied by the EE value for each.

The results are as follows:
1) Timber framed wall+double glazed window 0.48 GJ/m^2
2) Timber framed curtain walling 0.82 GJ/m^2
3) Reinforced concrete panel+dg window 0.70 GJ/m^2
4) Facing brick cavity wall+double glazed window 2.33 GJ/m^2
5) Facing brick cavity wall with steel shelf angle 2.54 GJ/m^2
6) Aluminium framed curtain walling 2.48 GJ/m^2
7) Steel framed curtain walling 1.26 GJ/m^2
8) Bolt fixed glazing 0.80 GJ/m^2

The wall configuration with the lowest embodied energy is the timber framed wall. The highest are the aluminium framed curtain walling and the facing brick cavity wall. When steel is used for the framing solution, the embodied energy of the curtain walling drops to approximately half the level of aluminium.

Among the options for opaque walls with a 1 metre square window, levels of embodied energy are relatively similar between timber and reinforced concrete but the brick cavity wall has almost 5 times the embodied energy of the timber framed wall. Among the glazed curtain wall options, levels of embodied energy are higher for steel than timber but bolt fixed glazing provides the lowest solution. With the obvious exception of aluminium and brick cavity, the levels of embodied energy are relatively similar for a given configuration of opaque and glazed areas.

The EE level of facing brick is nine times that of concrete block and twice that of common brick. Bolt fixed glazing minimises the use of materials, using glass as panels which are unrestrained along their edges. The use of aluminium framing results in there being three times as much embodied energy in the frame as in the glass. The use of steel framing is much better, using 60% more embodied energy compared to the bolt fixed glazed units. Nevertheless, from a performance point of view, there are problems to overcome concerning thermal breaks in steel.

What are the best mixes between high and low embodied energy materials in typical forms of construction?
In the examples, the combination of materials consuming the least EE tends to be the combinations using the materials most efficiently. A building constructed from a high embodied energy material, such as a steel framed building clad in glazed panels, uses far less material than an equivalent design in reinforced concrete and has a lower level of embodied energy. What is surprising is the comparison between different types of glazed walling and cavity brick construction. An uninsulated cavity wall with regularly spaced windows and a shelf support angle has three times as much embodied energy as double glazed bolt fixed glazing, but both forms of construction have a similar U-value.

The exercise suggests that low levels of embodied energy can be achieved using mixed methods of lightweight and heavyweight construction in a single building. From the above examples, the best combination might be a timber clad precast concrete solution or a bolt fixed glazed facade with a light-gauge steel cassette solution. The worst combination would be a brick clad composite concrete steel deck solution, but this building combination has been extensively constructed in recent years.

This puts greater emphasis on the need for an efficient use of material where high embodied energy materials are used. Aluminium seems to be a very extravagant material in terms of

energy. This is mainly because when used in building components, aluminium is required to have high rigidity as well as high strength. The material is used for the precision of its extrusions and castings rather than for any real qualities of lightness. This is not the case where aluminium is used in other industries. In aircraft design, aluminium is used for its strength and lightness. Rigidity is much less important, as part of the aircraft can deflect without significantly impairing performance.

Recycling and sustainability

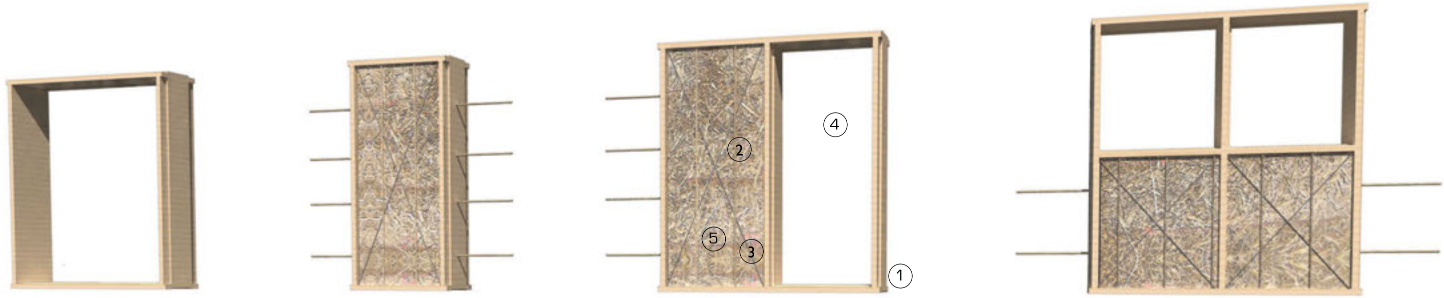
In attempting to reduce the embodied energy level in the construction of a building, the levels of EE in different materials might suggest that prestressed concrete and timber are preferable to steel and aluminium. However, these criteria must be seen within the overall context of recycling non-renewable resources and a sustainable approach to the use of renewable resources.

Bricks and blocks can be re-used, but are not used in many parts of the world, where the ready supply of timber, for example, can provide a more appropriate material. Steel and aluminium, with much higher embodied energies, are more easily recycled. Once manufactured, these metals are in a fairly 'closed' cycle of re-use. Aluminium is one of the easiest materials to recycle and at reasonable cost. Energy savings are made by recycling the material. The conversion of scrap aluminium back to high-grade metal requires only about 5% of the energy needed to make the same amount of metal from bauxite.

The manufacture of building materials has a direct impact on our environment. Removing raw materials from their natural environment can cause long-term damage to the environment. The extraction of ores to make steel and aluminium leaves holes in the ground. Mining areas can be re-instated. Trees cut down as a result of timber production can and should be replanted and replaced. The cost of this work will have to be added into future calculations of embodied energy. Care should be taken to establish the source of timber. An area of tropical forest corresponding to the size of the United Kingdom is being destroyed or seriously degraded every year. Therefore, timber should be selected from an audited and sustainable forest or from plantations already established on degraded land. Planning the life of the building as appropriate in environmental terms will become a higher priority. This might lead to the preassembly of shop-constructed components which can be readily adapted to suit changing needs using a kit of parts or can be dismantled and reassembled as the need arises. This might lead to a scenario where modern high embodied energy buildings will be demolished and recycled rather than maintained, but masonry buildings of heritage may be allowed to remain without fear of being recycled.

In conclusion, a well conceived light steel structure with bolt fixed glazed facades or a prestressed precast concrete structure with a timber facade may provide an optimised solution for low embodied energy and, hence provide a sustainable construction. Both solutions rely on a high degree of specialist prefabrication and preassembly. This is good news and bad news for traditional construction. The focus should be on prefabrication and efficient use of carefully selected materials. It appears that prefabrication and preassembly can provide the means to a future in construction that is flexible, adaptable and sustainable.

Embodied energy values used	GJ/tonne
1) Aluminium alloy	200 GJ/tonne
2) Synthetic rubber	150 GJ/tonne
3) Structural steel	26.8 GJ/tonne
4) Steel used in windows	31 GJ/tonne
5) Float glass	15 GJ/tonne
6) Softwood	13 GJ/tonne
7) Plasterboard	2.7 GJ/tonne
8) Facing bricks	11.7 GJ/tonne
9) Mortar	0.84 GJ/tonne
10) In-situ concrete structure above ground	1.09 GJ/tonne
11) Steel reinforcement	26.8 GJ/tonne
12) Plywood	17 GJ/tonne
13) Concrete block	1.31 GJ/tonne
14) Wall insulation	35 GJ/tonne
15) Plastic	150GJ/tonne



ModCell panel module.
ModCell is based on a 3 bale wide by 8 bale high standard module. A typical panel is approx 3.2m x 2.9 m x 510 mm unit.

Details
1. Timber frame
2 Straw/hemp/paper bales
3. Steel rods
4. Openings for windows doors etc.
5. Lime based render (applied over bales)

3D view of modularised components that can be created using the modCell system

Key U Value data
ModCell Straw 450mm 0.13
ModCell Hemp 300mm 0.26
ModCell Hemp 500mm 0.16
ModCell Paper 200mm 0.16
Building Regs Cavity Wall 0.35

ModCell is a modular system of building utilising renewable materials such as straw bales, hemp and paper as its insulating core. These off-site manufactured panels mean that buildings can be quickly and efficiently installed on site making it ideal for large scale commercial, school or office buildings.

Each panel is made up of a sustainably sourced timber frame into which the insulating material is inserted. The straw bale and paper panels are then kept in place by steel rods with all the panels finished off with a layer of lime render which as well as being a natural product also has the essential attribute of providing a breathable layer to the panels.

The diagram above illustrates some of the various modules that can be utilised in construction using panels of a certain width and height according to the individual project. Within these panels open areas for windows and doors can be left available according to the design. Currently these units have been used as loadbearing elements up to three modules (approximately 9 metres high).

A major advantage of these panels is their thermal performance which is up to 3 times higher than the current building regulations. As a result, buildings using ModCell can have zero heat requirements, saving money and CO2 emissions. The main disadvantage of these panels is with the thickness of the panels which typically are approx. 450mm thick.

The current range of ModCell panels uses three types of cellulose insulation cores (CIC):
ModCell straw
ModCell hemp
ModCell paper
Each has a particular set of performance criteria, designed for different applications:

ModCell straw uses straw bales as its insulation core. Straw is an agricultural by-product , and almost 3 million tons are disposed of annually in the U.K. alone. The straw panels creates a mass market use for a valuable and renewable resource that would normally be chopped and ploughed back into the ground. ModCell straw has exceptional insulation properties and can be used both dry lined and rendered.

ModCell hemp uses hemp mixed with lime in the panel; these panels are slightly thinner in depth to provide similar thermal mass benefits to that of the straw panels.

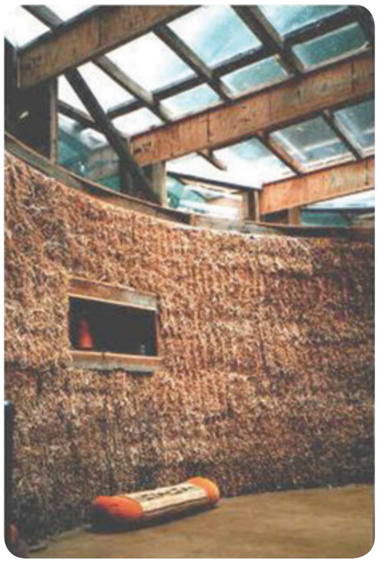
ModCell paper uses recycled paper which provides a lighterweight construction alternative to straw and hemp with again similar thermal advantages.

ModCell panels are constructed off-site but in order to minimise energy in transport in existing projects 'flying factories' have been set up for manufacture. These have been located within 10 miles of the site in agreement with local farmers who have been able to provide a source of straw and a suitable location to assemble the modular panels. By using local straw, skills and labour, the project's value can also be kept within the local economy.

ModCell straw panel being constructed (above) and Modcell hemp (below)

The Archimedia Project, Bristol, U.K. ModCell Straw

Strohaus, Switzerland. Architect: Felix Jerusalem



Strawbale dance studio, London, U.K.

Straw

Straw bale construction is a building method that uses straw bales as structural elements and as thermal insulation. As with the ModCell system it is a material that excels in the areas of cost-effectiveness, energy efficiency and ease of availability. A typical bale of straw has a U-value of 0.13W/m^{2}K.

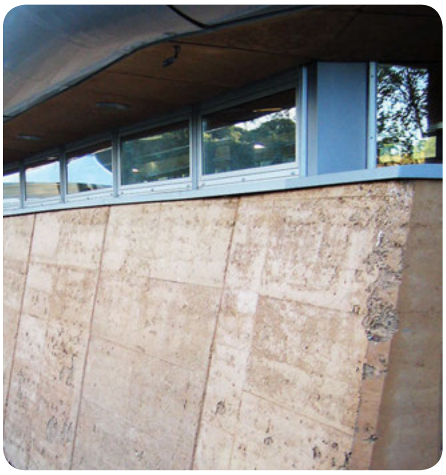
The construction typically consists of stacking rows of bales on a foundation plate with a vapour barrier to protect the straw from damp. These are then tied together with pins typically made with wood or with wire meshes. These walls can then rendered with a lime or earth/clay based mix. Because the building method is so straightforward, people without previous building experience can participate in the design and construction, thereby saving on labour costs.

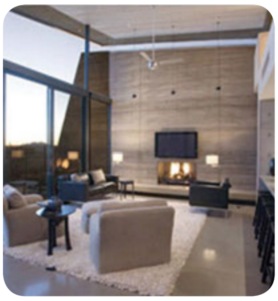
Typically bales created on farms with baling machines have been used, but recently higher-density 'precompressed' bales, or 'straw-blocks', can increase the loads that may be supported.

The main concerns with straw bale construction like many of these natural building materials have to do with keeping the bales dry. Splash back from rain bouncing up from the ground, rain causing high humidity or wind driven rain are the main problems. These however can be easily mitigated with adequate foundation design, a suitable render and protection by large overhanging roofs. They are also constructed of breathable materials and need not be waterproofed, though they must be weatherproofed.

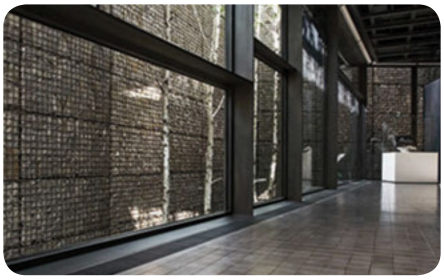
Strawbale classroom at Avon Tyrrell, New Forest, U.K.

The Straw House, London, U.K. Architect: Jeremy Till and Sarah Wigglesworth




Left to right: Entrance building, Eden Project, Cornwall, U.K. Detail of rammed earth wall, The Redding Residence, Kendle Design Collaborative, Scottsdale, Arizona, U.S.A. Detail of example of rammed earth colouration through various soil types

Leeum - Samsung Museum of Art in Seoul, South Korea. Architect: Jean Nouvel

Apartheid Museum, Johannesburg, South Africa

Compacted earth construction is a technique used in the building of walls using the raw materials of mud, chalk, lime and gravel where moist loose earth is compacted in layers between shuttering or formwork to construct a wall.

It is an ancient building method that has seen a revival in recent years. The nature of the materials used means that it is non-combustible, thermally insulating and very strong and hardwearing. It also has the added advantage of being a very low cost and simple way to construct walls.

The exact composition of the soil and water in rammed earth walls is critical for it success. A small proportion of cement or lime is sometimes added to the mix as a stabiliser to correct any deficiencies in its make up.

As well as this, good compaction optimises the strength and stiffness of the material. There are three main methods in which to do this:

- Static (block presses)
- Dynamic (rammed earth)
- Vibration (wacker plate)

After compression, the wall frames can be immediately removed and require an extent of warm dry days after construction to dry and harden. The structure can take up to two years to completely cure, and the more it cures the stronger the structure becomes. When the process is complete it is much like constructing a hand-made wall of solid rock.

Like other natural building materials rammed earth walls need to be protected from heavy rain. They are typically constructed on top of conventional footings or a reinforced concrete base, sometimes with extra ground insulation.

One of the significant benefits of rammed earth constructions is their excellent thermal mass (a typical rammed earth wall is about 360 mm); it heats up slowly during the day and releases its heat during the evening. On the other hand, rammed earth is not a good insulator and is often insulated in colder climates. The thickness and density of the walls lends itself naturally to soundproofing and the materials used in the walls make them highly fire resistant Rammed earth structures do utilise locally available materials, which means that they also have very low embodied energy and generate very little waste.

Coloured oxides or other items such as bottles or pieces of timber can be used in construction to add variety and texture to the finished wall.

Gabions are boxes made of metal, plastic or reed mesh filled in-situ with rock or cobbles and used as a basic building unit. Gabions have a long history in civil engineering, as retaining walls and in erosion control but today they are becoming commonly used in structural walls in buildings, particularly as a feature in projects where the cages can be filled with any recyclable material such as glass bottles.

The main advantages of the system are in the low embodied energy and use of local materials as well as providing a large thermal mass to control the internal environment of buildings. How they are weatherproofed is the main disadvantage with an additional layer required in addition to the gabion wall if a sealed environment is required within.

Adobe House, Choisica, Peru

The Cobtun House, Worcestershire, U.K.

Mud-brick, or adobe, is a natural building material made from sand, clay and water, with some kind of fibrous or organic material (sticks, straw, dung) which is shaped into bricks using frames and dried in the sun. It is similar to cob and mud-brick, although it requires a higher clay content than that for rammed earth. Excessive amounts of clay however may lead to shrinkage cracking in construction.

Bricks are typically made in an open frame. The mixture is moulded by the frame, and then the frame is removed quickly. After drying a few hours, the bricks are turned on edge to finish drying. Slow drying out in direct sunlight reduces cracking. Traditionally bricks are made on site in arid countries where there is little risk of rain for the drying period (between 2 and 8 weeks). Today many are made in factories constructed for the project on-site or in the locale.

Basic construction of adobe or mud brick buildings follows the principles of block masonry. The blocks are typically laid in weak cement lime, sand or earth mortar or can be dry stacked.

The main advantage of an adobe wall is in its thermal properties inherent in the massive walls typical in adobe construction. The cost of the material and low embodied energy associated with being found on site mean it has a very low environmental impact.

Adobe structures are extremely durable and account for some of the oldest extant buildings on the planet. However in order to protect them from damage from rain etc coatings renderings or cladding are usually applied to the structure and projecting roofs or from the other structures considered in the design to shed heavy water away from the walls. It is also important that the bricks are protected from damp by building onto a plinth at least 150mm from the ground.

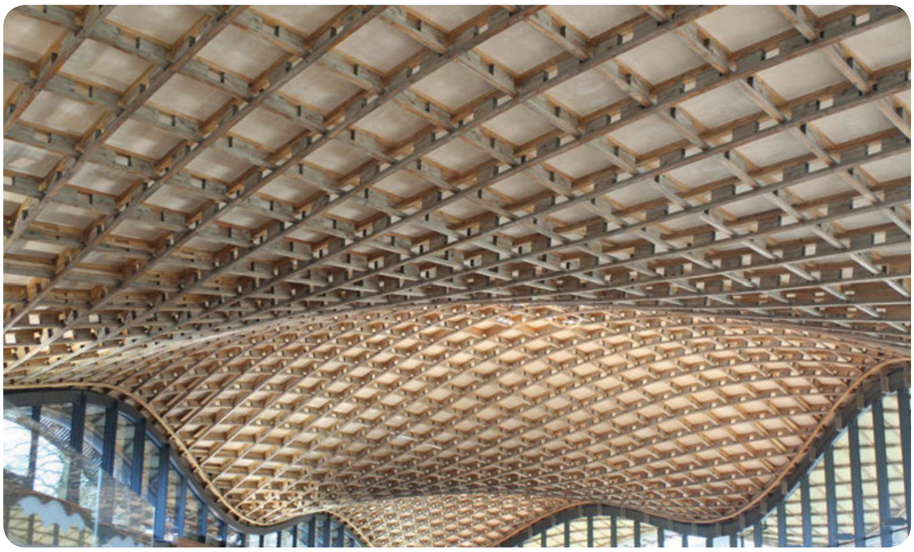
Other disadvantages are with the required thickness of the walls and the labour and time involved in the manufacture of the bricks. Particularly in the U.K. the weather poses a big threat to the construction and maintenance of an adobe/mud brick building. Due to these factors very few examples of this form of construction exist in the U.K. at present.

Cob is a building material consisting of clay, sand, straw, water and earth, similar to adobe. The main advantages of cob as a material is that it can be used to create artistic, sculptural forms using local materials. It is also fireproof, resistant to seismic activity and inexpensive.

In the U.K. cob is most strongly associated with the counties of Devon and Cornwall and in Glamorgan and Gower peninsula in the U.K. Traditionally it was made by mixing the clay-based subsoil with straw and water using oxen to trample it. The earthen mixture was then ladled onto a stone foundation in courses and trodden onto the wall by workers in a process known as cobbing. After drying, the walls would be trimmed and the next course built, with lintels for later openings such as doors and windows being placed as the wall took shape.

The walls of a cob house are about 600mm thick, and openings therefore become correspondingly deep set. The thick walls provide excellent thermal mass and the material has a long life span even in rainy climates if a tall foundation and large roof overhang are present.

Weald and Downland Gridshell, Singleton, U.K.



Above and right: The National Maritime Museum, Falmouth, U.K. Architect: Long & Kentish.

Visitor Centre, Savill Gardens, Windsor, U.K.

Green wood

As opposed to regular timber used in construction, green wood is timber in which the cavities contain water.

The primary reason for use of green oak, historically, was to enable it to be worked with hand tools. Dry oak is very hard and extremely difficult to saw, plane or chisel. Today the main reason is environmental in terms of the cost and time involved in drying. The rate of drying of oak is approximately 25mm per year, so that a 300 x 300mm timber would take 12 years to dry for construction.

The cost of freshly felled (green) oak is considerably cheaper than the dried product after processing. Freshly felled at the roadside a piece of timber costs approximately one tenth the cost of the material after processing at the sawmill, air drying (2 to 3 years) and then the kiln dry.

Green oak, like other forms of timber, is a carbon neutral product that has absorbed CO2 throughout its natural lifespan and does not emit carbon dioxide when it is felled or used for construction purposes.

It is also replenishable. Quick growing hardwood species like spruce and oak are ideal woods with which to build, providing load-bearing strength and durability.

Green oak frames are considered attractive because they showcase the skills of craftsmen, particularly the joints which are fixed using oak pegs. This is still done because metal fixings would corrode in the moist, acidic environment of the unseasoned wood. This method requires specific skills and techniques for the construction of green wood buildings, as well as the connections and detailing of buildings need careful consideration to compensate for any movement in the drying process.

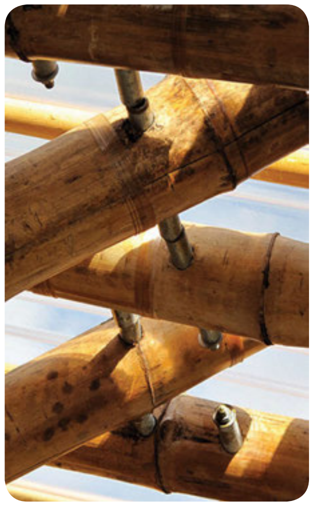
Bamboo

When treated, bamboo forms a very hard wood which is both lightweight and exceptionally durable unlike many other woods, which can be heavy and soft.

Traditionally, it is used in tropical climates in elements of house construction, scaffolding and as a substitute for steel reinforcing rods in concrete construction.

The main advantage environmentally is in bamboo's rapid growth which is very fast, up to 25metres over 6 months,

O Centro Cultural Max Feffer, Brazil, Architect: Leiko Motomura
Connection detail below



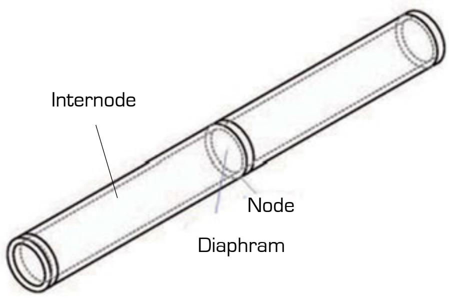
O Centro Cultural Max Feffer. The largest bamboo structure in Brazil. Architect: Leiko Motomura

METI School in Rudrapur, Bangladesh. Analogue construction using local resources.

with three to five years to mature. This unique characteristic makes it one of the most rapidly renewable construction materials available as well as a fairly inexpensive one. In the United States and in France, it is possible to have houses made entirely of bamboo, which are earthquake and cyclone-resistant and internationally certified.

However, bamboo wood can become easily infested with wood-boring insects unless treated with wood preservatives or kept very dry. The main disadvantage in terms of use as a global building material is in the current limited regions in which it is grown. Bamboo can be grown in a variety of climates including the U.K. but currently it is more economical to import the material in from existing bamboo plantations which incurs large cost to the environmental accreditation of the material through transportation.

The structure of bamboo consists of hollow cylindrical stems called culms. The culms are segmented into nodes and internodes. This structure gives the material very good compressive and tensile strength in construction as well as the huge benefit in weight in comparison to other wood materials.



Modular system with soil substrate:
Eco Store, London, U.K.

Tensioned wire green wall, Heathrow Airport, U.K.

Modular planting unit

Green wall design

Green walls are living, self-regenerating cladding systems that allow building facades to be covered completely with vegetation. The concept has been in existence for centuries. In the Mediterranean, plants are often trained over facades to act as a natural means of climate control. Fruit plants in particular thrive in this situation since the heat stored in the backing wall is particularly conducive to plant growth.

In recent years, however, the use of 'living walls' has expanded into the public realm to the extent that vegetation can now be seen adorning the facades of museums, shops, community centres and offices.

Living walls can help to link buildings with their natural environments. In cities large planted facades have a dramatic visual effect and can act as an oasis of nature within what may otherwise be barren and industrial surroundings. While climbing plants can be seen as temporary additions to buildings, technological advancements have enabled living walls to become fully integrated facade systems in new developments.

Advantages and disadvantages

Living walls offer a number of environmental benefits:
Planted facades can help regulate internal temperatures. In the summer the vegetation shades the wall from the sun and can reduce daily temperature fluctuations by up to 50%. In the winter an evergreen facade will provide insulation not just by trapping air between the planted zone and the wall, but also by reducing the wind chill on the facade.

Living walls can also benefit the surrounding environment by altering the local microclimate. Vegetation helps with noise absorption and can lead to an improvement in the atmosphere through the dust trapping effect and their absorption of CO_2. Planted facades also help with the retention of rainwater after heavy rainfall. They reduce intense local heat gains experienced in cities and create a cooling effect as a result of evaporation.

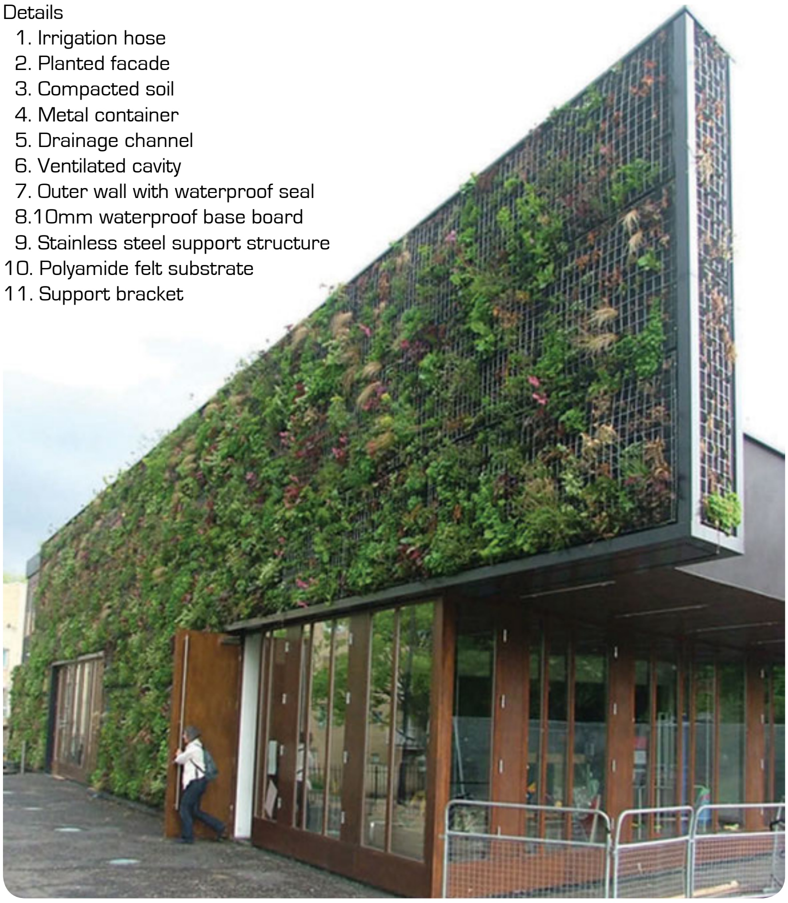
Living walls are an excellent way of introducing biodiversity into urban environments although the presence of mice or insects may cause problems.

Without proper planning living walls can cause building damage. Planting systems can impose additional loads on external walls. They can also affect the structural balance of the building. Roots and tendrils can break through waterproof seals or force their way behind cover strips and window abutments and without regular maintenance, leaves and other dead matter can block gutters and rainwater pipes.

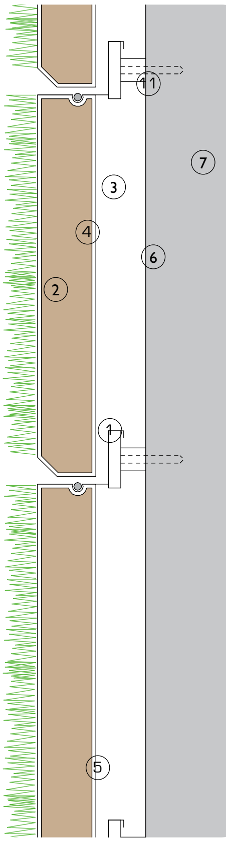
System overview

Living walls fall into two main categories: Individual point plantings require almost no supporting structure and there-

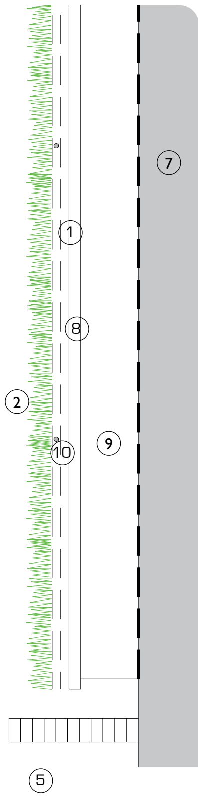
Details
1. Irrigation hose
2. Planted facade
3. Compacted soil
4. Metal container
5. Drainage channel
6. Ventilated cavity
7. Outer wall with waterproof seal
8. 10mm waterproof base board
9. Stainless steel support structure
10. Polyamide felt substrate
11. Support bracket



Modular system with rockwool substrate:
Paradise Park Childrens Centre, London, U.K. Architect: DSDHA



Modular green wall system



Hydroponic green wall system

fore provide the simplest method of installation to both new buildings and existing facades. Plants are grown in individual containers and trained across trellises or wires fixed back to the facade. Because plants grown in this manner will have a maximum height to which they will grow it is often necessary to distribute many containers across the facade to achieve growth beyond this range. It can take many years to achieve a dense, homogeneous coverage.

Planting beds, laid vertically on the facade, allow for full surface coverage. Plants grow horizontally out from the wall rather than vertically up it and this allows for a wider range of plant types to be used.

Living wall systems fall into two categories, distinguished by their method of plant cultivation:

Modular systems
Modular systems use cassette elements filled with a soil substrate that plant roots draw nutrients from. The modular units are usually cultivated off-site until they reach maturity. These modules can then easily be fixed to a supporting structure on site to complete the facade.

Because of their modular nature, substrate walls often take on a chequerboard pattern, however it does give great flexibility and allows panels to be replaced individually if necessary.

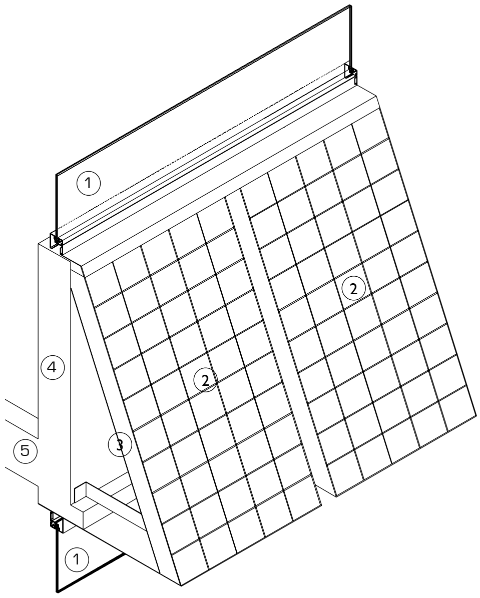
Hydroponic walls
Hydroponics is a method of growing plants without the need for a soil substrate. An irrigation system distributes nutrient enriched water droplets across the facade which are absorbed directly by the roots.

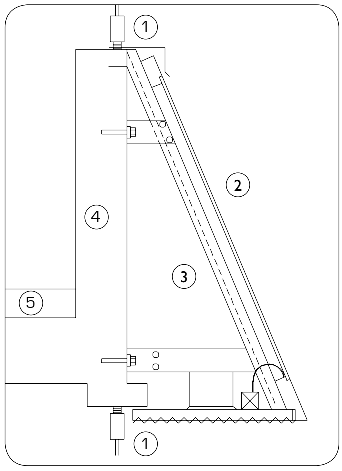
Hydroponic walls have a much reduced constructional depth and impose significantly reduced loads on the building facade (around 30kg/m2) when compared to substrate systems.

The standard form of construction provides felt pockets in which plants can be individually located. Roots spread radially within the felt and can support plant growth of up to six metres. Horizontal irrigation pipes run along the outer edge of the felt at the top of the facade. The supply of water is computer controlled to ensure the regularity of operation is in keeping with external conditions. The exact calibration of the system needs to be calculated prior to installation taking into account the facade dimensions, plant types and local climate, to ensure adequate supply of nutrients to all plants.

With correct cultivation and maintenance living walls have a lifespan of around 30 years.

Government Training Centre, Herne-Sodingen, Germany.
Architect: Jourda Perraudin.





Details
1. Window
2. Photovoltaic panel
3. Supporting frame
4. Structural wall
5. Floor construction

Photovoltaic panels

Photovoltaic (PV) cells are used to generate electricity from sunlight. The power generated is then used inside the building to contribute to the electrical demands of the building and, in some cases, the power generated can be sold back to the electricity supplier. Electricity is generated in arrays of cells set in panels on roofs and facades. The orientation of panels is important. Those inclined close to the horizontal produce more electricity annually than those inclined vertically. Panels are set as close as possible to the angle at which the most amount of electricity is generated over a one year period, taking into account the varying path of the sun during that period and the effects of diffused solar radiation. Panels comprise a glass substrate coated with tin oxide, forming a transparent electrode, which is covered with layers of silicon together with a coat of aluminium film, which forms the other electrode. Particles of ultraviolet light called photons interact with electrons in the semi-conductor to convert sunlight into direct current electricity. PV cells are of three types: multi-crystalline, which produces the most amount of power per unit area, mono-crystalline, which produces less but is cheaper, and the thin film type which is currently made only in one fixed panel size but which is yet cheaper and can be fixed into a glazed walling system.

The photovoltaic process has the advantage of requiring no moving parts. It requires no fuel and needs relatively little maintenance. The amount of energy required to manufacture the PV cells and deliver them to site is estimated by manufacturers to be equivalent to the amount of energy delivered in the first three years of use; the PV installation will continue to produce power for the next twenty years or more.

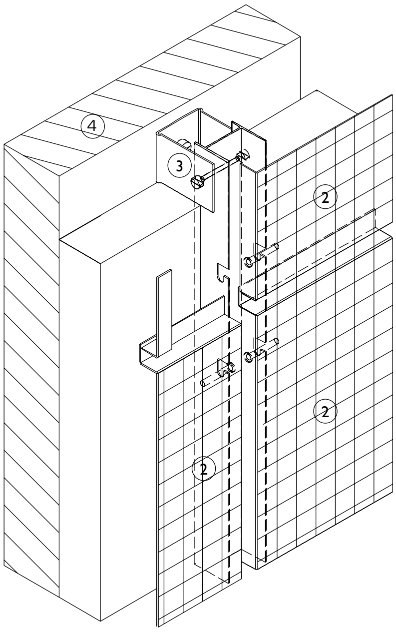
A sampled photovoltaic panel installation

An early large-scale PV installation, from which a relatively long performance has been recorded, is at the University of Northumbria in England. The output of electrical power fluctuates with weather conditions and it is necessary to supplement the supply with electricity from conventional sources. Daily operating periods range from fifteen hours in May to eight hours in January. It is estimated that the installation paid back the energy used in the manufacture of the cells within three years and is still expected to produce electricity for a further 20 years. However, the cost of generating electricity is about four times the current commercial rate. The PV cells are integrated into the facade with a rainscreen cladding system. The cladding is inclined at 26º to the vertical, also providing passive solar shading. Ventilating the void behind the panel disperses heat, a by-product of the photovoltaic process.

Here, the array of PV cells is divided into a series of units 3.0 x 1.36 metres. Each panel is demountable for ease of maintenance or replacement. The cells are bonded to an extruded aluminium frame with structural silicone. Excess electricity can be exported to the electricity supply company. The electricity generated meets 50% of the building's electricity needs in summer and 10% in winter, which averages out at 30% over a one-year period.

Solar heating

Solar heating systems consist of collector panels that absorb heat from solar energy to warm circulating water. Heat absorbed by the water is transferred to a storage tank by pumping or when positioned above the collector the two components form a thermal circulating system. In the latter case, the thermo-siphon effect of water movement is created by the density



Daggett Solar Farm, California, U.S.A.

Solarchis Solar Houses, Japan. Architecture Studio and Maeta Concrete.

difference between hot and cold water. The heated water is normally used to exchange heat with a building's system water, which is then distributed around the building as required for either heating water or as domestic hot water. The amount of heat generated is significant and whilst it is currently suited to climates that have abundant sunshine for much of the year, the performance efficiency has developed to the extent that Northern European states can also benefit.

Collector panels should ideally be orientated to face south and in the U.K., they should be angled at 45^{0} from the horizontal. Panels traditionally consisted of sheets of clear high light transmission glass that allows maximum solar radiation penetration, trapping this radiation to be absorbed by the receiver surface. This surface is a copper base plate that transmits the heat to a continuous pipe fixed to its rear face. The pipes are enclosed in thermal insulation to reduce heat loss to the air. The most popular types of panels currently in use are: a) flat plate collectors, b) vacuum flat plate collectors and c) evacuated tube, (the latter being the most efficient over a typical annual temperature/solar radiation yearly profile, whilst the addition of a vacuum void to flat plate collectors significantly improves their efficiency).
Solar absorbers have been used for many years to provide warm water of up to 50^{0}C for swimming pools. They consist of special solar absorbing high-grade rubber mats with integral water flow channels for circulating the pool water. They can also be used for domestic warm water supply.

A recent example is the Solarchis Housing System in Japan, set up by the Solar Architecture Studio and Maeta Concrete Industry Ltd. Demonstration houses built in the Yamagata Prefecture, Japan, use roof-mounted solar water heaters in conjunction with a photovoltaic array on the roof and a wall construction with high thermal mass internally and thermal insulation fixed externally. The Iyama House has a solar water heater installed in a transparent roof that produces domestic hot water at 50ºC in a 300 litre storage tank. Food is cooked mainly by a solar steam cooker with the support of an electromagnetic induction heater which uses high-temperature solar domestic hot water from a 20 litre storage tank. The House of the Sun (above) has a system of evacuated tubular solar collectors heating water stored in a 300 litre tank. The cooking system is similar to that used in the Iyama House.

Devices for obtaining hot water directly from solar energy have been in development since the 1850s. An early example was a boiler and power plant for water pumping built near Cairo in 1913. It consisted of five long parabolic mirrors, each 4.2 metres wide by 62 metres long. Steam was produced at slightly above atmospheric pressure and used to drive a 20hp water pump. It was abandoned during the First World War. Modern solar furnaces still use a similar system of mirrors. Recent developments, prompted by the space programme in thermo-electricity and photo-electricity, are used both to run water-heating systems and to generate electricity. Only a few large-scale solar furnaces have been built. The 10.5 metre diameter mirror and heliostat at Montlouis in the French Pyrenees are used for research into materials at high temperatures rather than as an economic source of heat.

A recent installation is that at Daggett Solar Farm, California, U.S.A. where electricity is generated from an array of parabolic mirrors, arranged in long rows, that heat liquid in pipes set into them.

Kitakame Canal Museum, Japan.
Architect: Kengo Kuma and Associates.

Furniture House, Yamanashi Prefecture, Japan. Architect: Shigeru Ban.

Electrical lighting

The two main types of electric light source are tungsten filament lamps or incandescent lamps and discharge lamps.

Incandescent filament lamps

These lamps produce light by passing a current through a thin tungsten filament in a glass bulb containing either a partial vacuum or an inert gas. The filament glows and produces a mixture of light and heat. When an inert gas such as halogen is used, the lamp runs more efficiently as more of the electrical power is converted into light rather than heat.

The most common lamp is the general lighting service (GLS) light bulb. It has clear, coloured or pearl glass and its shape can vary from the common bulb form to spherical or linear. Some bulbs have their end silvered to reflect light upwards, reducing glare. The bulb used for spotlights or floodlights is the internally silvered reflector, or IS lamp. Its characteristic shape is designed to reflect light in a particular direction. A bulb with better directional focus, due to a reflector and a lens at the front, is the parabolic aluminised reflector, or PAR lamp, which is particularly suitable for spotlights and floodlights. Some lamps have dichroic filters in front of the bulb to reduce the amount of heat projected forward of the fitting. PAR lamps are also produced in a tungsten halogen type.

All these three lamps run on mains power (house current). The GLS and IS types last approximately 1,000 hours, while the PAR lamp lasts up to 2,000 hours.

Another type called low voltage tungsten halogen lamps, run off 12 volts and require a transformer. They produce sharply directional beams of light, making them useful for illuminating displays. They can last up to 4,000 hours. They are also used for car headlights.

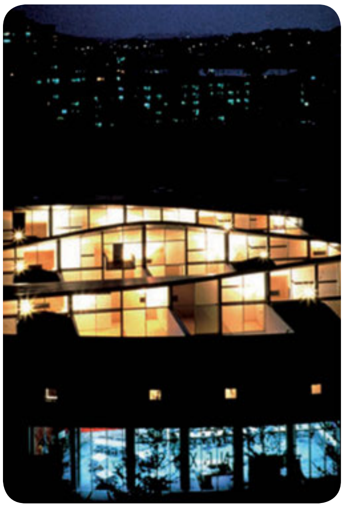
Discharge lamps

These lamps work by discharging an electric current through a gas or vapour in a sealed glass tube or bulb, which causes it to glow. These produce more light and less heat than a tungsten lamp for the same amount of power. The most common type is the fluorescent tube, which is filled with low-pressure argon and proportionally small amount of mercury. The tube is coated with a fluorescent powder, and lengths vary between 320mm to 2400mm (13in to 96in). There is no standardisation in the production of these tubes, and each manufacturer designs lamps to their own specification. Tubes can last up to 10,000 hours, but their efficiency is slightly diminished with use. The low-pressure sodium discharge lamp is another common type used in many countries for road lighting, which has a characteristic yellow colour. It is extremely efficient and lasts approximately 12,000 hours.

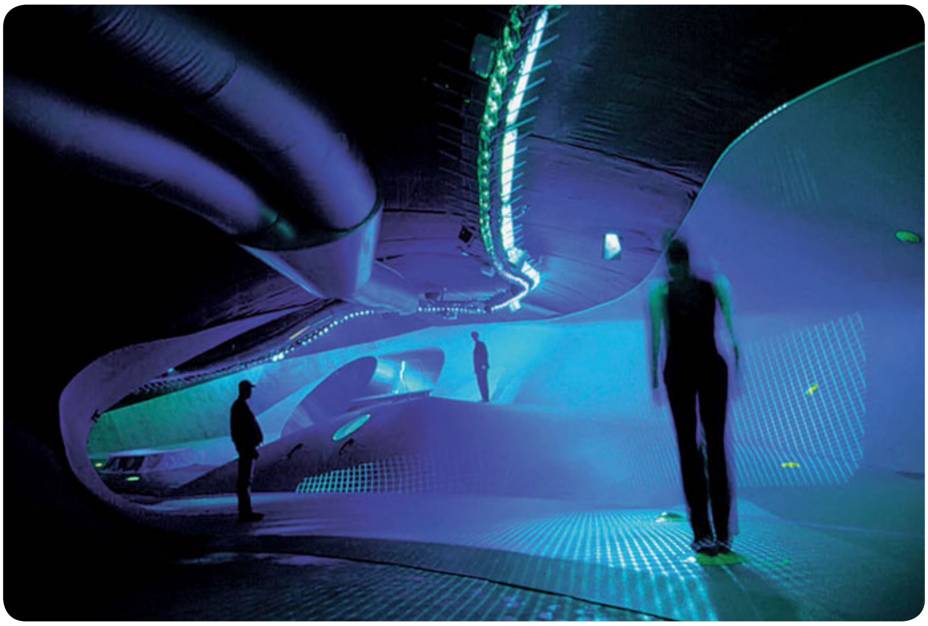
High-intensity discharge lamps have a wider range of colour rendering, use much less electricity and last longer than an equivalent tungsten filament lamp. Mercury vapour lamps are used for lighting large spaces, such as factories, where colour rendering is not a determining factor as they have a yellow/blue colour. Metal halide lamps have excellent colour rendering and are commonly used in all types of buildings from commercial offices to public buildings. Both types of lamp last approximately 10,000 hours. Compact fluorescent lamps, which are used as a substitute for GLS and are compatible with tungsten fittings, offer significant energy savings as a direct substitution for incandescent fittings.

Luminaires

Luminaires are used both to hold the lamp and direct light to the point of use. They are used for both incandescent filament and discharge lighting. A huge range of luminaires is available, each suited to its intended use, location and method of directing light by diffusion, reflection or absorption. Manufacturers'



International Housing Exhibition, FU.K.uoka, Japan. Architect: Rem Koolhaas, Office for Metropolitan Architecture.



Freshwater Pavilion, Neeltje Jans, Holland. Architect: NOX.

catalogues use polar curves to plot the intensity of light radially around a cross-section or long-section through a light fitting. This helps the design team to understand how light from a single fitting will be directed.

Ceiling mounted types

Luminaires on ceilings are either pendant (hanging), surface mounted or recessed. The pendant is the most flexible, allowing light to be thrown up, down or a mixture of both. Surface mounted luminaires can direct light to the side or downward. Recessed fittings throw light downward by concealing the lamp and luminaire behind the ceiling plane. Pendant luminaires are often used where there is no suspended ceiling. They can be fixed directly from the ceiling or housed in a track that is attached to the soffit. Huge varieties of ceiling tracks are available and some incorporate both fluorescent strips and tungsten filament spotlights in a single length.

Ceiling fittings are often co-ordinated with low energy mechanical features such as chilled ceilings and beams. Fittings suspended from a thermally exposed soffit can be designed to incorporate acoustic absorbent material to help address reverberation. Ceiling light fittings can also form part of integrated servicing fingers, often used to service exposed soffit areas, incorporating sprinklers, air supply, chilled beams and high level electrical services.

Wall mounted types

Luminaires on walls can also be pendant, surface mounted or recessed. Pendant fittings are mostly used in conjunction with a track hung from the wall on a cantilevered bracket. Most wall-mounted fittings are surface mounted which can direct light in all directions away from the wall, either directly or by reflection. Recessed wall lights have either a diffuser in front of the lamp or a reflector to avoid glare.

Floor mounted types

Freestanding floor mounted uplighters are often used in offices to provide or supplement office lighting. They are generally better for glare control than ceiling mounted lights. Energy efficiency is lower with this type of fitting as the light has to be reflected from the soffit to illuminate the space.

A recent development in luminaire design is the recessed floor type. These have a cover that is strong enough to walk on and which is designed to minimise glare when looking down at the floor. This type has to be capable of dissipating its own heat generated in use, and as a result the casings are often made from metal alloys with high thermal conductivity such as brass.

Exterior luminaires

Exterior lighting utilises all of the above fixings. Luminaires must be either waterproofed or sheltered from the weather and power supplies must be planned well in advance so as to incorporate cable ways and access boxes into the external works.

Emergency lighting

Emergency lighting allows escape routes and stairs to be sufficiently illuminated in the event of a fire or other emergency. The lighting can be permanently illuminated or switched on automatically by a fail-safe system in the event of a power failure. Both tungsten filament and discharge lamps are used. Power to emergency lighting is normally supplied by batteries charged continuously by the mains using separate circuits. Emergency generators should be used in buildings where mains failure can affect life safety and other essential equipment. Batteries are usually housed within plant rooms.

Cleaning gantry allowing underside of roof to be cleaned and maintained without cleaning platform from below.
B8 offices, Daimler Chrysler Projekt, Potsdamer Platz, Berlin, Germany. Architect: Richard Rogers Partnership.

Roof-mounted facade cleaning systems

With the increased use of metal, glass and composite materials in facade design there has been a greater requirement for cleaning and maintenance. Building facades 30 years ago were detailed with low levels of maintenance envisaged, with the use of brick, concrete, stone and timber dominating architectural design. Facades would be cleaned only rarely, with details that would weather well with the passage of time. Windows in masonry walls were detailed to be openable, partly to admit fresh air for ventilation and partly for cleaning access. With the increased use of sealed facades without openable windows came an increased requirement for cleaning equipment.

Facade cleaning systems for twin wall facades (discussed in Modern Construction Facades) are often provided in the form of walkways set at each floor level. Most systems, however, are roof-mounted and are required to be integrated into the roof design, usually with a minimum of visible equipment. These roof-mounted types are discussed here. Most facades are cleaned with either davits, monorails or trolley systems mounted at roof level, with larger buildings having a mixture of these systems on a single roof.

Davit systems

A davit is a jib or scaffold-shaped frame from which a cleaning cradle is hung. A single cleaning cradle, holding one or two persons, is usually hung on cables from a davit at each end of the cradle. Davits are moveable and when in use are secured to bases in fixed positions near the roof edge. Davits are very useful for roofs where the permanent visual presence of a monorail or trolley system is not the preferred solution to facade maintenance.

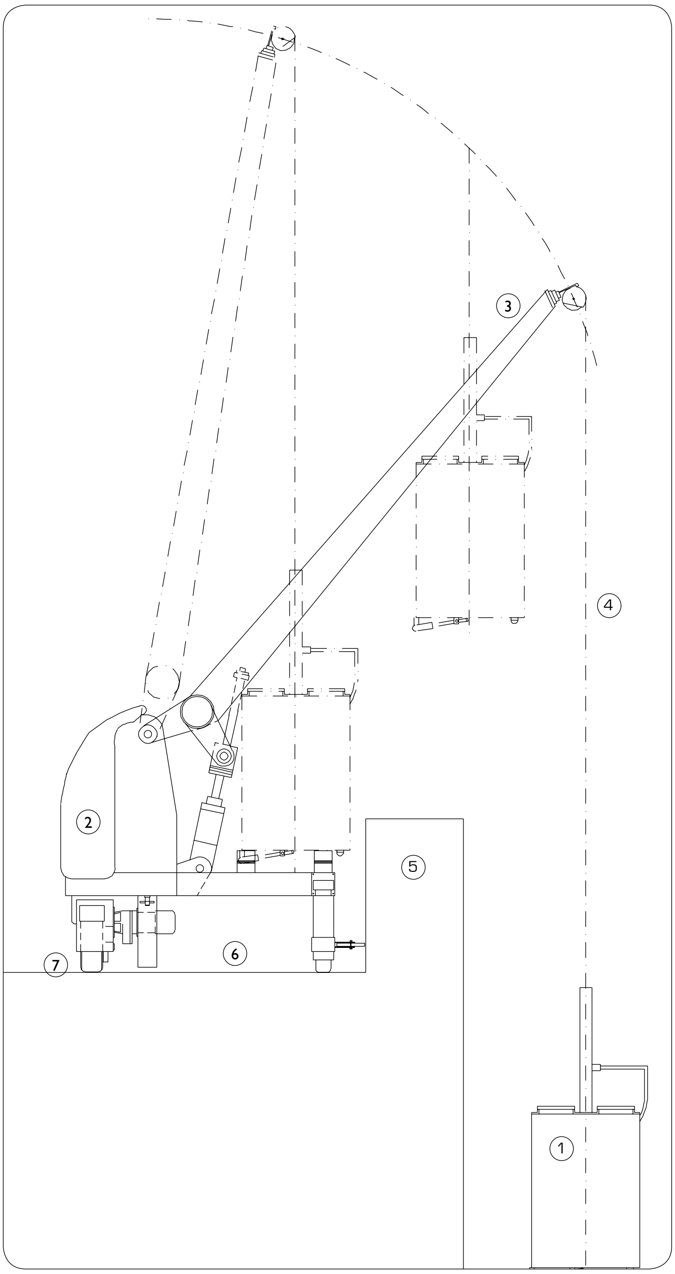
Davits are usually made of mild steel or aluminium tube and are moved with wheels at their base. This makes them sufficiently lightweight and mobile to be handled by one or two people when they are moved into position and fixed for use. Davits are usually dropped into position onto a set of bolts projecting up from the roof surface, typically as either plinths in the form of short columns, or as a recessed box below the level of the roof finishes where the bolts are concealed from view, as on an accessible roof terrace. The davit is lifted into position, usually by a person pulling it up with a rope secured to the top of the post. The arm of the davit can be swung outward once it is fixed in place. Cables, secured to the end of the davit arm before it is lifted into position, are lowered down the facade to be attached to the cleaning cradle below, at the base of the facade. The cradles usually have wheels which enable them to be moved to suit each new pick-up position for the davits as they are moved to each new fixing point on the roof. The cables are connected to the cradle, allowing it to be raised up the facade. The cradle is fitted with an electric winding mechanism and rubber fenders to avoid direct contact with the facade. There is no winding mechanism at the level of the davit, whose function is to support the cables only. The electrical power supply for the cradle motors is from points either at roof level or at the base of the facade, supplied to the cradle by a power cable. In the event of a power supply failure, a manual system in the winch allows the cradles to be lowered to the ground. Various proprietary systems of winch motors and lifting equipment are available, all with different safety features.

When one vertical strip of facade is cleaned by a cradle that is raised and lowered from a pair of davits, the cradle is moved to its next position by descending to its lowest level and disconnecting the cables. The davits are then unbolted and lowered

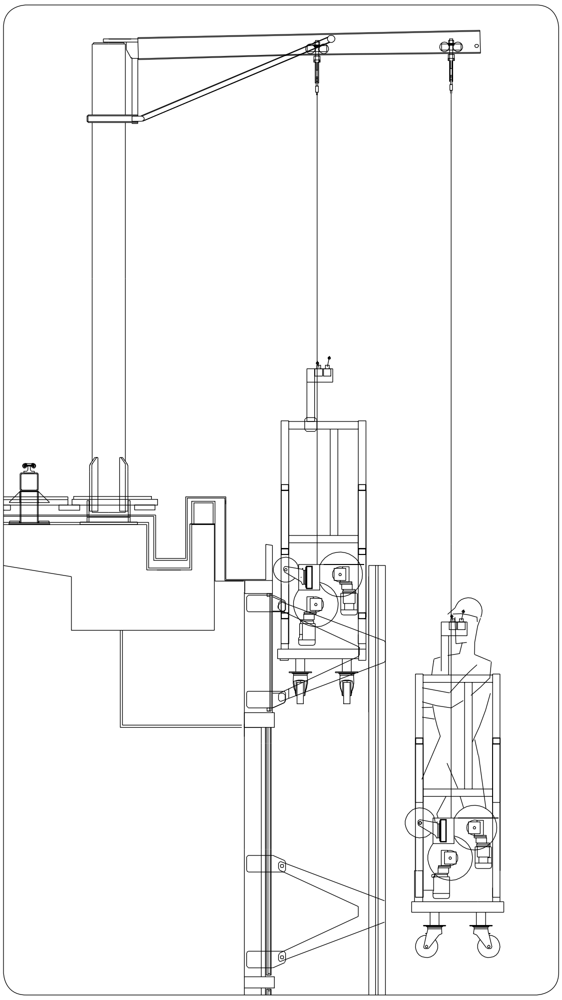
Details
1. Cleaning cradle
2. Motor and counterweight
3. Hydraulically operated arm
4. Steel cable
5. External wall parapet
6. Roof surface
7. Wheels or guide rails

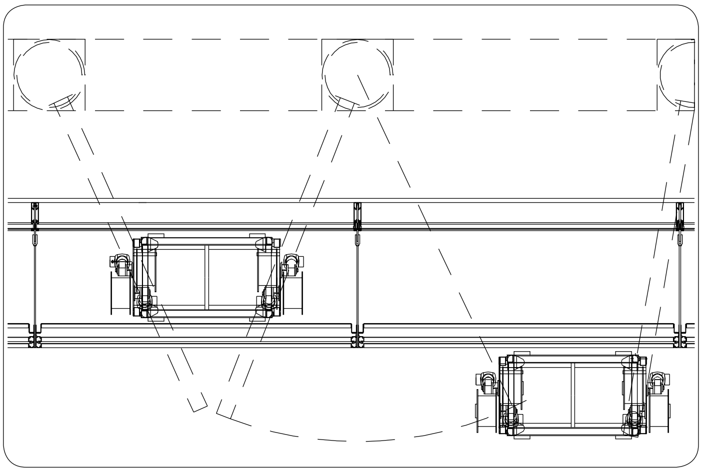
Above and below: Cleaning equipment, Lloyds Building, London, U.K.
Architect: Richard Rogers Partnership

Cleaning equipment on this building has been specially designed and integrated into the overall architectural aesthetic being highly visible at all times from the surrounding city streets



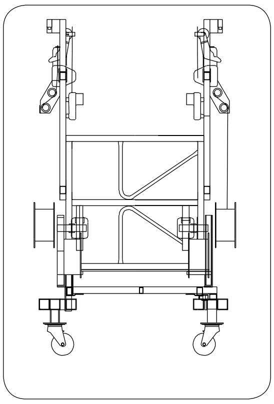
Section 1:50 Roof mounted cleaning crane

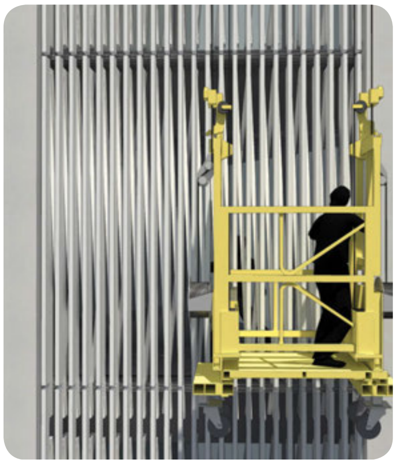




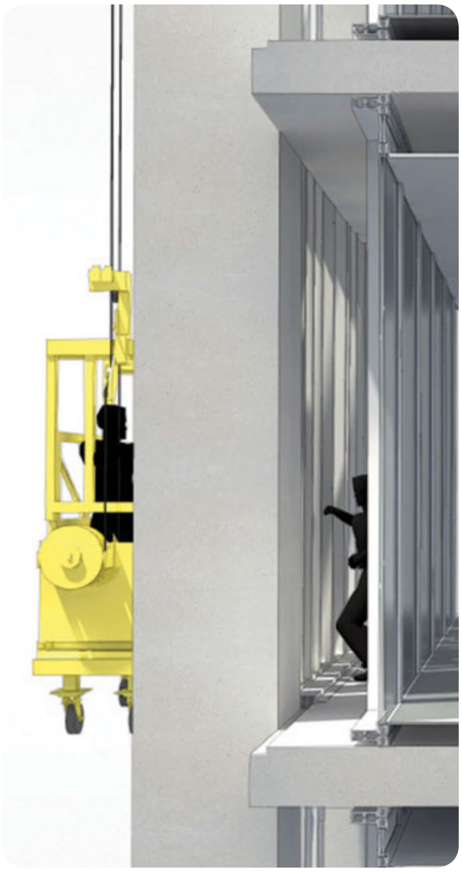
Plan 1:50 Davit supporting cradle in two positions

Section 1:50 Davit supporting cradle in two positions

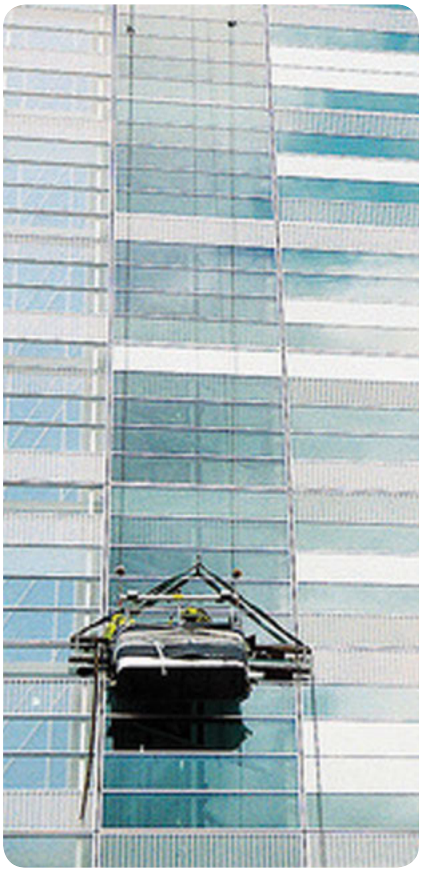




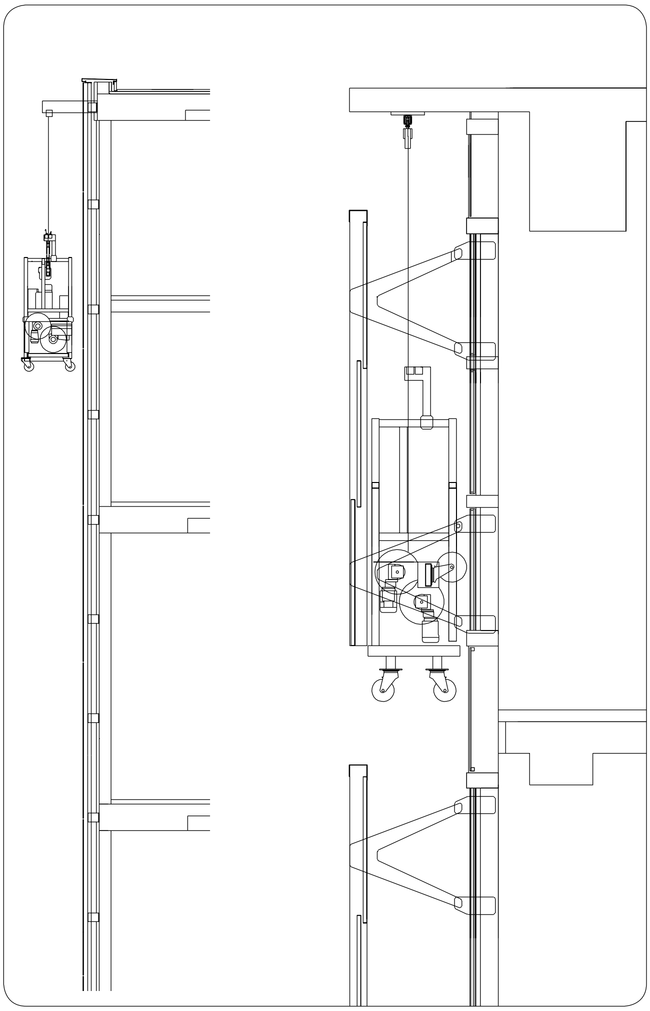
Elevation 1:50 and 3D view of typical cleaning cradle



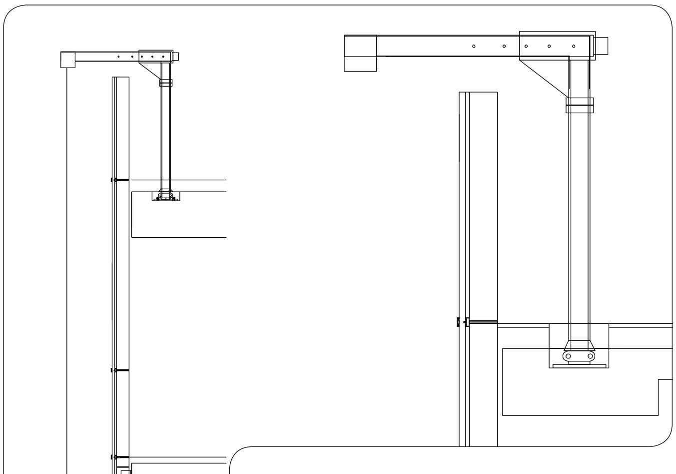
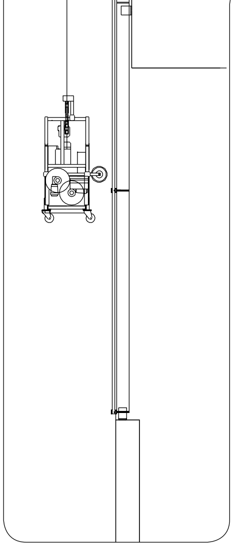
3-D views of typical cleaning cradle on facade



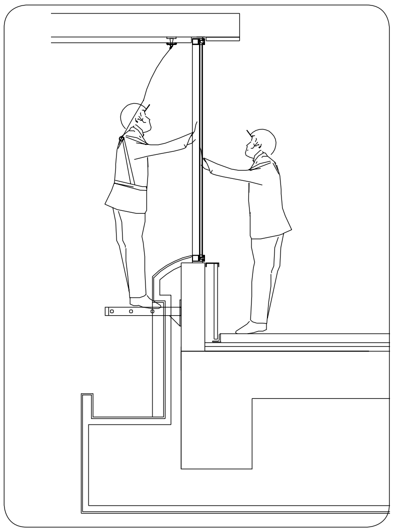
Cleaning cradle on glazed facade



Section 1:100 and 1:50 Monorail supporting cradle from cantilevered brackets/ beam

Section 1:100 and 1:50 Davits supporting cradle



Section NTS cleaning with harness on a platform

from their bases before being moved to the adjacent base positions for re-connection.

While this is a relatively slow process involving erecting davits, setting up the cables and cradle, then disconnecting the parts and moving the davits again, this method avoids a permanent and visible cleaning system being mounted on the roof. The davit system is most commonly used where the roof is used as an accessible roof terrace or garden, and where a permanent cleaning system would not be visually desirable.

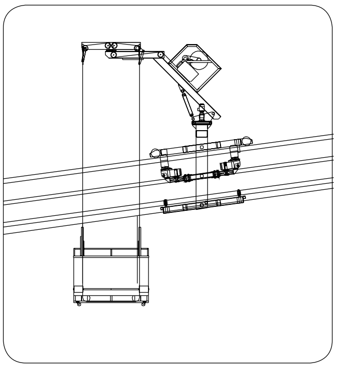
Monorails

In the monorail system, a continuous single rail is fixed at roof level, from which a cleaning cradle is hung from a cable at each end. The monorail is set around 500mm beyond the edge of the roof to allow the cradle to hang slightly forward of the facade, typically on brackets cantilevered from the roof structure as shown in (A). The monorail is a visually strong element that is integrated into the overall design for the edge of the roof. An alternative to cantilevered fixing brackets is to cantilever the edge of the roof out by around 500mm as shown in (B). The rail is usually made from mild steel which is painted or enclosed in a decorative metal cover, usually in folded aluminium sheet. Where cantilevered support arms are used these can be castings or standard structural steel sections to suit the design. The monorail, set horizontally, is usually formed as a channel-shaped section that allows a pair of wheels to run inside the rail. Sets of wheels are operated either by sliding the cleaning cradle beneath manually, or under electrical power for larger installations. As with the davit system, cables are connected from wheeled pulleys which travel inside the monorail. The cables are lowered down and connected to the cleaning cradle, which is set at the bottom of the facade. As each vertical strip of facade is cleaned, the cradle is moved along the facade, usually when it is at roof level, just below the level of the monorail. When manually operated, the cradle can be moved when at the bottom of the facade if maintenance personnel are assisting at roof level. The monorail offers a visually discreet method of providing a permanently fixed cleaning system at roof level.

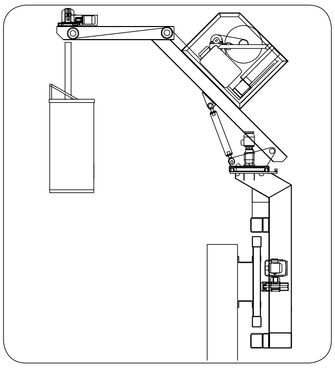
Where the monorail is hung from the underside of a balcony or slab soffit, the monorail can be concealed with cladding panels set on either side of the rail. From below, only a single continuous groove is visible. A gap of around 20mm is provided between the monorail and the adjacent panel to allow for movement of the monorail itself when in use. This joint is either left open or closed with a flexible seal, typically EPDM sheet.

Trolley systems

Where a facade is required to be cleaned from a roof which is either sloping, or has a stepped profile in elevation, a horizontal monorail is a much less practical solution for supporting cleaning cradles. Davits are usually difficult to handle on sloping roofs. Trolley systems are better adapted to reaching facades from a sloping roof and where the facade itself is of complex geometry. Trolleys are typically mounted on wheels and are secured to a

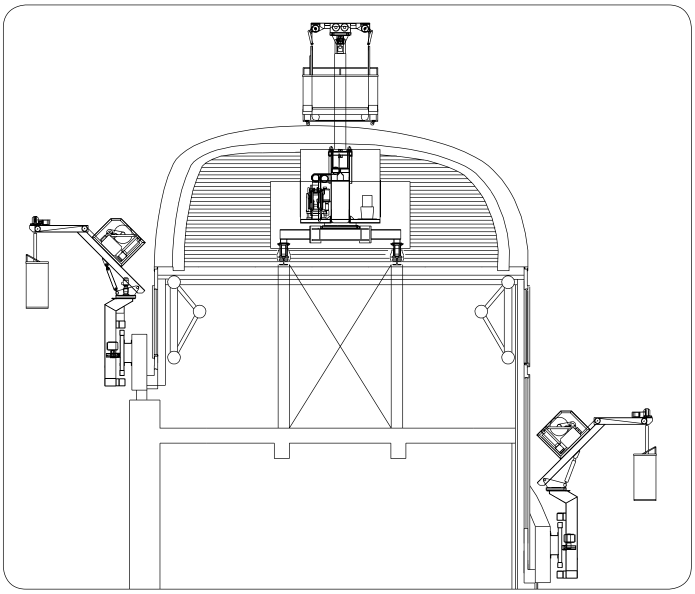


Elevation 1:200 Trolley supporting cradle



Elevation 1:100 Trolley on vertically set rails

(Above). Cleaning cradle on trolley around Swiss Re building, London, U.K. Architect: Foster and Partners



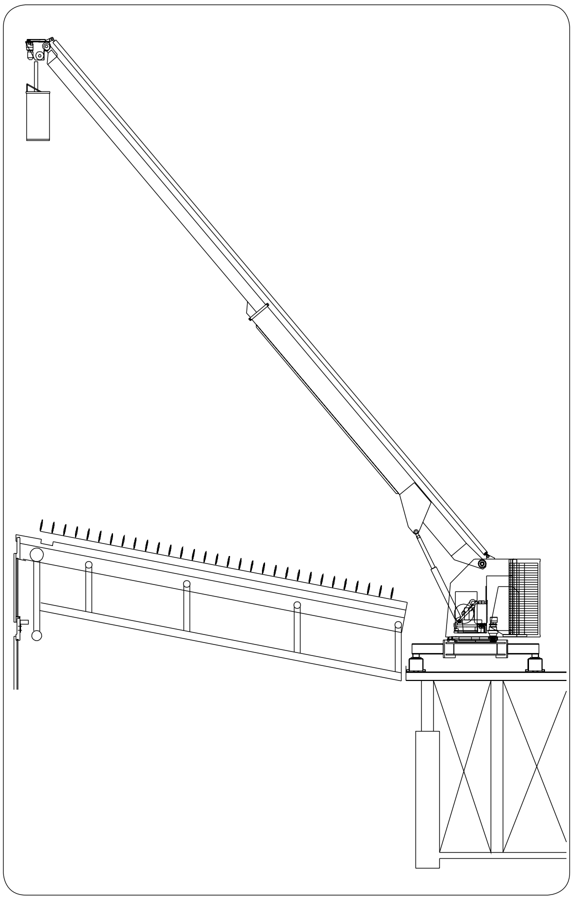
Elevation 1:200 Trolley supporting cradle

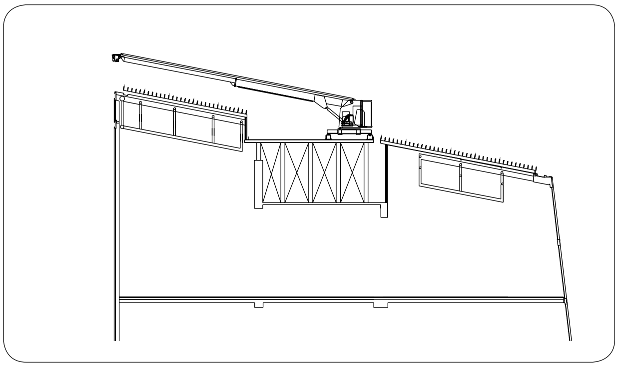
continuous track, which may be beneath the trolley, as roof-mounted rails, or may be set vertically. The trolley usually has arms which project out over the edge of the roof which support a cleaning cradle from cables fixed to the ends of the arms. The arms are sometimes telescopic (hydraulically operated) in order to reach either the facade or, for example, solar shading panels in front of the facade. The arms are usually raised or lowered to bring the cradle in and out from the facade and to bring it to rest at roof level. The trolley itself houses the motors for both moving the equipment along its rails, moving the arms, and raising and lowering the cradle itself. The trolley is usually controlled from within the cradle, allowing it to move both vertically and horizontally.

This system is not usually suited to roofs which are fully accessible to building users due to the presence of rails or a dedicated path, as well as the visual presence of the trolley itself. As the trolley is controlled remotely, safety at roof level is a critical consideration. Where roofs are required to be accessible, rails are mounted above the roof, but their dominant appearance may deter this solution in practice. Where the trolley can be seen from below, it is usually concealed behind a screen or in a small enclosure, allowing it to be protected from the effects of the weather. Trolley systems are well suited to being mounted on sloping or curved roofs where they climb steep slopes, typically up to around 45°.

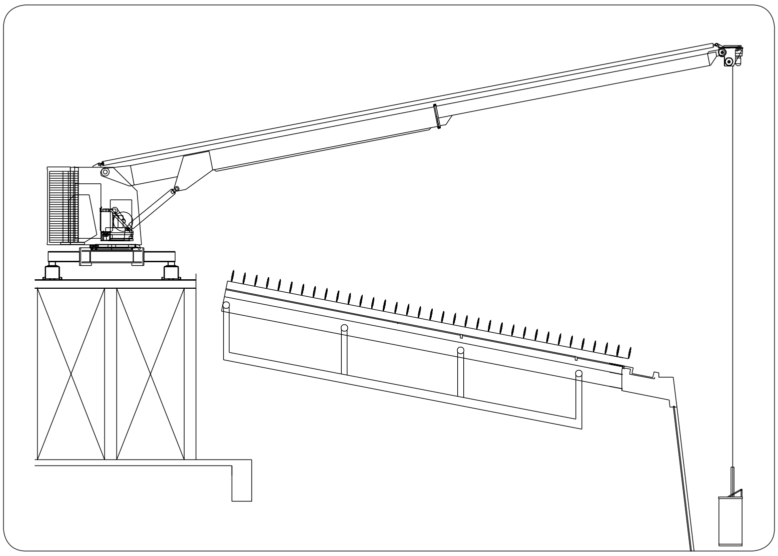
Where facades step in at a lower level, the cradle can be offset from its supporting cables by the use of counterweights attached to the cleaning cradle. The cradle can be moved by an arm fixed directly to the supporting cables. As the arm moves from a vertical position to the horizontal, the cradle swings away from its cable. The movement is balanced by a counterweight at the other end of the arm which keeps the cradle level and stable. This method is useful in facades that either step outwards as they rise up or are inclined outwards through their height. The mixture of a trolley system and cradles allows complex facade and roof forms to be cleaned and maintained from a single cleaning cradle. With facade and roofs of complex geometry, the trolley rails can be concealed in a gutter at roof level where facade and roof form a single and continuous form.

In the example above a trolley is set behind a parapet formed by solar control louvres. It is set on a track that forms a continuous loop to suit the shape of the building. As the trolley moves around its circuit it is able to reach all parts of the facade. The trolley is able to reach the facades with telescopic arms that can be adjusted both in length and height to suit the facade being cleaned. A single trolley is usually provided for a single building, but more than one may be required, working on the same track, to suit different facade geometries beneath. Not all large-scale trolleys require tracks to restrain them. Trolleys with wheels that move on a raised portion of roof deck are also used.

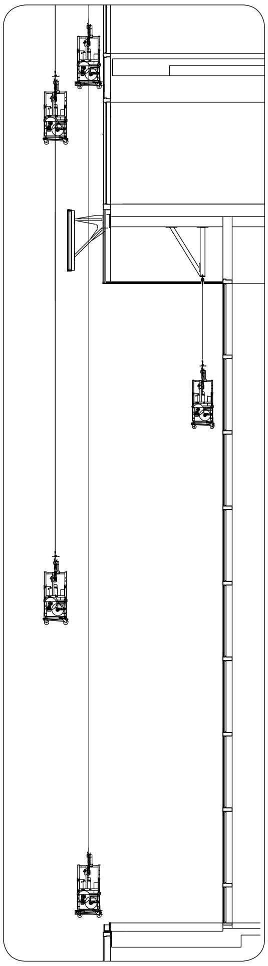




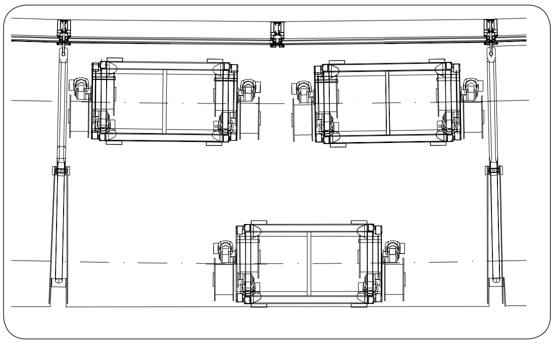
Elevation 1:500 Trolley with reach over adjacent facades



Left and right: Elevation 1:200 Trolley with reach over adjacent facades

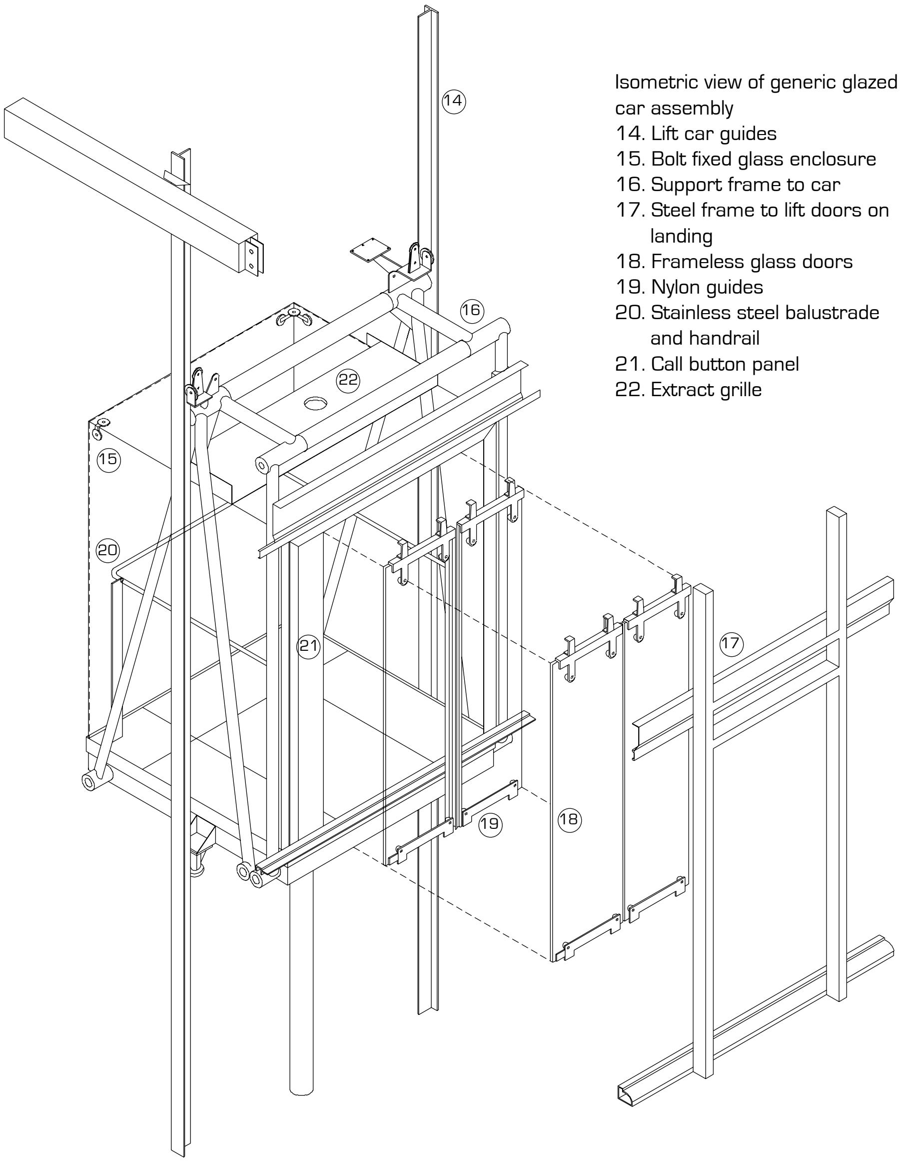


Section 1:200 Cradles hanging from trolley and monorail



Plan 1:50 Cradles hanging from trolley

88 Wood Street, London, U.K.
Architect: Richard Rogers Partnership.



Isometric view of generic glazed car assembly
14. Lift car guides
15. Bolt fixed glass enclosure
16. Support frame to car
17. Steel frame to lift doors on landing
18. Frameless glass doors
19. Nylon guides
20. Stainless steel balustrade and handrail
21. Call button panel
22. Extract grille

There are two generic types of elevators: traction, where the elevator car is suspended on cables with counterweights, and hydraulic, where the elevator car is fixed on a ram which is sunk into a shaft. In both cases the elevator cars run on vertical guides which are attached to the inside of an elevator shaft or, in the case of open wall-climber elevators, directly to the edge of floor structures. It is common in tall buildings to use fast elevators that stop every ten floors. Intermediate floors are accessed from separate elevators that run between the fast elevators.

The type and number of elevators for any installation is established by the following criteria:

- Approximate passenger load
- Maximum acceptable waiting time
- Number of persons each car will carry
- Elevator speed
- Expected passenger load at peak times

Elevator cars consist of metal frames clad with solid or transparent panels. Doors to the elevator cars can be single or double, sliding on either one or both sides of an opening. Width restrictions, particularly where elevators are set side by side, may mean that doors are set off-centre to the elevator car or that twinleaf doors are necessary.

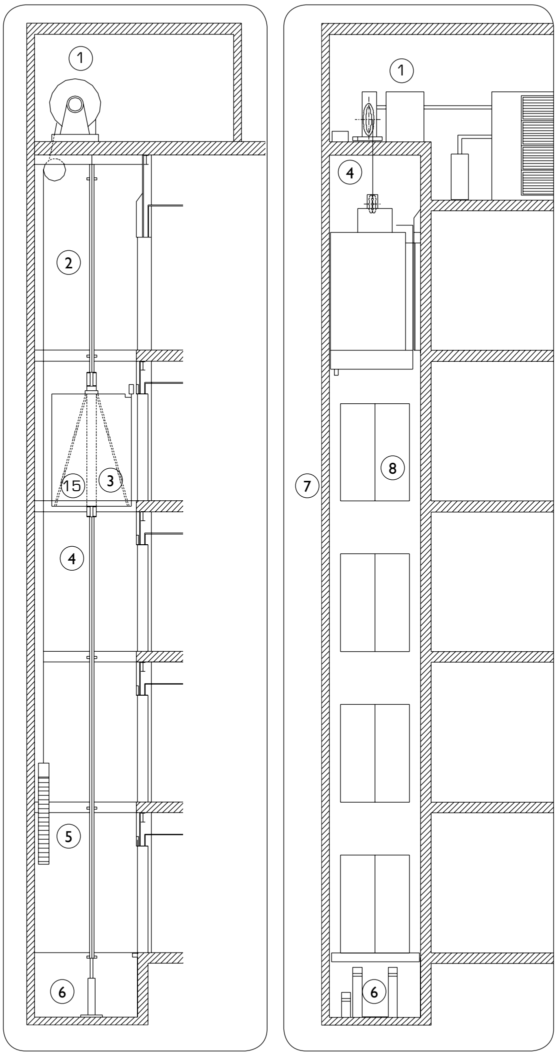
At each level served there are elevator landing doors, which can be solid or transparent. These doors open only when engaged by the elevator car doors. When the elevator is in an open shaft there is a need to protect people on each landing from the moving parts of the elevator mechanism. In this case, each floor is provided with landing screens which are incorporated into the elevator landing doors. Where the elevator is in an enclosed shaft the risk of fire spread from floor to floor must be taken into account. In such a case, the elevator landing doors may need to be fire resistant. Call buttons are located on each floor. In larger installations, calls are registered by the control gear and automatically dealt with in sequence. Banks of elevators have co-ordinated control systems that respond to calls in a given sequence.

Hydraulic elevators can carry a maximum of around thirteen passengers. In theory, there is no limit to what a traction elevator can carry. For cars carrying up to thirteen people the same size well can be used for both traction and hydraulic elevators. An eight-person elevator is usually the smallest which can comfortably admit a wheelchair. The minimum door width is usually 900mm.

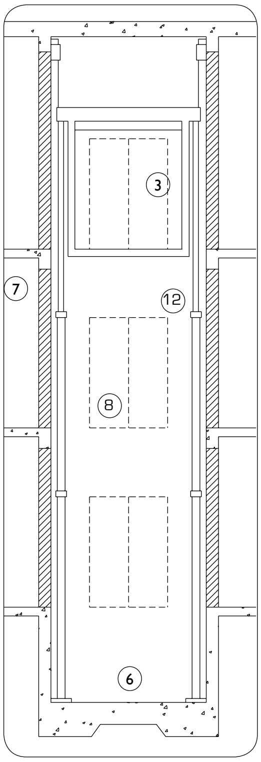
Traction elevators are electrically powered. Cables, running over pulleys and balanced by counterweights in order to minimise the efforts of the elevator motor, support cars. Both car

Section and plan details

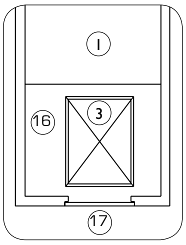
1. Lift motor room
2. Guide rail
3. Elevator car
4. Cable
5. Counterweight
6. Elevator pit
7. Enclosing wall
8. Doors to landing set into enclosing wall at each level
9. Doors to car
10. Doors to landing
11. Single hydraulic piston
12. Telescopic hydraulic pistons as alternative to single piston
13. Piston cylinder well
14. Vent to outside
15. Car deck
16. Lift well
17. Access panel/ vent



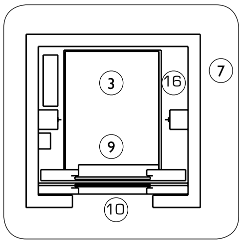
Vertical section
Traction lift



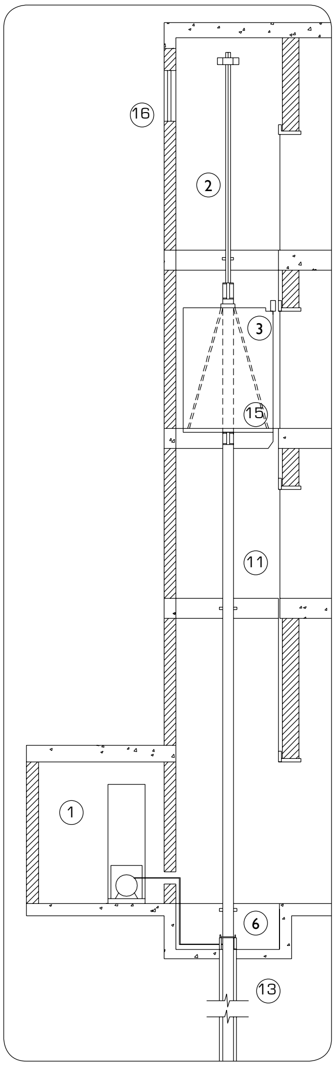
Vertical section
Hydraulic lift



Horizontal section
Traction lift



Horizontal section
Hydraulic lift



and counterweight move in vertical steel guide rails. Traction elevators have advantages over hydraulic elevators with their higher speed and hardwearing qualities. Speeds vary from 0.5 metres per second for smaller installations to 6.0 to 7.0 metres per second for tall buildings.

Traction elevators have an over-run space at the top of the shaft. This protects anyone working on top of the elevator should the car travel to the top floor accidentally. The overrun also allows cables to run over the pulley to the motor. The overrun space also accommodates the cable pulleys. Motor rooms house the elevator motors and ancillary equipment that drives the cars. These are usually located at the top of the shaft, adjacent to the overrun. The motor room can also be positioned to one side of the elevator pit at the bottom of the shaft, but this requires more sophisticated cabling. Motor rooms require ventilation because of heat generated by the machinery.

A pit is located at the bottom of the elevator shaft. It is usually about two metres deeper than the lowest floor served in order to accommodate the underside of the elevator car. The top of the elevator shaft is vented to the outside to ensure that air is drawn up the shaft and out of the building in the event of fire.

A hydraulic elevator consists of a piston cylinder set into a well beneath the elevator pit, which accommodates the underside of the elevator car at the lowest floor level. The piston can be a single or telescopic tube. If it is a single tube, the well must be deep. The hydraulic piston is fixed to the bottom of the shaft and connected to the elevator car. The ram is activated by hydraulic oil which is forced into the cylinder well under high pressure, which then moves the elevator car. Hydraulic elevator mechanisms are suited to installations serving up to five floors. They are usually slower than traction elevators, with speeds ranging from 0.63 to 1.00 metres per second. The motor room can be located a short distance away from the elevator shaft, rather than next to it, either at the bottom or the top, which is an advantage in small buildings. Hydraulic elevators are also useful where an overrun cannot be accommodated easily at the top of the elevator shaft.

The machinery room can be independent of the elevator shaft, and may be located up to five metres away. Machine rooms are smaller than those of traction elevators, and contain pumps, motors, fluid storage tanks and control equipment. Machinery rooms require ventilation due to heat generated by the equipment. Hydraulic elevators have an overrun at the top of the elevator to protect anyone working on the top of the car, in case it accidentally rises to the top of the shaft. Like traction elevators, the top of the shaft is externally vented to ensure that air is drawn up and out of the building in the event of fire.

6

APPLICATIONS

1 Working with industry
2 Triangular panels for twisted facades
3 Twisted panels with flat glass for curved facades
4 Solar shading louvres
5 Double-skin facades
6 Precast concrete panels for facades of complex geometry
7 Exoskeleton facades of complex geometry
8 Diagrid structures
9 Hybrid systems forming facades of complex geometry
10 Opaque cladding interface with full-height glazing
11 Complex curved glazed roofs
12 Large-scale glazed facades
13 Panelisation of complex building surface geometry
14 Opaque rainscreen cladding
15 Full-height glazing with GRP-clad structural frame
16 GRC cladding interfaces
17 Full-height entrance glazing
18 GRP lovures on stick glazing system
19 GRC cladding
20 Windows in GRC cladding
21 Windows and unitised glazing with GRC cladding
22 Unitised glazing with GRC cladding
23 Complex glazed roofs with supporting steel structure
24 Glazed roofs with complex geometry
25 Louvres and stick glazing
26 Tiled cladding
27 Rainscreens

The relationship between the design team of architects and engineers and those that construct facades is defined by whether fabrication work is done on-site or off-site. Facade construction work that is conducted on-site, such as in-situ concrete, masonry cavity walls and timber walls to the platform frame, are fabricated and installed with materials delivered directly from a materials supplier to the building site. With on-site fabrication, the building site becomes the workshop for facade assembly from its constituent components. Work is done by building contractors who buy their components not directly from manufacturers, but from building suppliers. This is because building contractors for brick cavity walls or in-situ concrete or timber walls, for example, are involved in constructing with a wide range of construction technologies, with construction conditions changing from job to job. As a result, they do not generally form close ties with particular manufacturers, but are instead involved with a large number of individual suppliers for a large range of components, some of which will have been specified by the design team at the tender stage. Architects and designers work through development, mock-ups and performance testing in the same way as for factory- and workshop-based companies that use a high degree of prefabrication.

Facade fabrication done off-site in factories and workshops involves the design and assembly of proprietary components and systems. Examples are glazed curtain walling, metal walls, plastic-based cladding and precast concrete which are designed and fabricated off-site, then installed in the building. Off-site fabrication involves manufacturers, fabricators and installers. Some manufacturers supply systems for others to assemble, while other companies design, manufacture and assemble systems, allowing others to install the facade assemblies on site. Architects and engineers can work independently with all three groups of manufacturers, fabricators and installers.

Manufacturers do not install their own systems but instead focus on the design and manufacture of systems and their components. Each company usually has a set of installers with whom they have an agreement. The manufacturers supply the facade systems together with technical support for their application, while the fabricator provides the skills required to assemble them. The manufacturer supplies facade systems in varying amounts of fabrication, for example standing seam sheet metal systems are supplied as either sheet in rolls, sheet with standing seams pre-formed and folded, or as coiled metal with a forming machine for use directly on site. If the sheet is pre-formed, then the manufacturer will have very specific requirements for fixings which will be conveyed to the installer. If the sheet is delivered to the site as a roll, then much more expertise for forming and fixing is required of the installer. In the case of composite metal panels, the panels are manufactured for installing on site with very specific requirements for fixing provided by the manufacturer. This may involve a detailed installation manual, with some installation training provided for the installer, by the manufacturer. The architect or designer must be aware of how a particular product is procured so that an appropriate input to the detailed design can be made.

For glazed systems, specialist items such as windows and doors are usually assembled by the manufacturer. Other materials such as glass, metal sheet, timber sections and stone are obtained from other manufacturers. Architects and engineers work increasingly with both manufacturers and fabricators throughout the design development stages, with greater emphasis on working with installers as the project progresses towards the construction phase. The manufacturer designs the systems, while the installer assembles them in place from project to project. In some cases manufacturers buy the raw material from the supplier, while in other cases they manufacture the raw material as well. Examples are steel or aluminium companies which both manufacture metal, and roll, profile or extrude it for immediate use in facade systems, usually where manufacture of the primary material is their core business. Similarly, glass manufacturers sell their material on to companies who make double glazed units. Systems provided by manufacturers are fully designed and tested. While architects can use the systems in ways prescribed by the manufacturer, there is relatively little scope for changing them, or even adapting them for use on a particular building, except in large-scale projects. This happens because the systems are manufactured as a set of standard components which are made specially to deal with a range of options available within the system. In addition, the test certificates obtained for their use are specific only to the standard system. Deviation from the tested systems adds both time and cost to a project, the implications of which are weighed up before incorporating these changes into the tested system. Some manufacturers have their own test facilities, which can speed up the process of testing variations on standard systems, while others use independent test facilities, which can take longer to obtain results. If the modified design does not successfully complete testing, then further modifications will need to be made, adding further time to the design programme. Testing is primarily concerned with structural rigidity, infiltration of air and water, thermal and acoustic insulation, and fire resistance.

Standard systems from manufacturers are not necessarily optimised solutions. They are in constant development and become 'frozen' for manufacture at a particular stage of development,

subject to their achieving a given technical and aesthetic performance.

Some installers do not only erect facade systems supplied by a single manufacturer or a range of suppliers. The large companies, which operate all around the world, also develop designs with architects and engineers in order to provide specific solutions for individual buildings, usually those of a larger scale. This method of working with large facade contractors can make use of parts of systems by specific manufacturers, or be developed from designs developed for use on previous building projects.

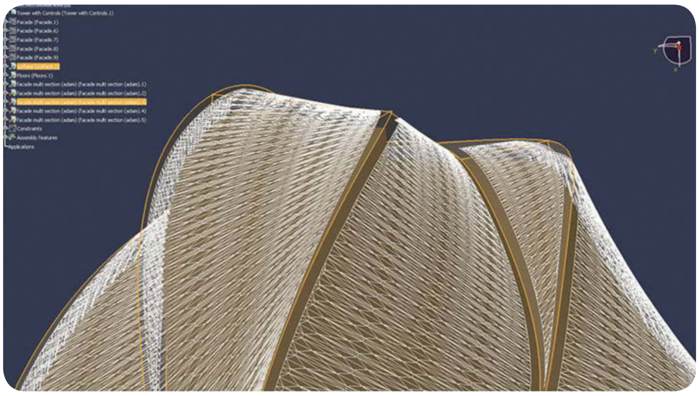
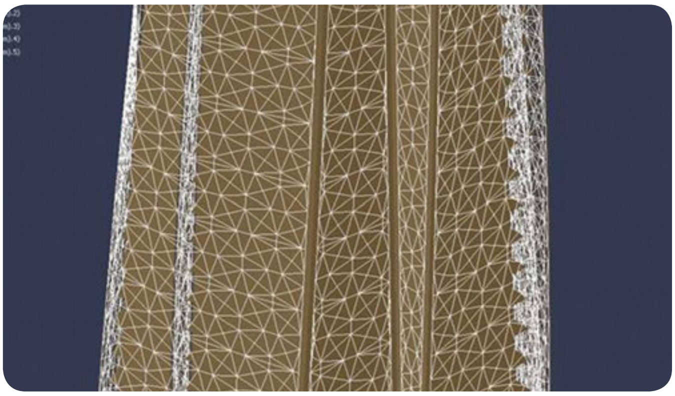
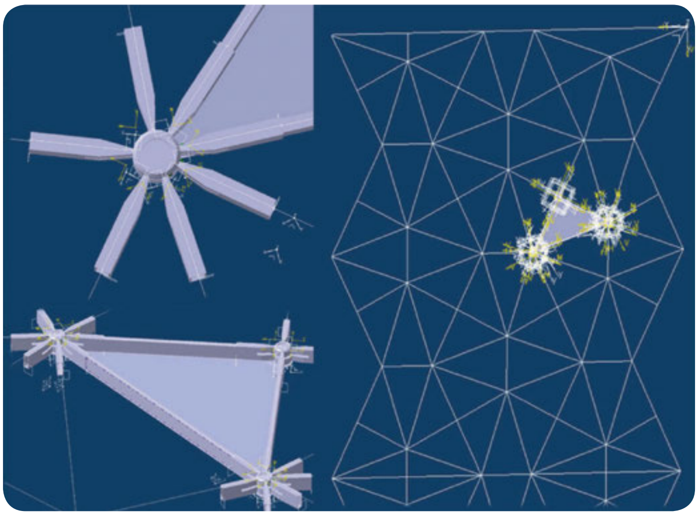
As a building project develops at the design stage, the question arises as to when facade manufacturers, fabricators and installers should become involved with the project. All groups will give informal advice at this stage of the project, though the amount will vary from company to company, as well as what agreement, if any, has been made about their involvement in tendering for the project. Large-scale projects will usually have access to a more significant input from manufacturers and fabricators before tender. Involvement from these two parties will ensure that the facade design being developed for tender will fall roughly within the budget. This avoids unpleasant surprises after the tender evaluations have taken place.

Facade designs and details drawn in too generic a way do not interact with what manufacturers can produce reasonably economically, so an understanding of the constraints of each facade type is essential to being able to design for a non-specific manufacturer, fabricator or installer, thus providing even-handed tender documents. On the other hand there is always a risk of working too closely with one manufacturer or fabricator at the design stages before tender, only for that party to be unsuccessful at the tender stage. This results in both the tenderer having spent considerable time and resources on a project only to be disappointed and leaves the design team with a solution that does not conform to the approach of the successful tenderer. An even-handed approach ensures that none of the parties become involved in too rigid an approach.

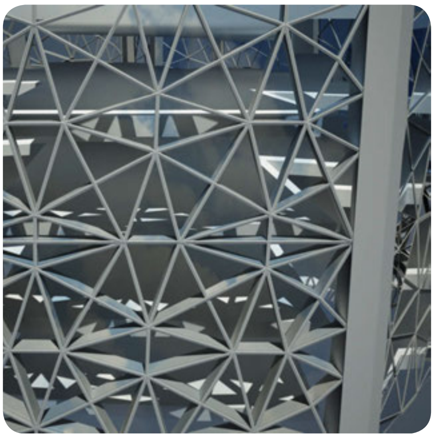
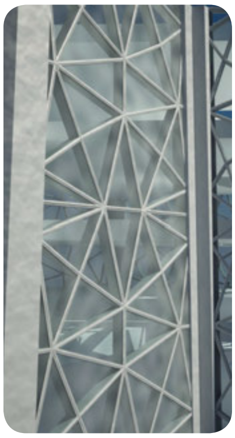
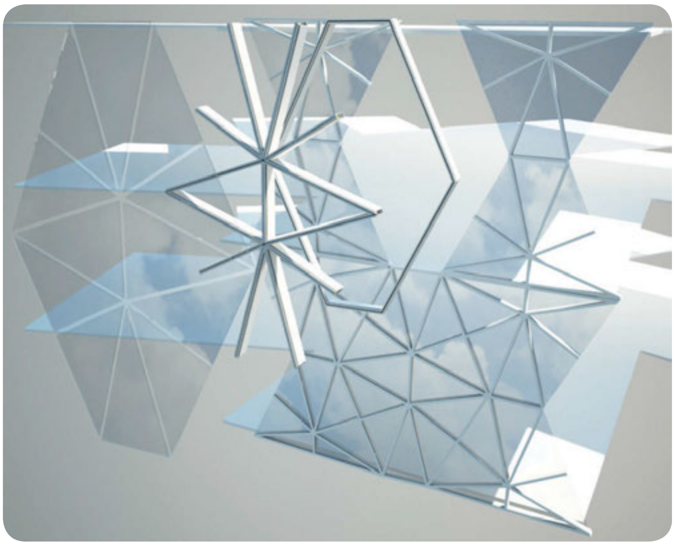
An alternative approach for the design team is to develop a facade system, or set of systems for a project, to a detailed stage without assistance from manufacturers or fabricators. This is particularly appropriate if the building design involves a new facade technology that is an essential component of the success of the design. A team of architects and engineers can develop a facade system to tender stage with a comprehensive set of structural calculations in place to determine the section size of the most important components. The system will be designed to a stage where a set of full size visual mock-ups and a performance mock-up for testing can be constructed immediately after the tender is awarded. During the tender stage each tendering company is invited to comment on the proposed system and either accept the system or modify it until they find it compatible with their own approach. Tenderers may also propose their own facade system if it meets the performance requirements of the proposed system and abandon the proposed solution altogether.

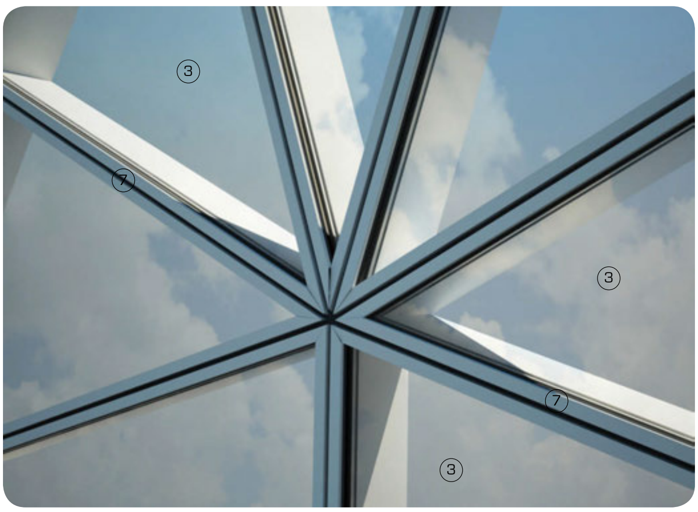
In some projects, the building owner or client may have a specific company, or set of companies, with whom they like to work. This approach gives greater scope for working with a single manufacturer / fabricator team that can proceed more quickly to a detailed design with visual mock-ups and results from previous performance testing on related systems. Regardless of how the design team develops a project to the tender stage, it is essential for the design team to visit the facilities of all potential tenderers at the earliest possible opportunity. This allows the designers to understand the range of systems, skills and experience of each manufacturer / fabricator and to understand the working method of each company. These visits help the design team to understand how materials are made, worked and formed into components, and how they fit together into the final assembly. This method also helps the designers to appreciate the level of quality produced by each company.

These factory / workshop inspections are also vital immediately after tender, when the successful tenderer can again show how the facade systems or components will be made. This is very useful during the workshop drawing phase, when the design team can work with designs from the manufacturer, fabricator and installer to give the best possible result on site. It is far easier to exert influence in the factory at this stage than it is on site, where changes and modifications to systems are very difficult to make. In prefabricated systems it is usually too late to push for higher quality on site, since this work has already been done in the factory. The same is true of site-based work such as in-situ concrete and sheet metal cladding, where visual mock-ups and performance testing mock-ups, as well as visual mock-ups of important junctions, should be considered at the stage immediately after tender. Site inspections for facades should focus on the correct setting out, replacement of damaged items and the fine tuning of a few interfaces that may not have been considered during the production phase in the factory. It is essential that dialogue and co-ordination occur at the appropriate time of the project and not be left to a late stage of the project.

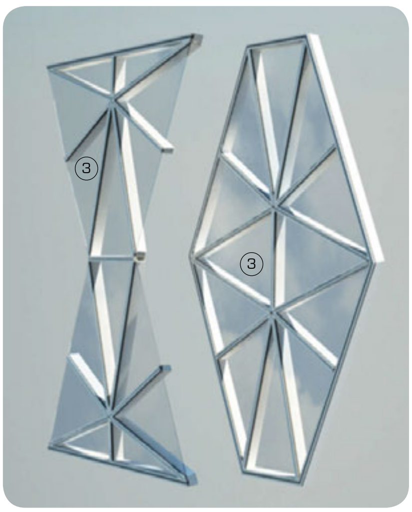




Working digital models of triangular unitised glazing panels for twisted facade

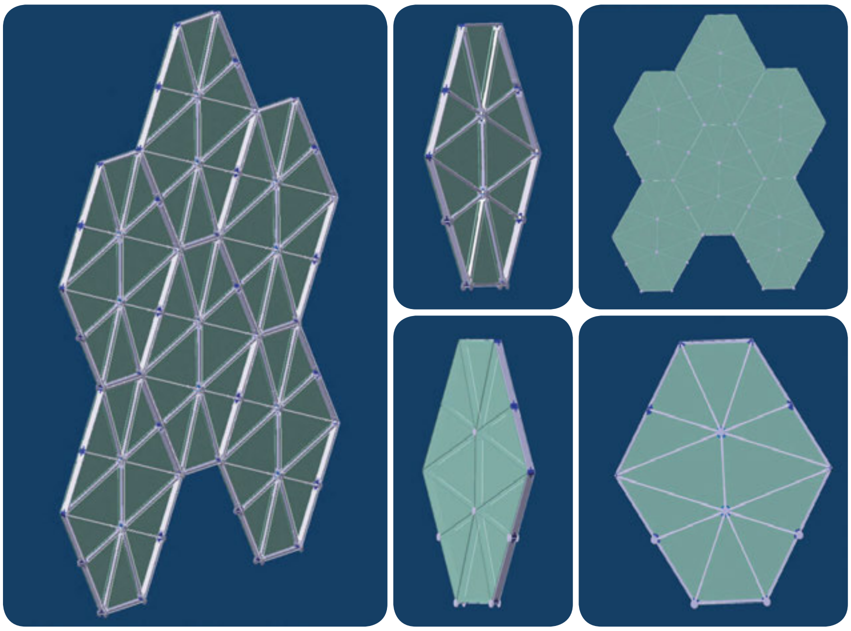



3D detail views showing triangular unitised glazing panels for twisted facade



3D views showing triangular unitised glazing panels for twisted facade

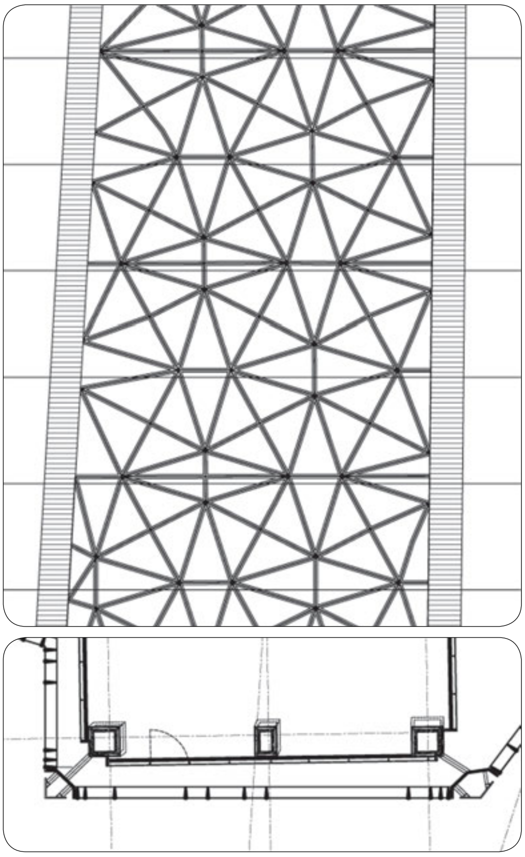
Details
1. Primary steel structure
2. Primary concrete structure
3. Aluminium unitised double glazed panel
4. Floor slab
5. Cladding for primary structure
6. Silicone seal
7. Glazing frame cap
8. Internal floor finish



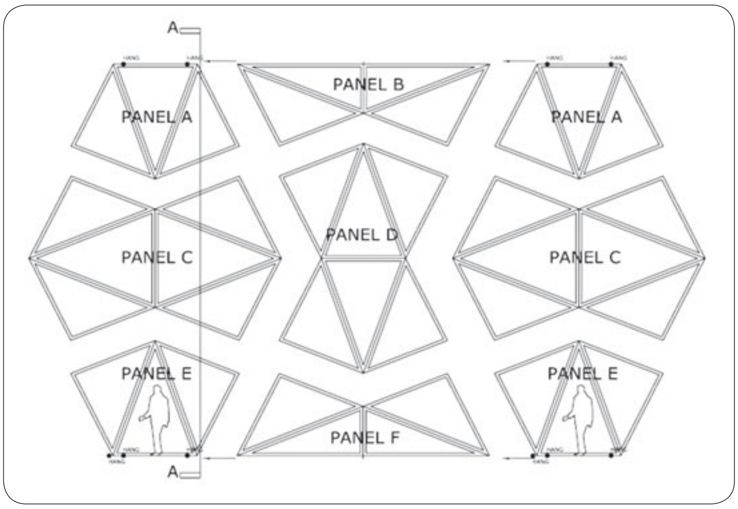
Working digital models of triangular unitised glazing panels for twisted facade

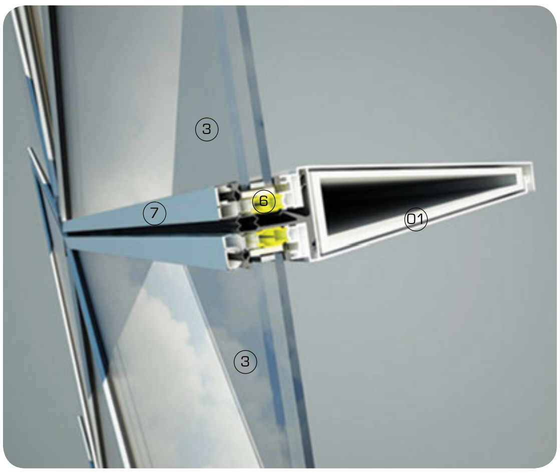
Details

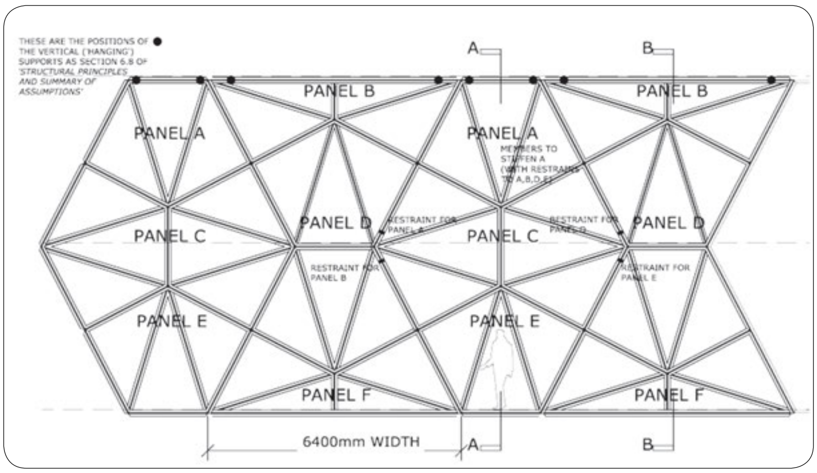
1. Primary steel structure
2. Primary concrete structure
3. Unitised aluminium glazing frame
4. Floor slab
5. Cladding for primary structure
6. Silicone seal
7. Glazing frame cap
8. Internal floor finish



Elevation and horizontal section. Triangular unitised glazing panels for twisted facade







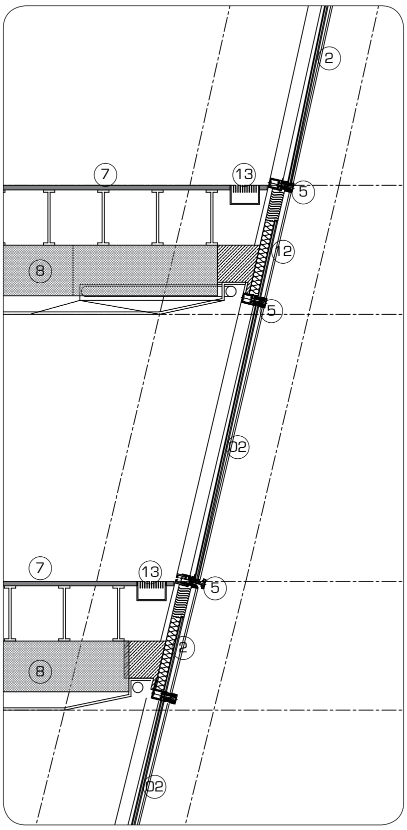
3D sectional detail views showing triangular unitised glazing panels for twisted facade

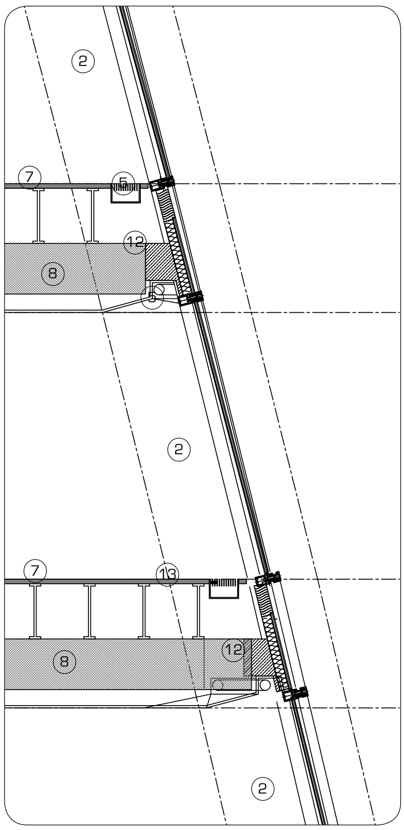
2D layout. Triangular unitised glazing panels for twisted facade

3 Twisted panels with flat glass for curved facades

3D views of unitised glazing panels with twisted frame and flat glass to achieve curvature and externally-fixed louvres

Details
1. Primary steel structure
2. Unitised double glazed facade panel
3. Outer glazed wall
4. Inner glazed wall
5. Perimeter frame to panel
6. Intermediate horizontal framing member
7. Floor finish
8. Floor slab
9. Ceiling finish
10. Structural column
11. Metal cap pieces fixed to front of unitised frame
12. Insulated opaque spandrel panel
13. Gutter
14. Double glazing

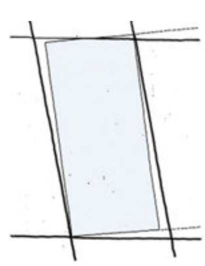


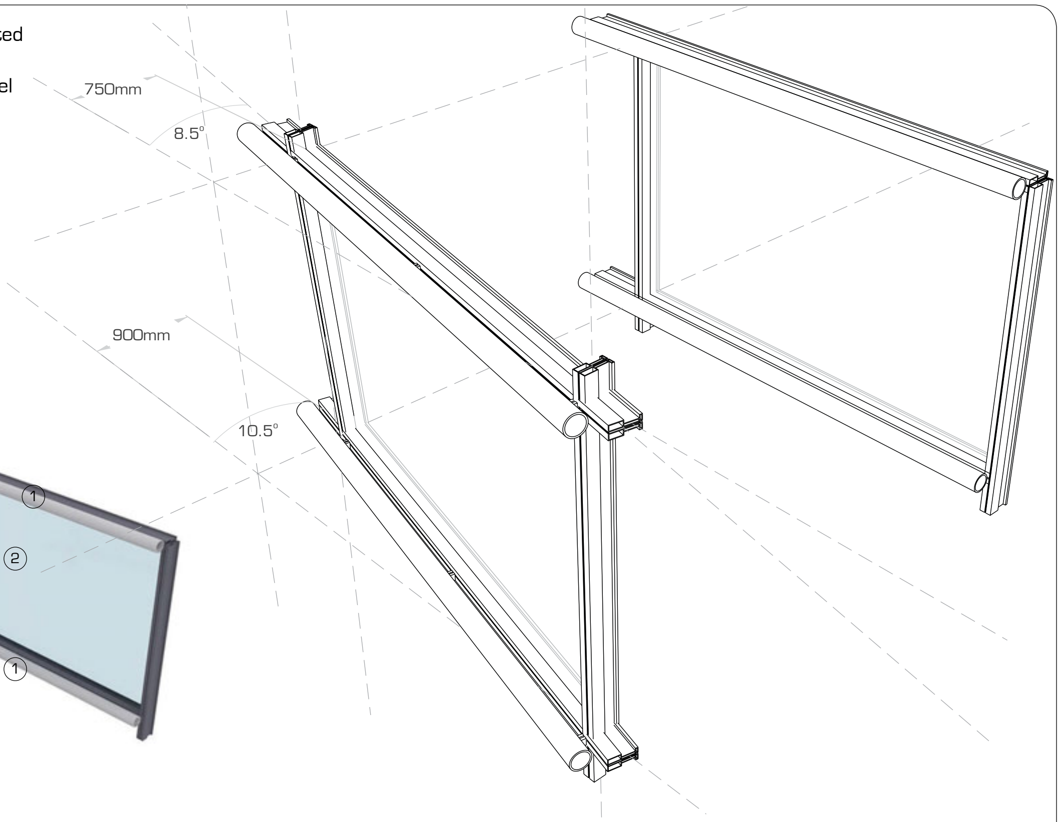


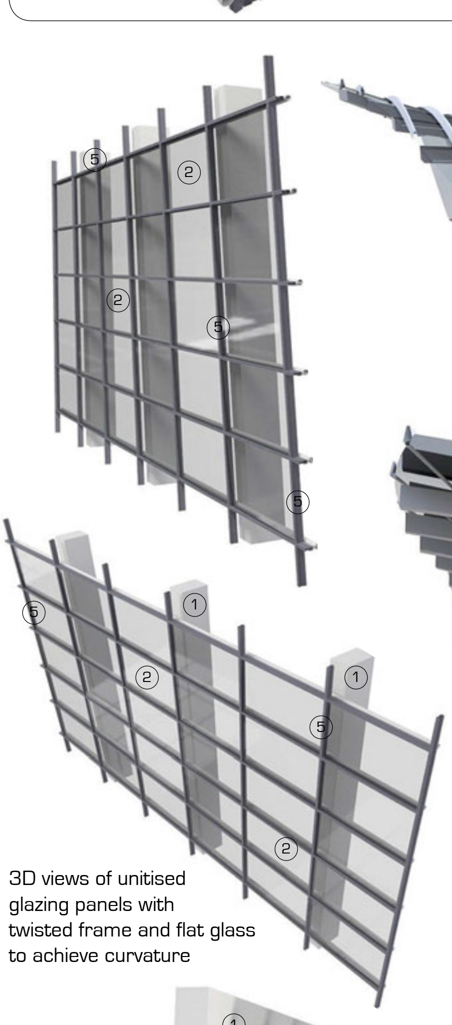
3D views showing unitised glazing panels with twisted frame and flat glass to achieve curvature and externally-fixed louvres

Vertical sections. Unitised facade panel system with opaque spandrel panels at floor level

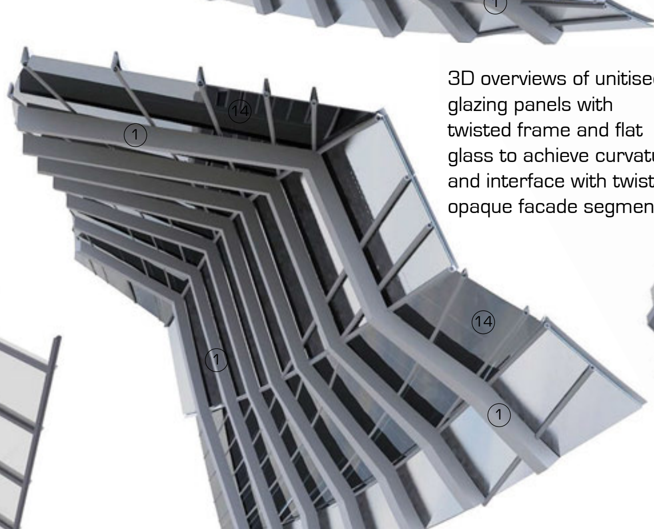
Glazed facade detail with segmented louvre elements:
Twisted frame panel, with flat panel glass to achieve curvature

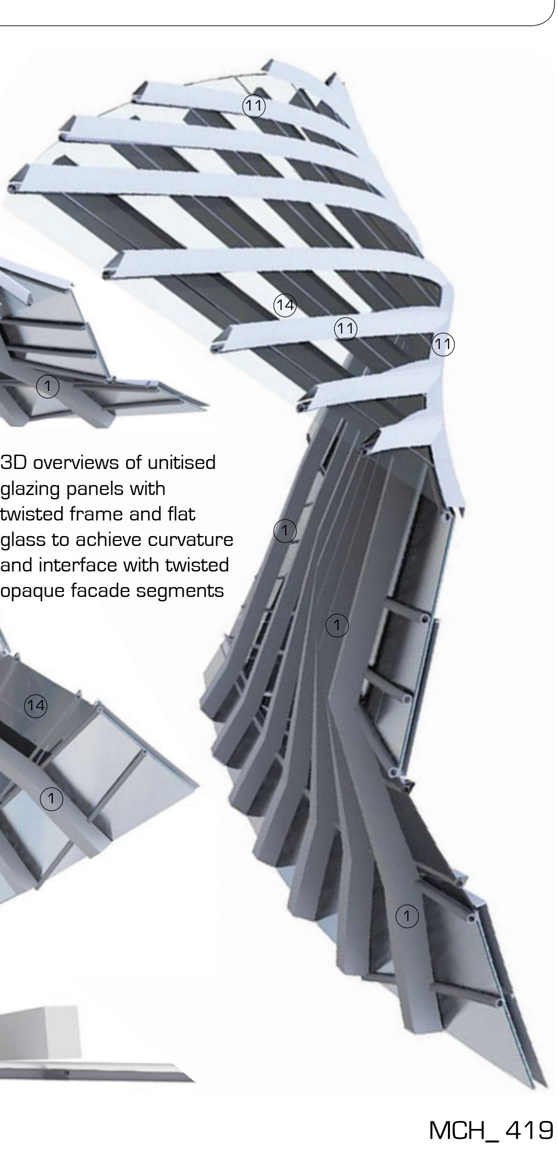






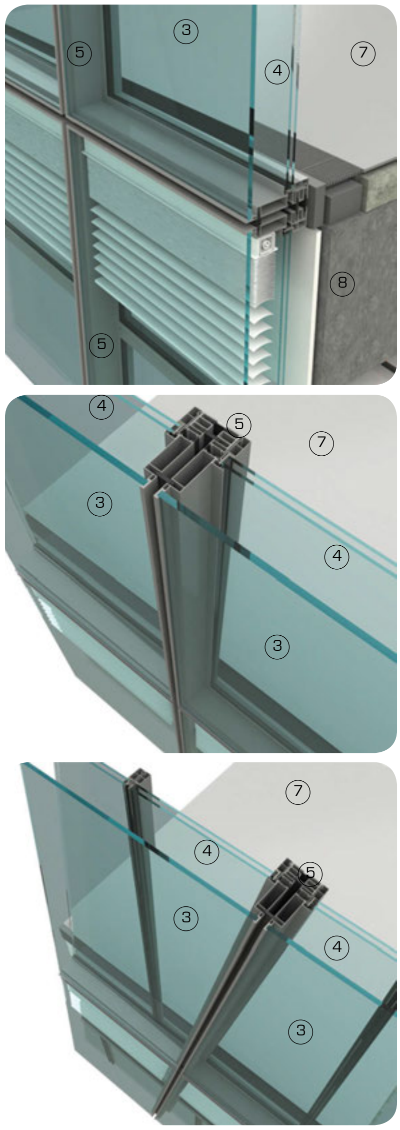
3D views of unitised glazing panels with twisted frame and flat glass to achieve curvature





3D overviews of unitised glazing panels with twisted frame and flat glass to achieve curvature and interface with twisted opaque facade segments

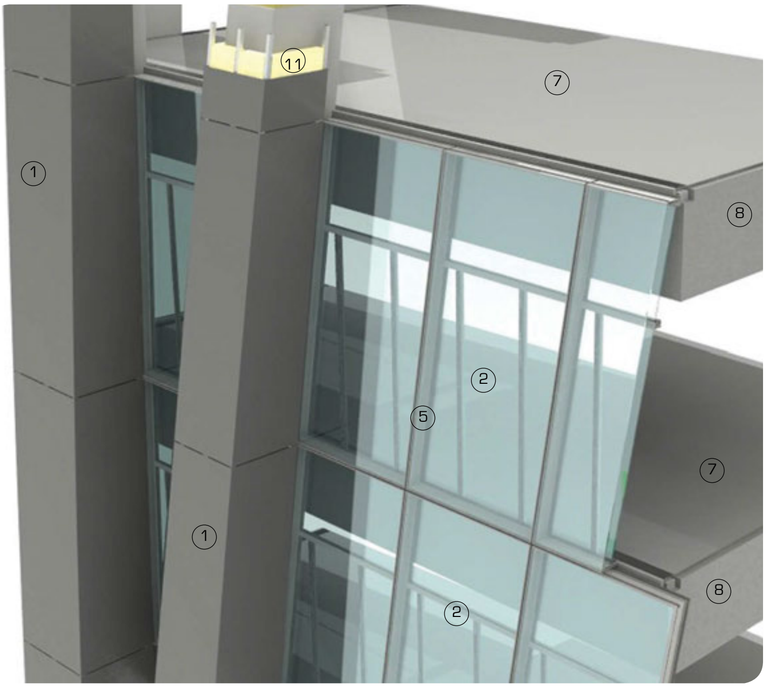
3D fragment view showing unitised double skin glazed facade panel system for twisted facade

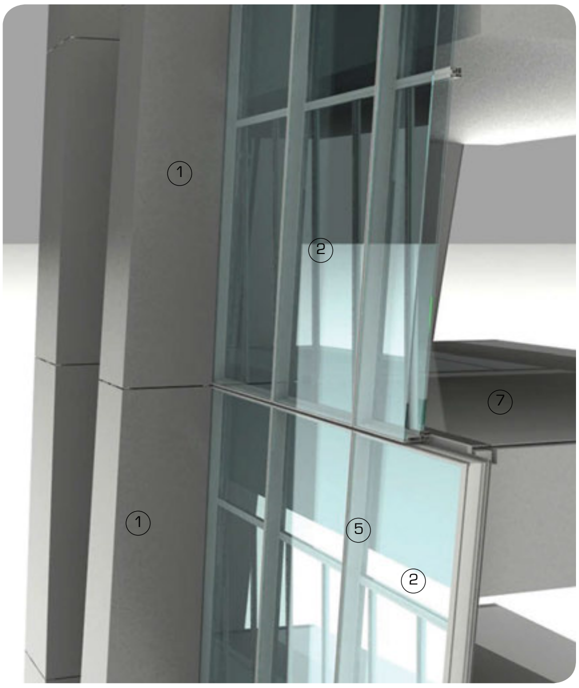


3D detail views showing unitised double skin glazed facade system for twisted facade

(Below) 3D overview showing unitised double skin glazed facade panel system for twisted facade

Details
1. Metal cladding to exoskeleton structure
2. Unitised double skin facade panel
3. Outer glazed wall
4. Inner glazed wall
5. Perimeter frame to panel
6. Intermediate horizontal framing member
7. Floor finish
8. Floor slab
9. Ceiling finish
10. Structural column
11. Thermal insulation
12. Double glazing
13. Opaque spandrel panel



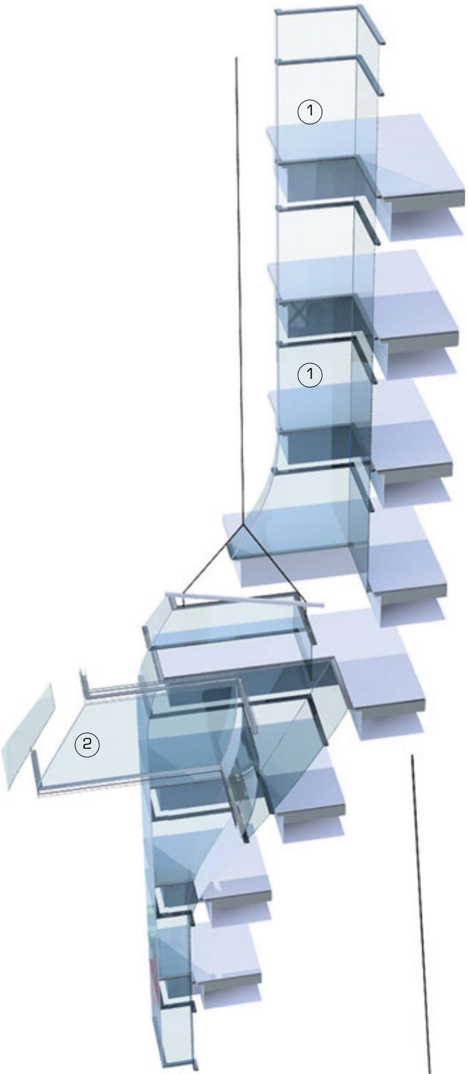


3D sectional views showing unitised double skin glazed facade panel system for twisted facade

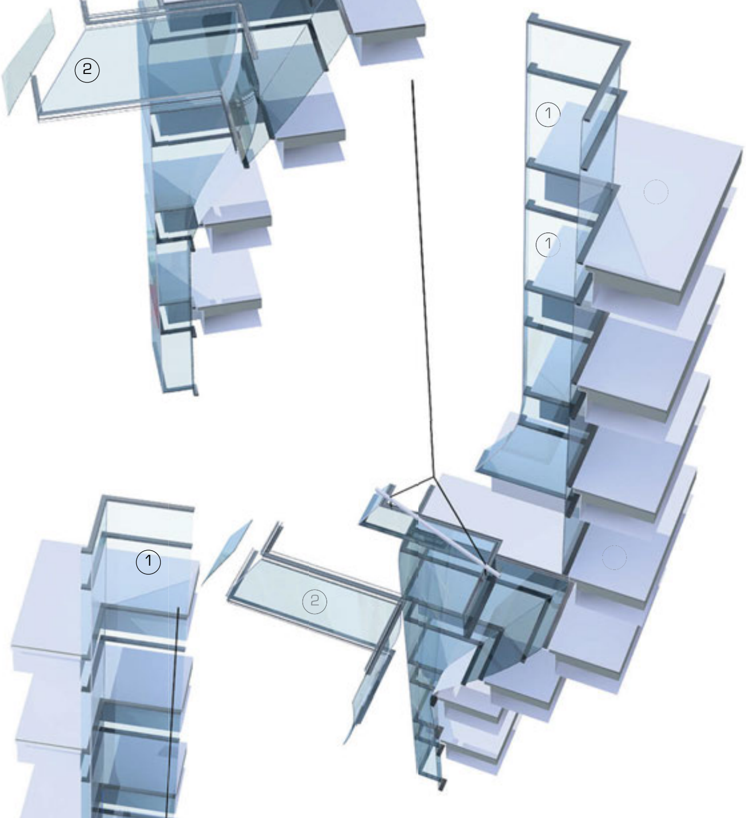
3D views showing unitised double skin glazed facade panel system for twisted facade

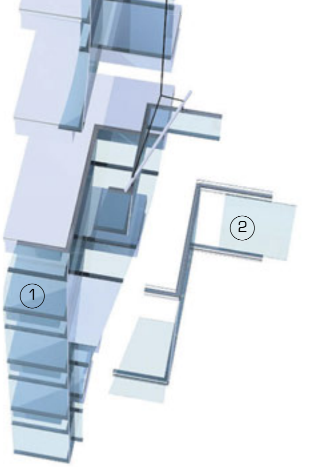
(Above) 3D exploded view showing unitised double skin glazed facade panel system for twisted facade

(Left) 3D view showing unitised double skin glazed facade panel system for twisted facade

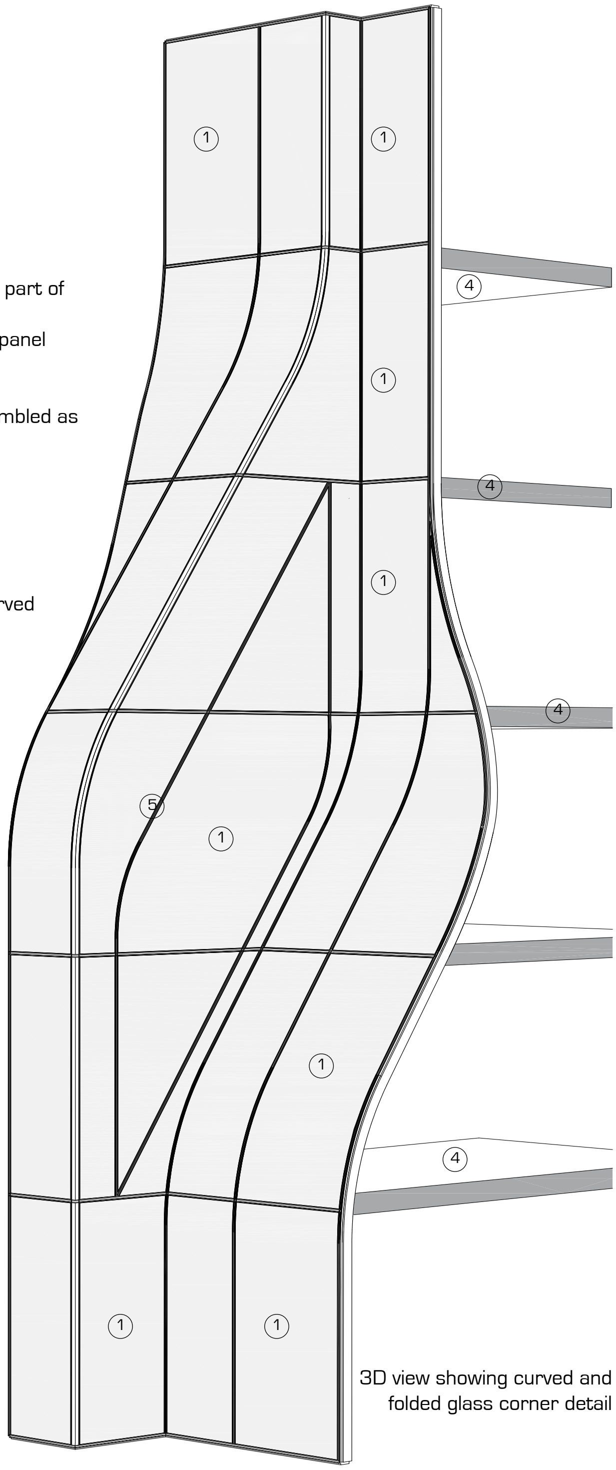


Details
1. Curved glass (assembled as part of the unitised panel)
2. Factory assembled unitised panel
3. On site crane
4. Concrete floor slab
5. Curved glazing frame (assembled as part of the unitised panel)

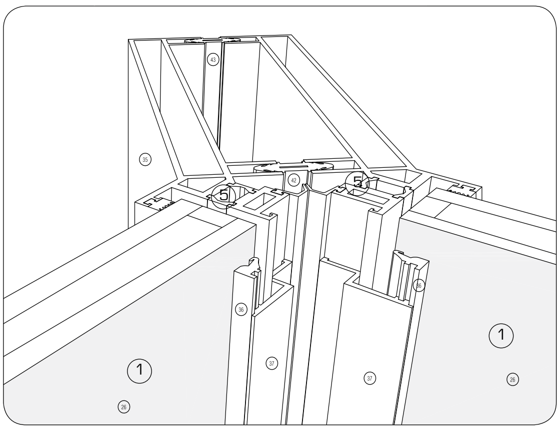


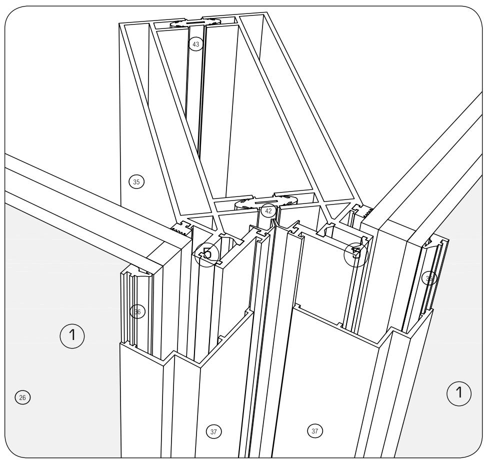


3D exploded views showing curved and folded glass corner detail

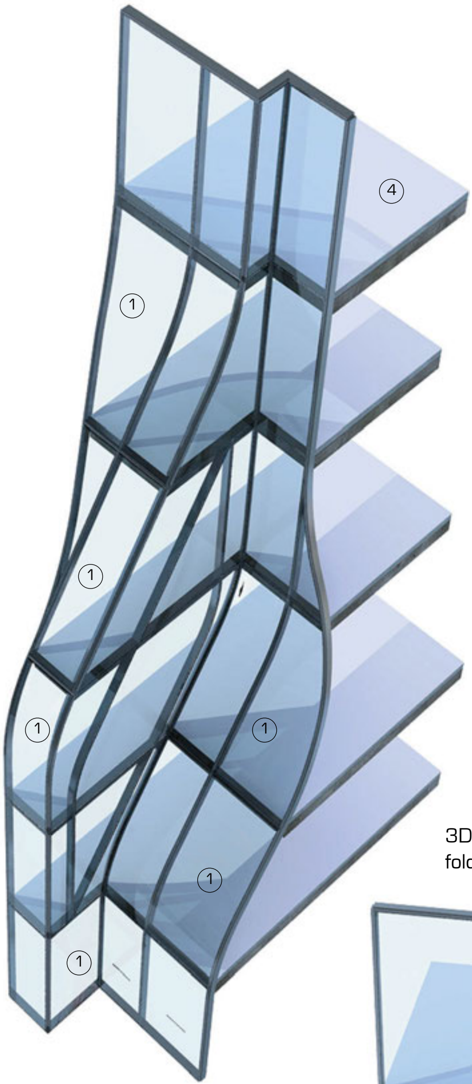


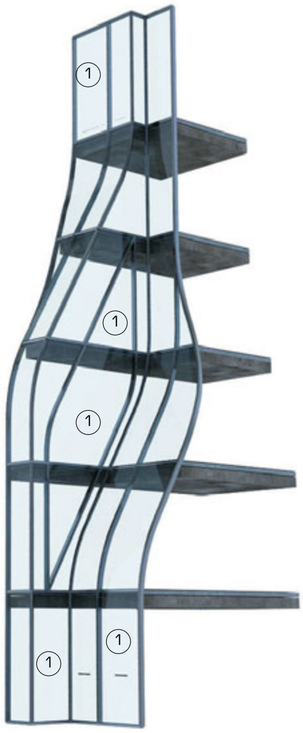
3D view showing curved and folded glass corner detail



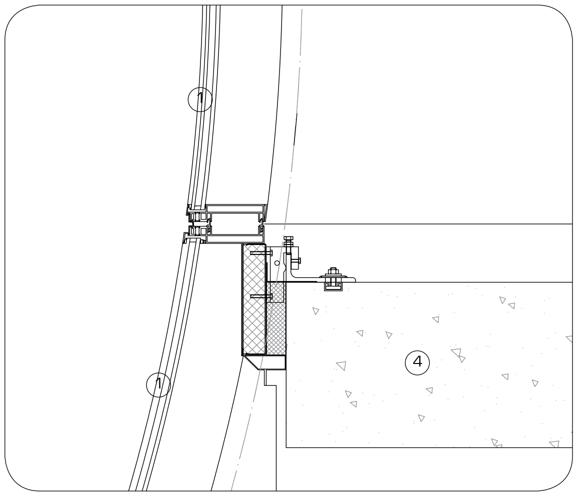


3D views showing curved and folded glass corner detail

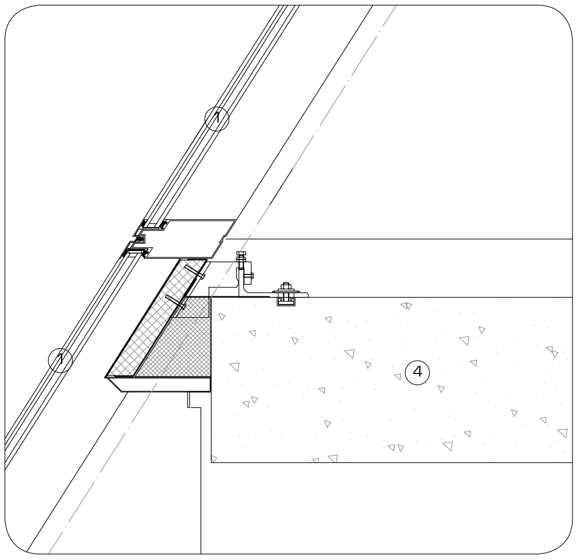




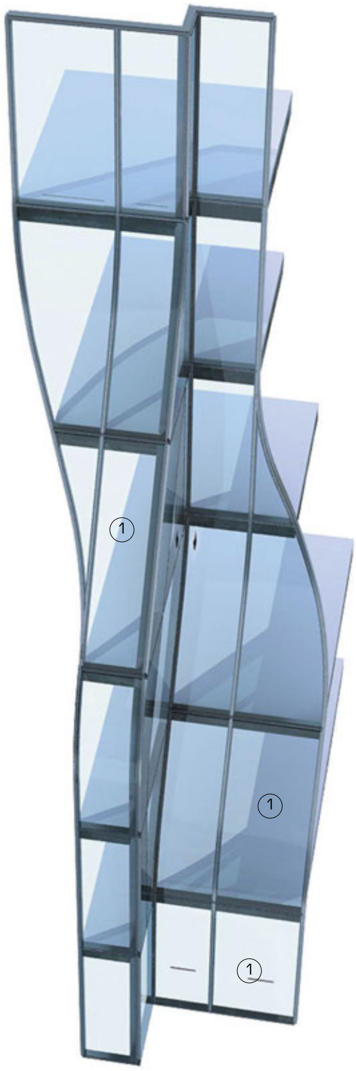
3D views showing curved and folded glass corner detail



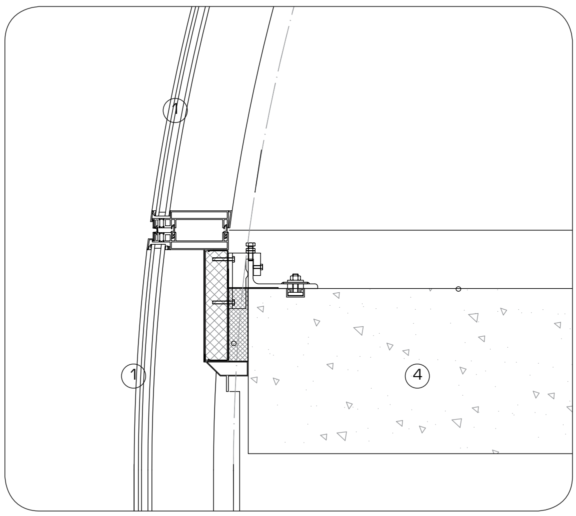
Vertical section. Curved unitised glazing at floor-slab junction



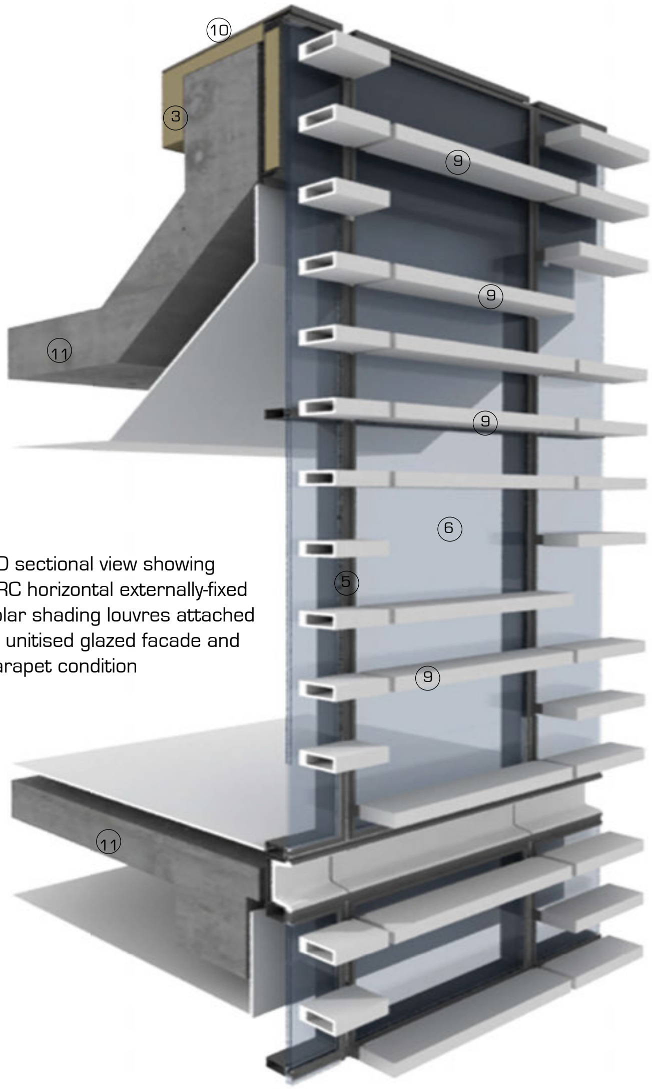
Vertical section. Curved unitised glazing at floor-slab junction



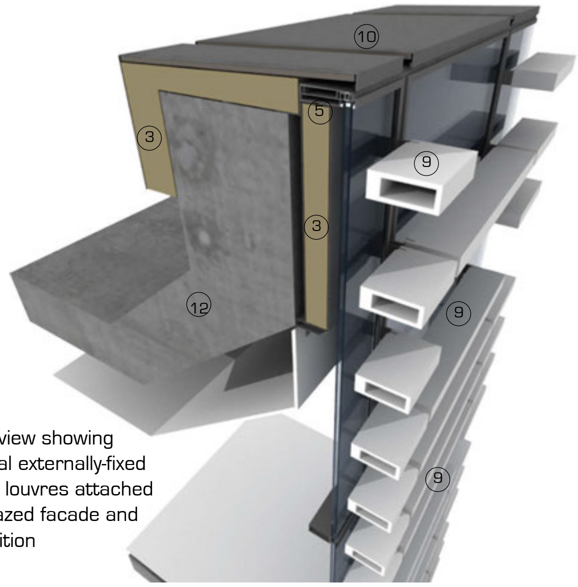
3D views showing curved and folded glass corner detail



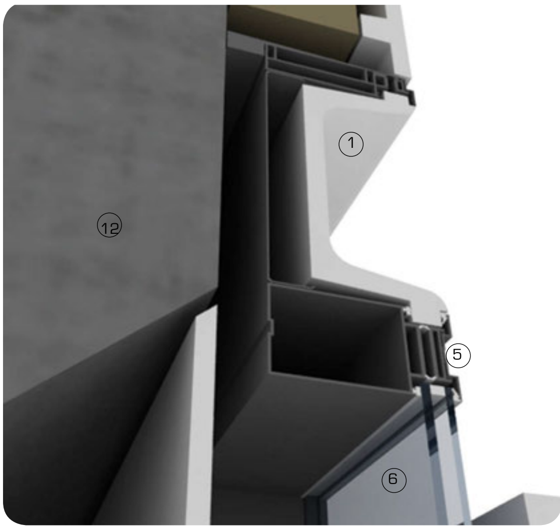
Vertical section. Curved unitised glazing at floor-slab junction



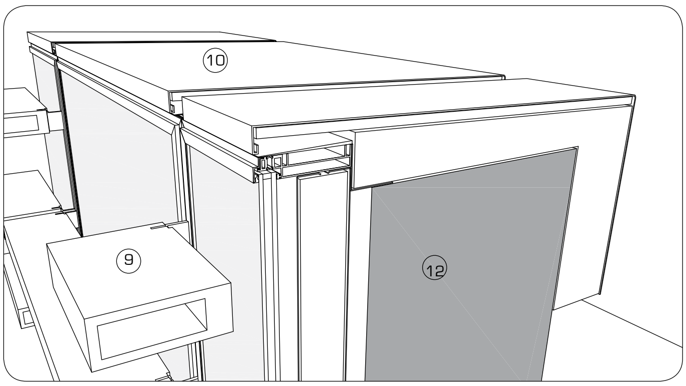
3D sectional view showing GRC horizontal externally-fixed solar shading louvres attached to unitised glazed facade and parapet condition



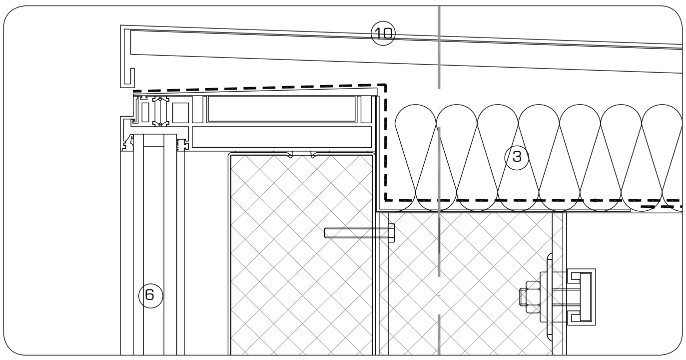
3D sectional view showing GRC horizontal externally-fixed solar shading louvres attached to unitised glazed facade and parapet condition



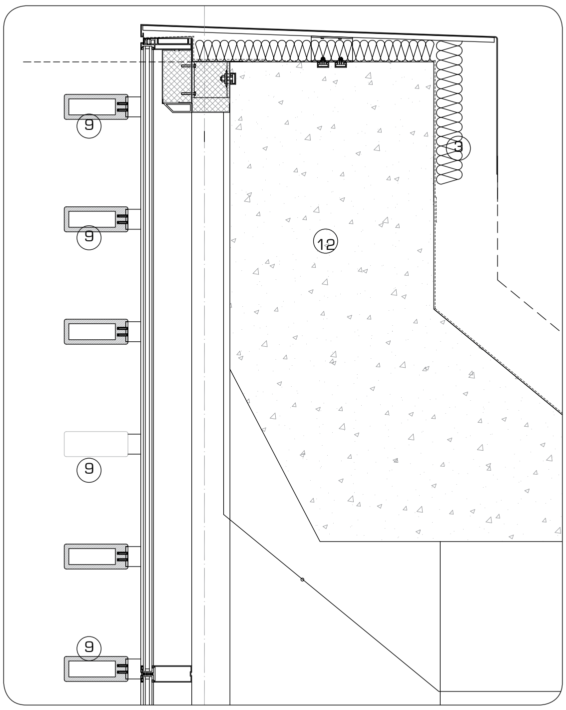
3D sectional view showing GRC horizontal externally-fixed solar shading louvres attached to unitised glazed facade at floor slab



3D sectional view showing GRC horizontal externally-fixed solar shading louvres attached to unitised glazed facade and parapet condition

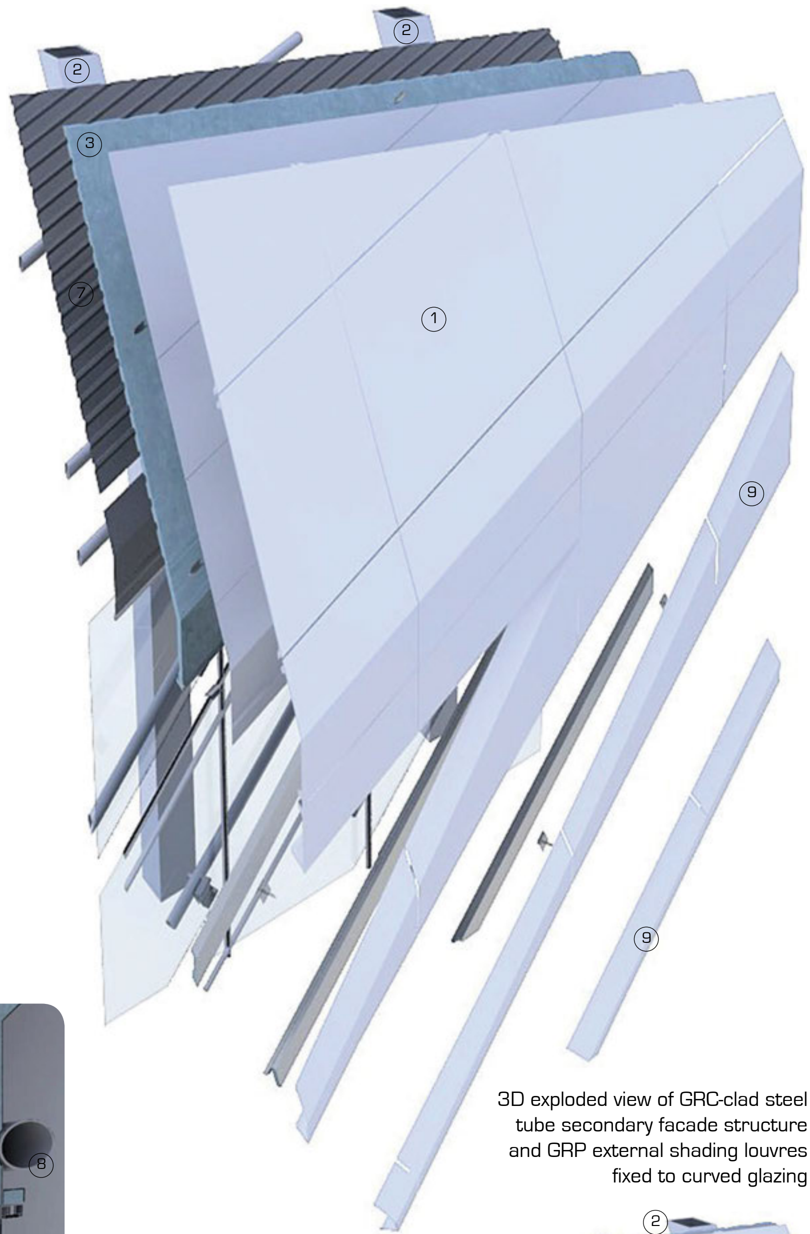


Vertical section. GRC horizontal externally-fixed solar shading louvres attached to unitised glazed facade at parapet condition

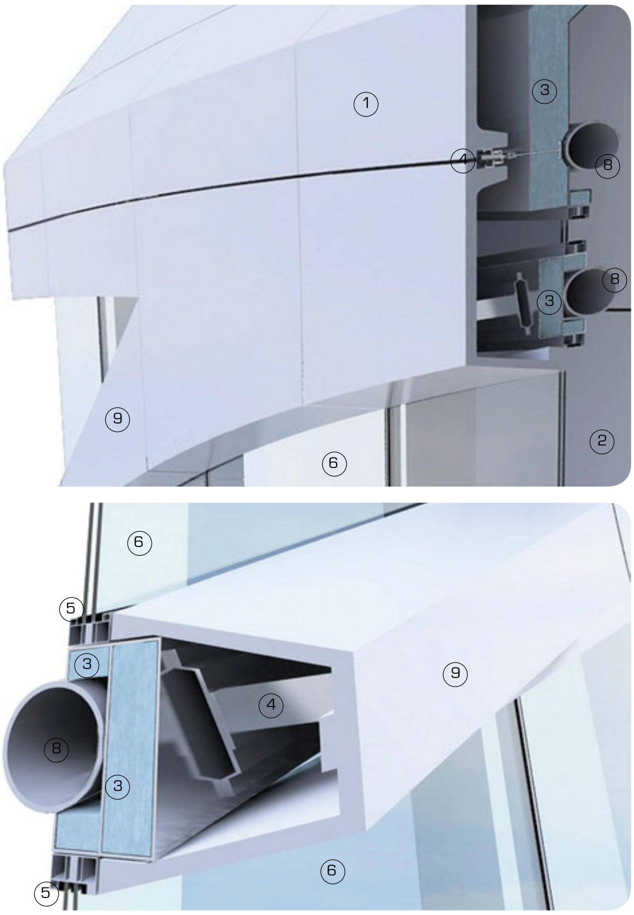


Vertical section. GRC horizontal externally-fixed solar shading louvres attached to unitised glazed facade at parapet condition

3D sectional view showing GRC-clad steel tube secondary facade structure and GRP external shading louvres fixed to curved glazing



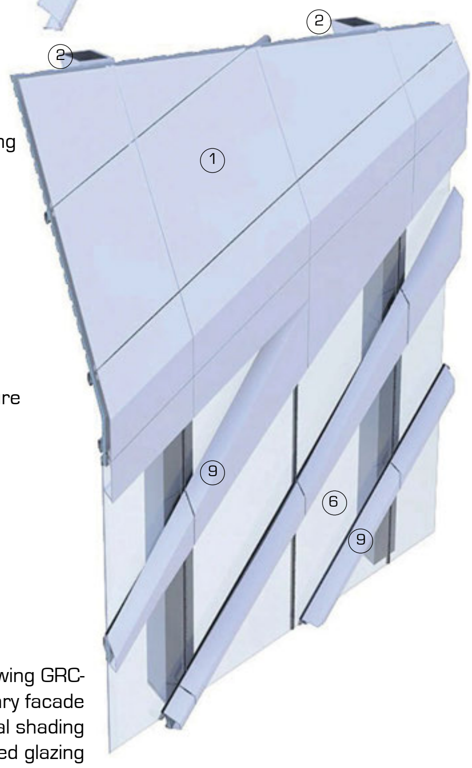
3D exploded view of GRC-clad steel tube secondary facade structure and GRP external shading louvres fixed to curved glazing



3D detail views showing GRC-clad steel tube secondary facade structure and GRP external shading louvres fixed to curved glazing

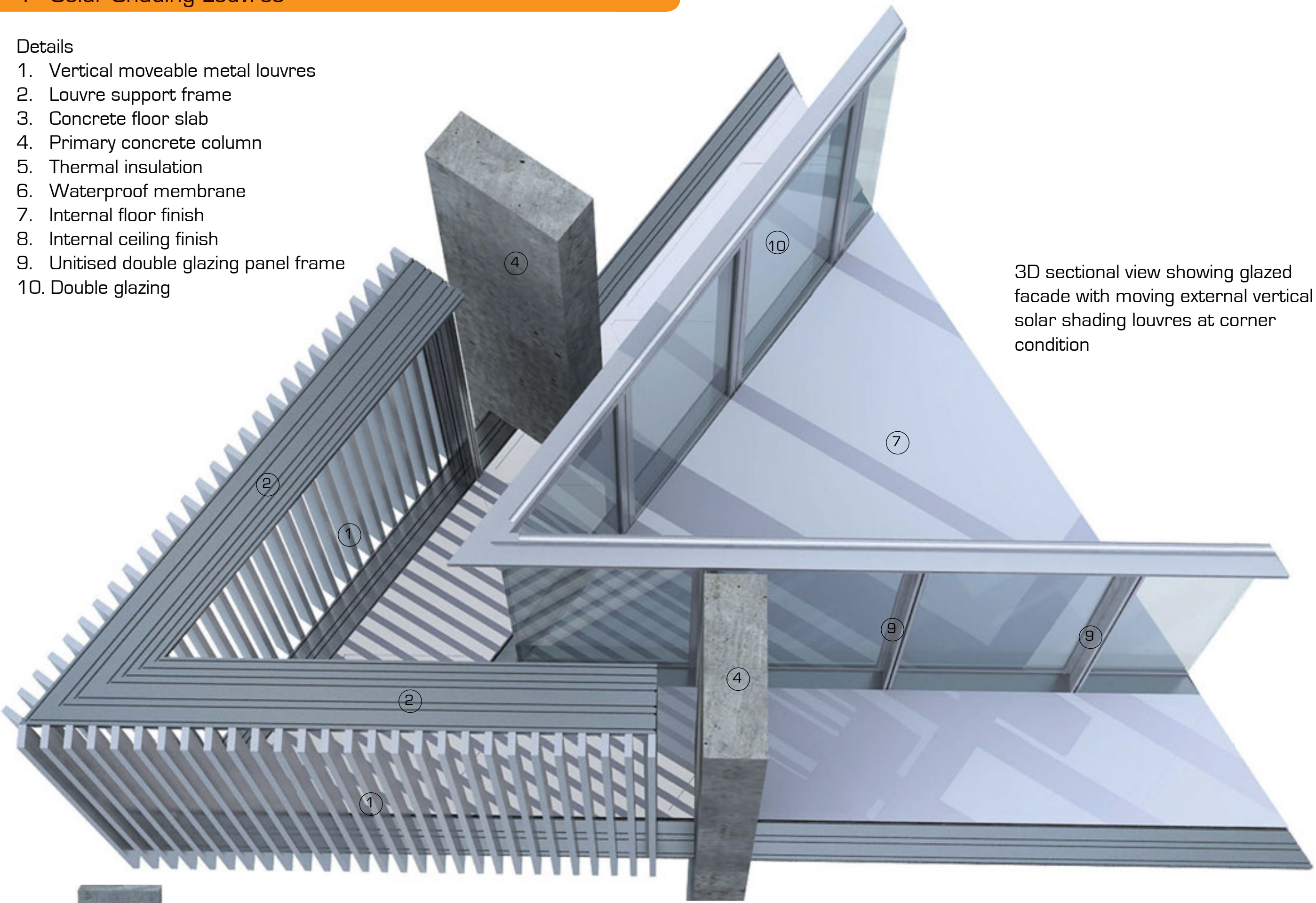
Details

1. GRC rainscreen cladding
2. Primary steel columns (insulated and faced)
3. Thermal insulation
4. Rainscreen panel fixing system
5. Glazing frame
6. Double glazing
7. Profiled metal deck
8. Steel tube secondary facade support structure
9. GRC external shading louvres
10. Parapet cladding
11. Concrete floor slab
12. Concrete primary structure

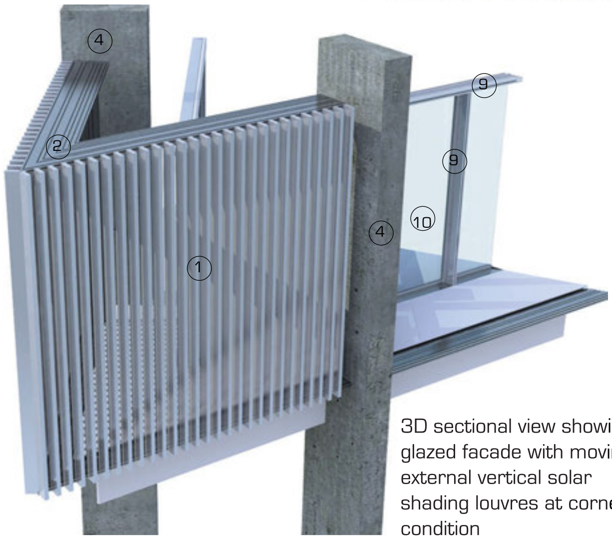


3D sectional view showing GRC-clad steel tube secondary facade structure and GRP external shading louvres fixed to curved glazing

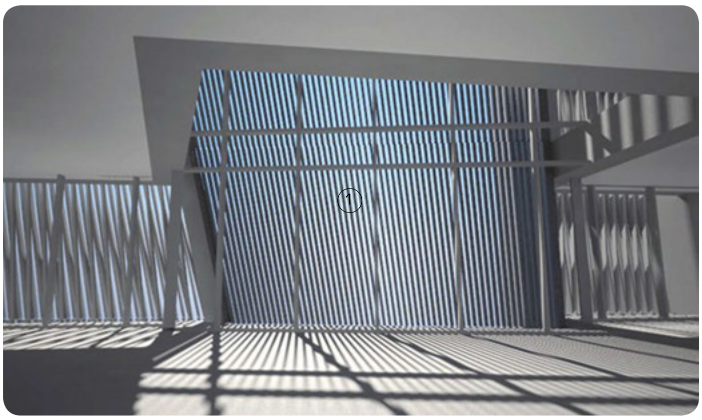
Details
1. Vertical moveable metal louvres
2. Louvre support frame
3. Concrete floor slab
4. Primary concrete column
5. Thermal insulation
6. Waterproof membrane
7. Internal floor finish
8. Internal ceiling finish
9. Unitised double glazing panel frame
10. Double glazing



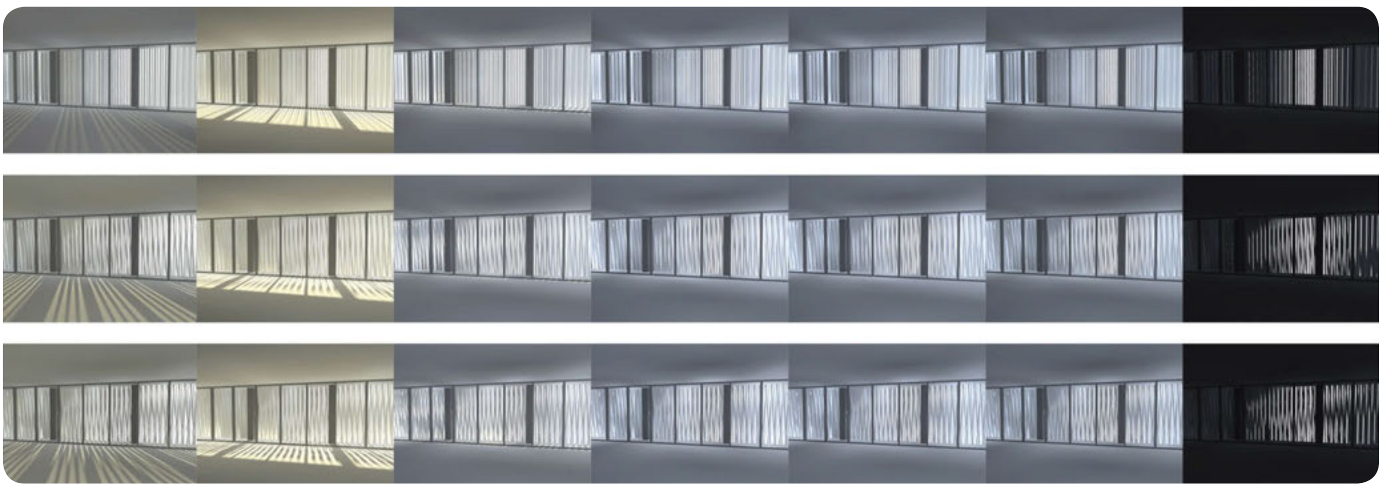
3D sectional view showing glazed facade with moving external vertical solar shading louvres at corner condition



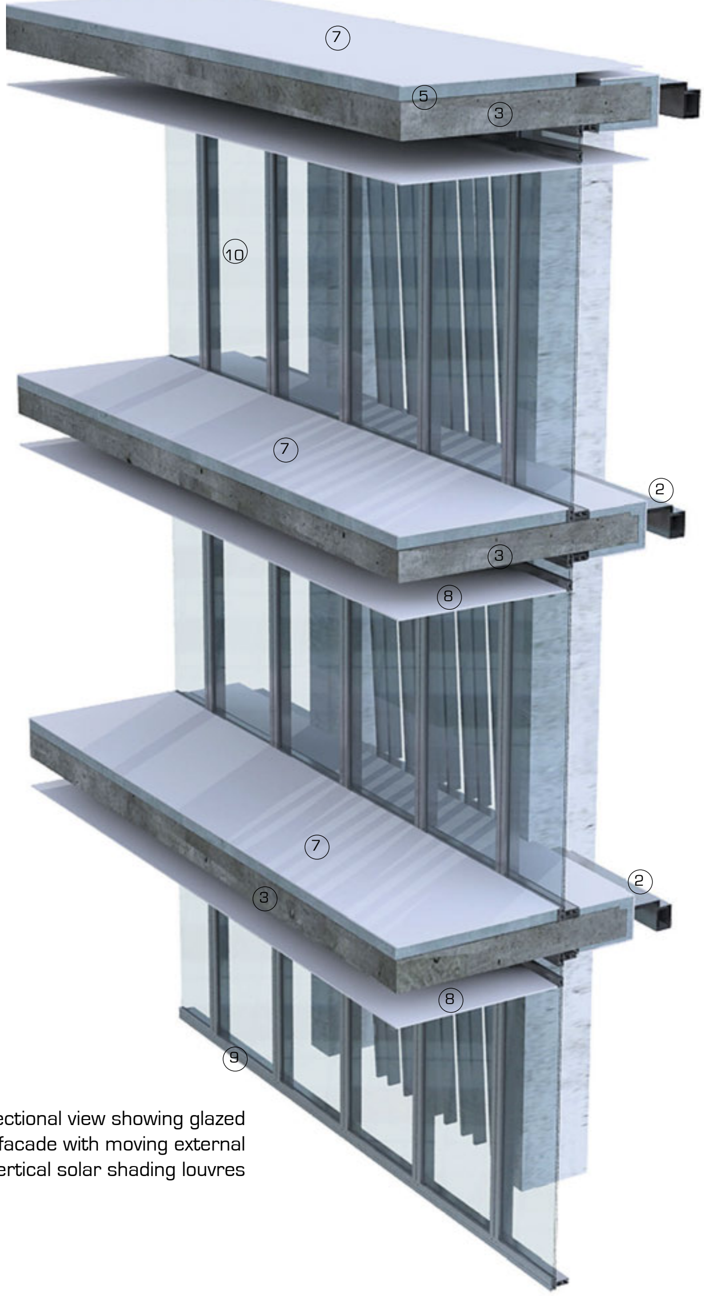
3D sectional view showing glazed facade with moving external vertical solar shading louvres at corner condition



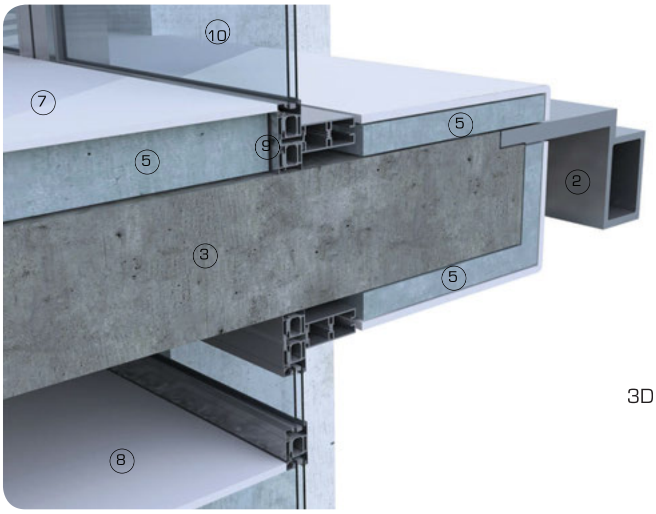
3D internal view showing glazed facade with moving external vertical solar shading louvres



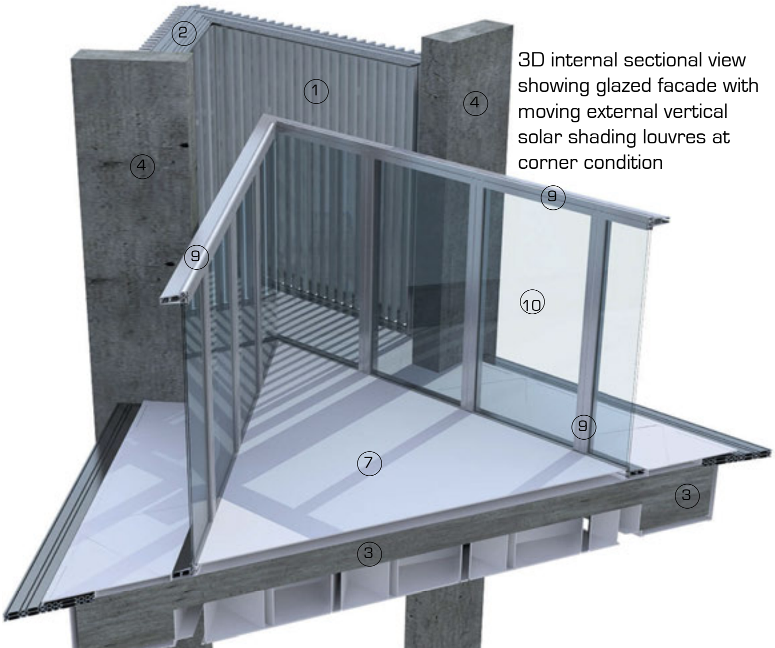
3D internal views showing effects of external vertical shading louvres throughout the day



3D sectional view showing glazed facade with moving external vertical solar shading louvres

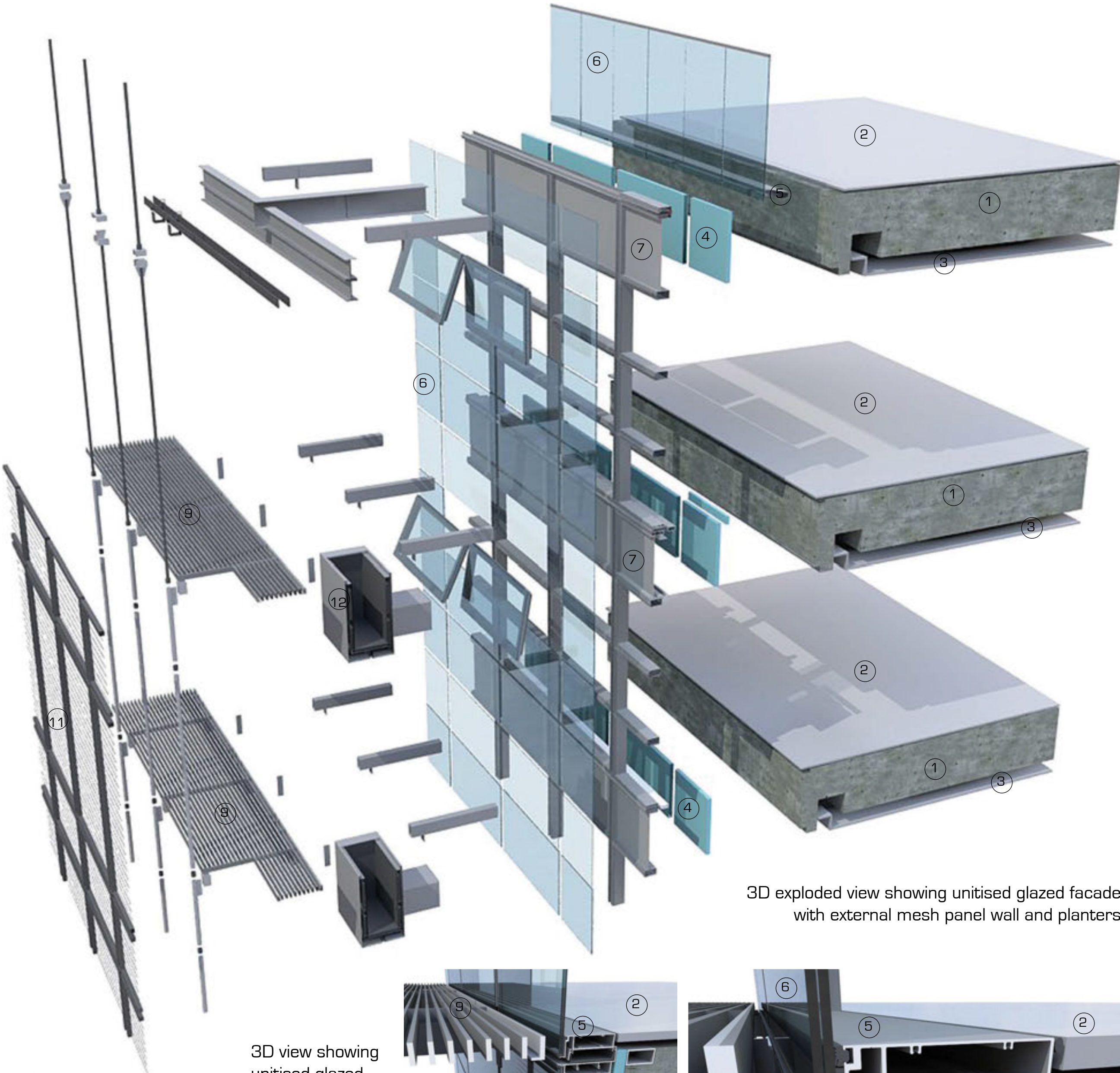


3D detail sectional views showing glazed facade with moving external vertical solar shading louvres

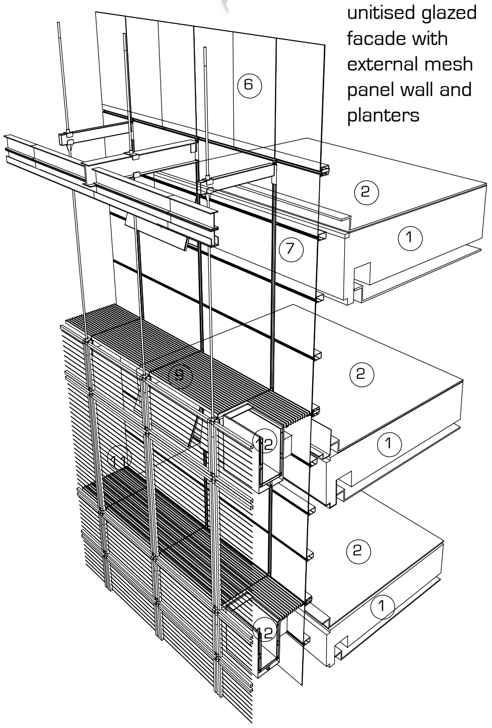


3D internal sectional view showing glazed facade with moving external vertical solar shading louvres at corner condition

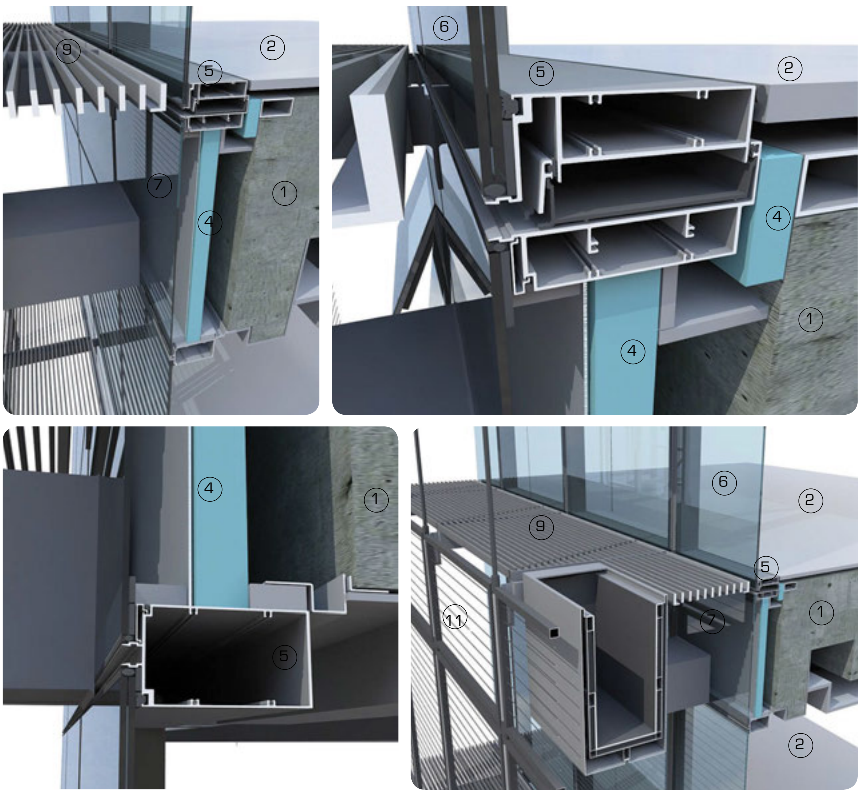
3D detail sectional view showing glazed facade with moving external vertical solar shading louvres



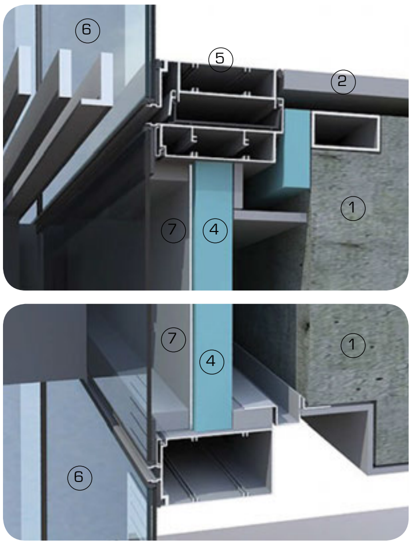
3D exploded view showing unitised glazed facade with external mesh panel wall and planters



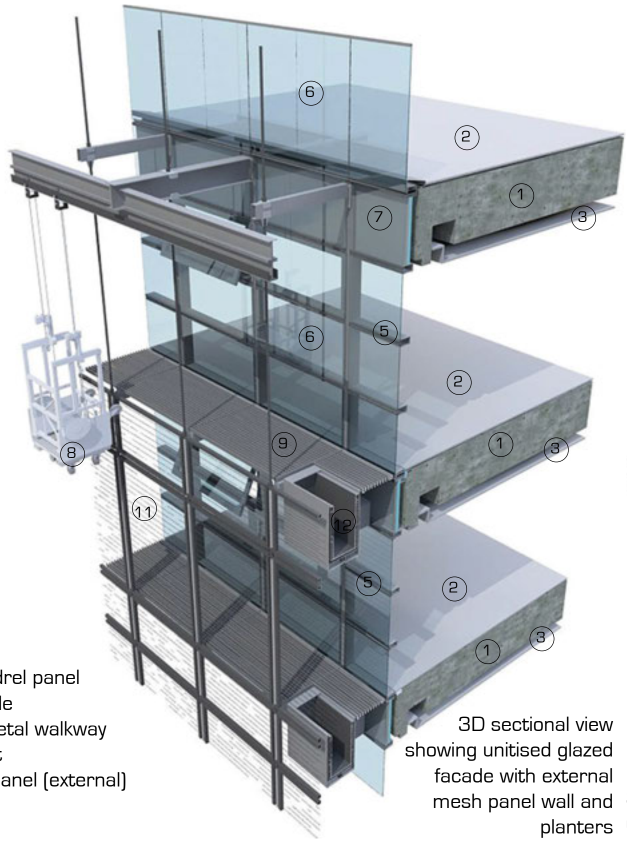
3D view showing unitised glazed facade with external mesh panel wall and planters



3D detail views showing unitised glazed facade with external mesh panel wall and planters at floor slab interface



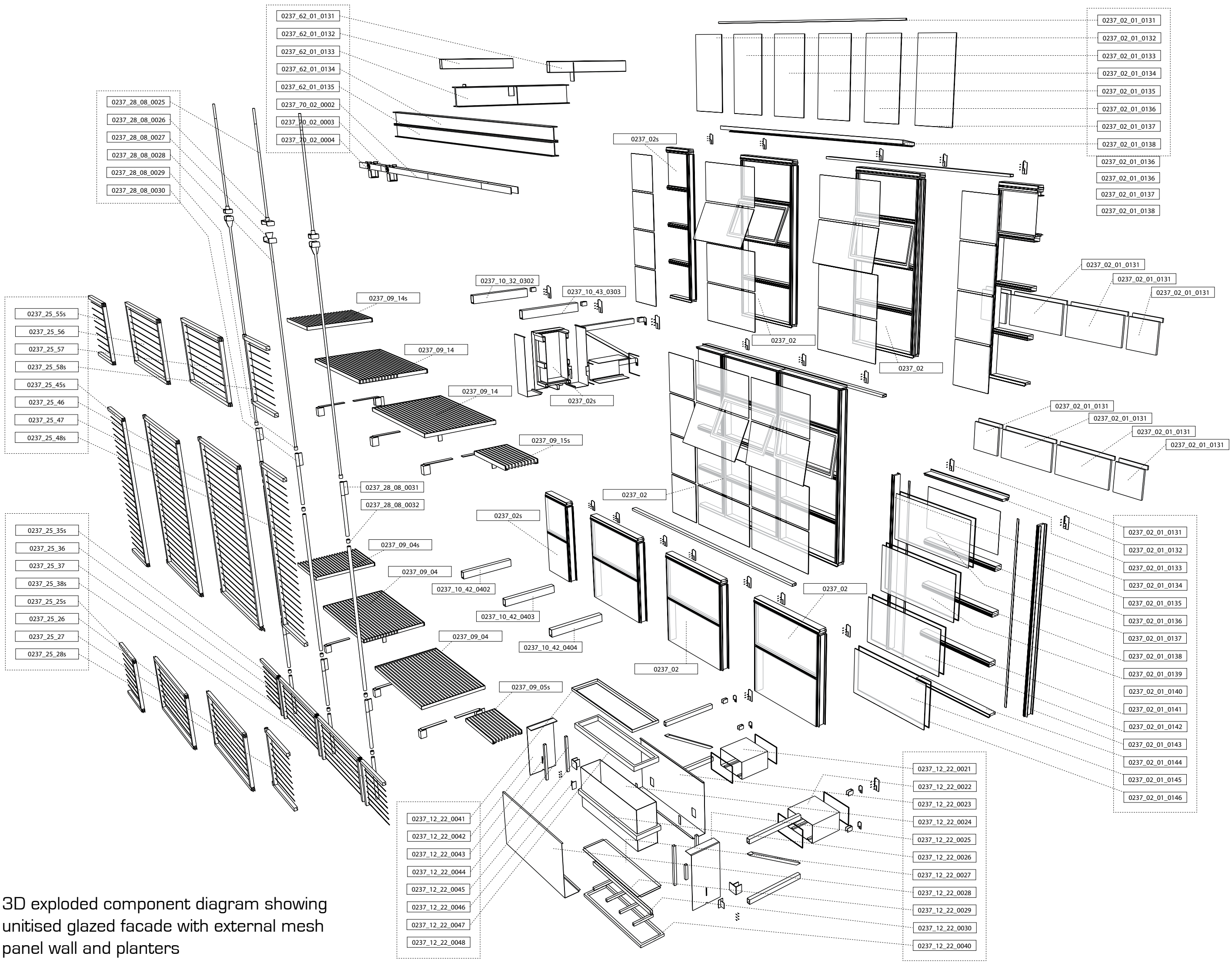
3D views showing unitised glazing details on full-height glazed facade



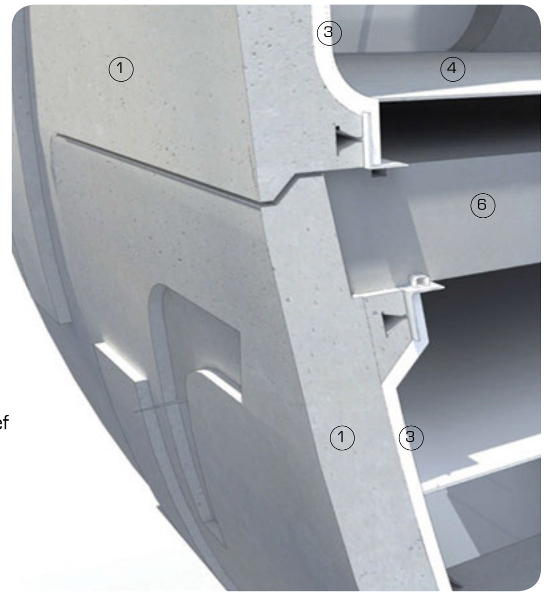
Details
1. Floor slab
2. Internal floor finish
3. Internal ceiling finish
4. Thermal insulation
5. Unitised glazing frame
6. Double glazing
7. Opaque spandrel panel
8. Cleaning cradle
9. Perforated metal walkway
10. Metal bracket
11. Metal mesh panel (external)
12. Planter

3D sectional view showing unitised glazed facade with external mesh panel wall and planters

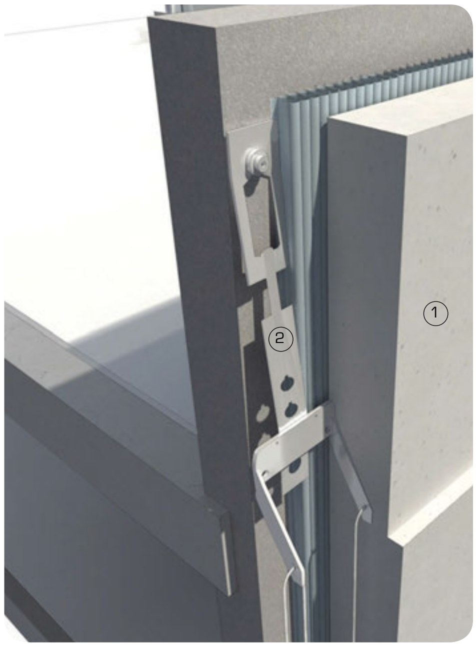
3D sectional internal views showing unitised glazed facade with external mesh panel wall and planters



3D exploded component diagram showing unitised glazed facade with external mesh panel wall and planters



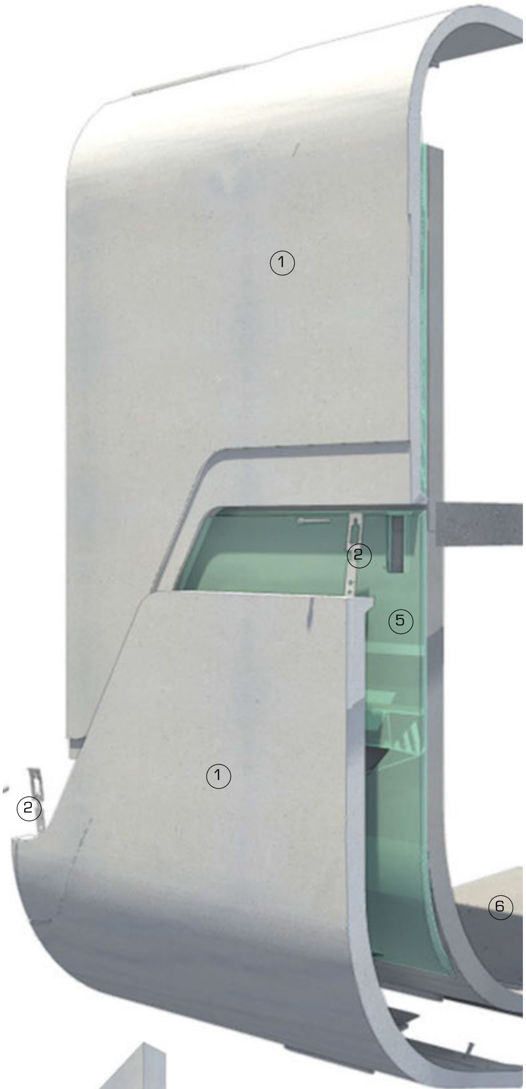
3D views showing large precast concrete cladding panels with moulded surface relief and cast-in window openings



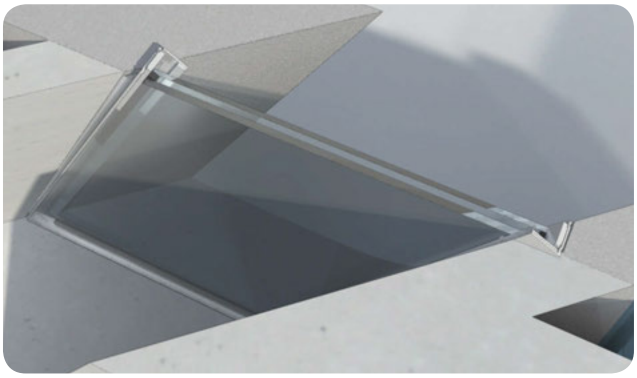
3D sectional views showing fixing system for large precast concrete cladding panels with structural reinforced concrete wall behind

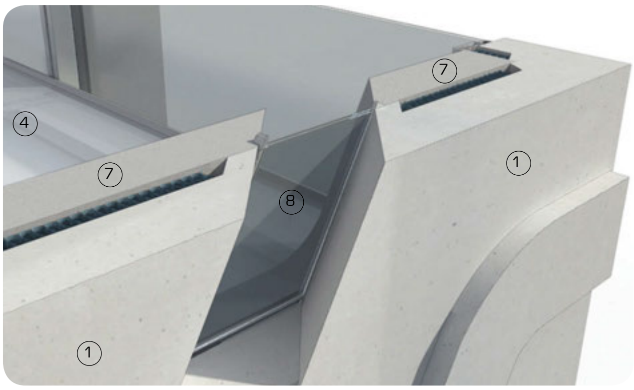
3D exploded, sectional view showing fixing system for large precast concrete cladding panels with structural reinforced concrete wall behind

Details
1. Precast concrete cladding panel
2. Concrete cladding panel lifting hooks (cast-in)
3. Internal wall finish
4. Internal floor finish
5. Thermal insulation
6. Concrete floor slab
7. In-situ cast concrete structural backing wall
8. Unitised double glazed window panel

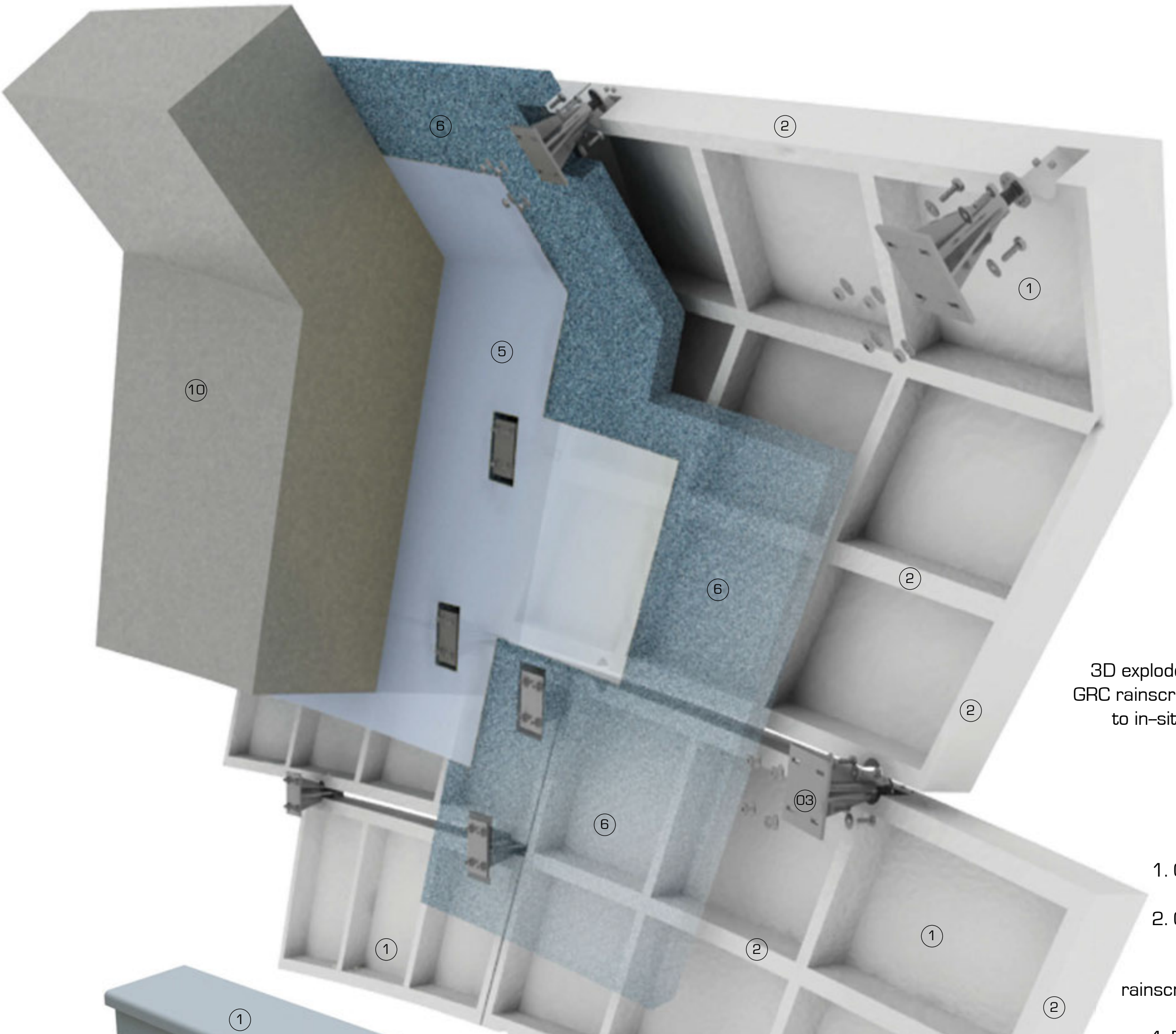


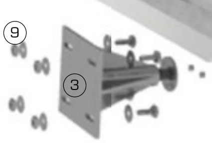
3D exploded, sectional views showing fixing system for large precast concrete cladding panels with structural reinforced concrete wall behind





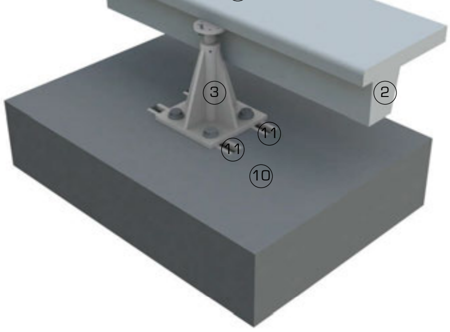
3D sectional views showing window within large precast concrete cladding panel facade system (with structural reinforced concrete wall behind)



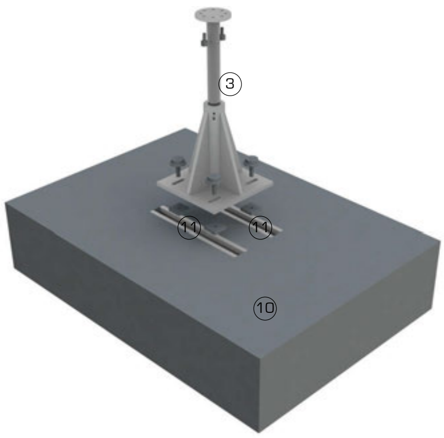


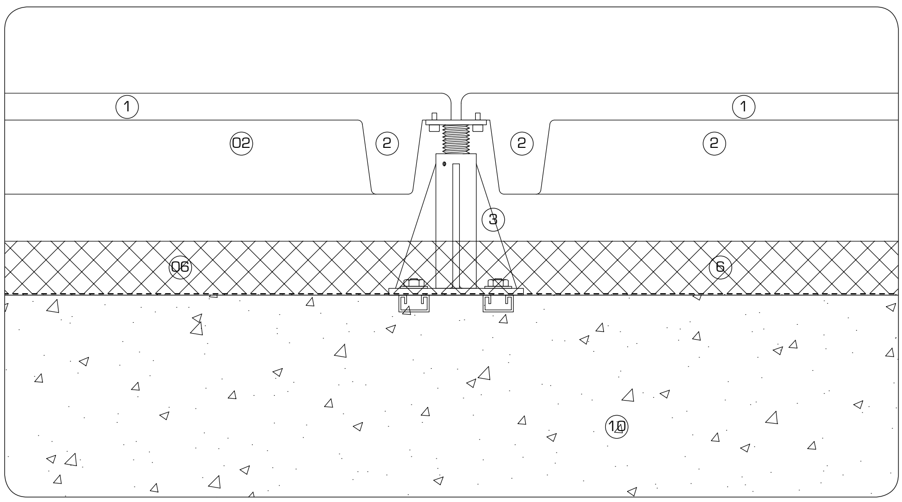
3D exploded view showing GRC rainscreen panels fixed to in-situ cast concrete

Details
1. GRC rainscreen panel
2. GRC rainscreen panel rib
3. Adjustable rainscreen panel fixing bracket
4. Fixed rainscreen panel fixing bracket
5. Waterproof membrane
6. Thermal insulation
7. Primary steel structure
8. Internal wall/ceiling finish
09. Bolt
10. In-situ cast concrete primary structure
11. Cast-in channels

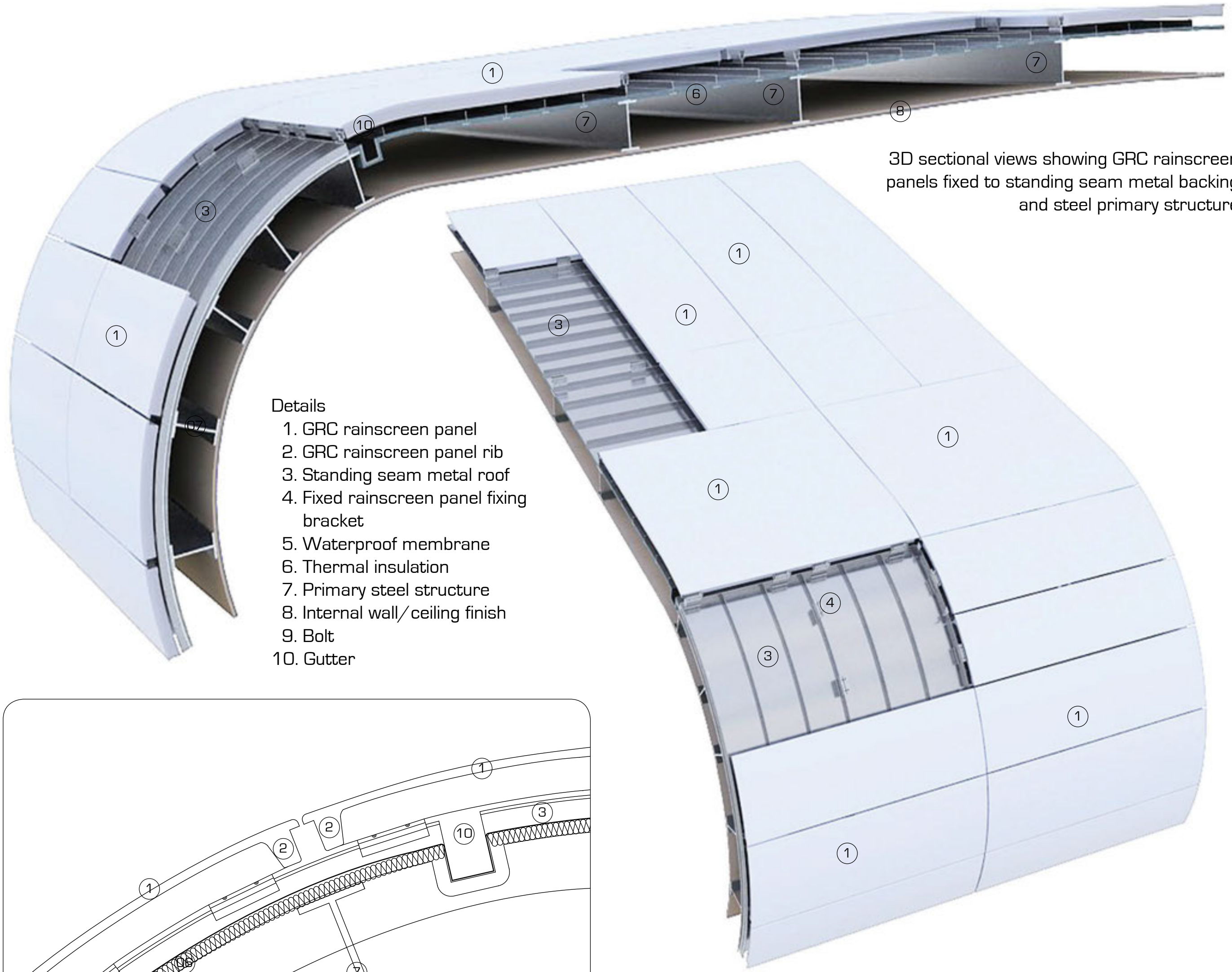


3D fragment views showing GRC rainscreen panels fixed to in-situ cast concrete with adjustable fixing bracket



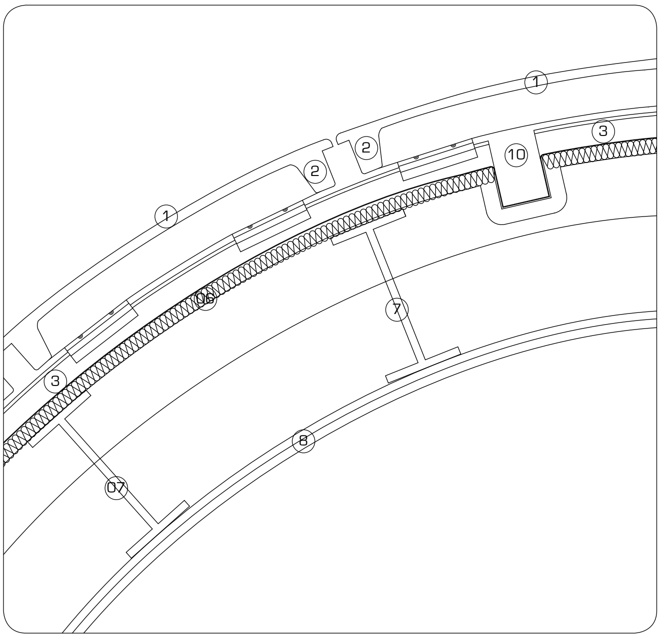


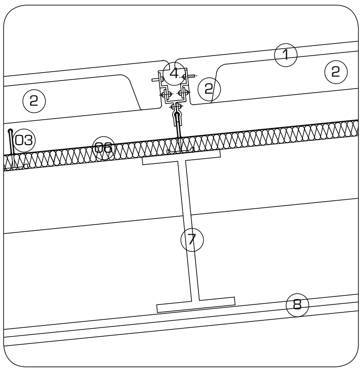
Vertical section. GRC rainscreen panels fixed to in-situ cast concrete

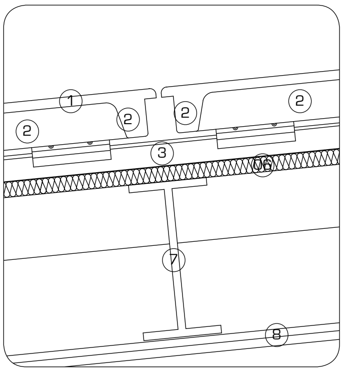


3D sectional views showing GRC rainscreen panels fixed to standing seam metal backing and steel primary structure

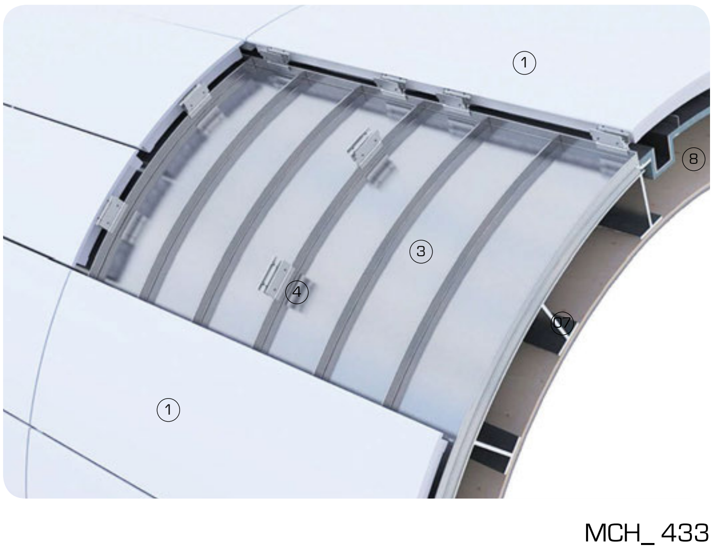
Details
1. GRC rainscreen panel
2. GRC rainscreen panel rib
3. Standing seam metal roof
4. Fixed rainscreen panel fixing bracket
5. Waterproof membrane
6. Thermal insulation
7. Primary steel structure
8. Internal wall/ceiling finish
9. Bolt
10. Gutter







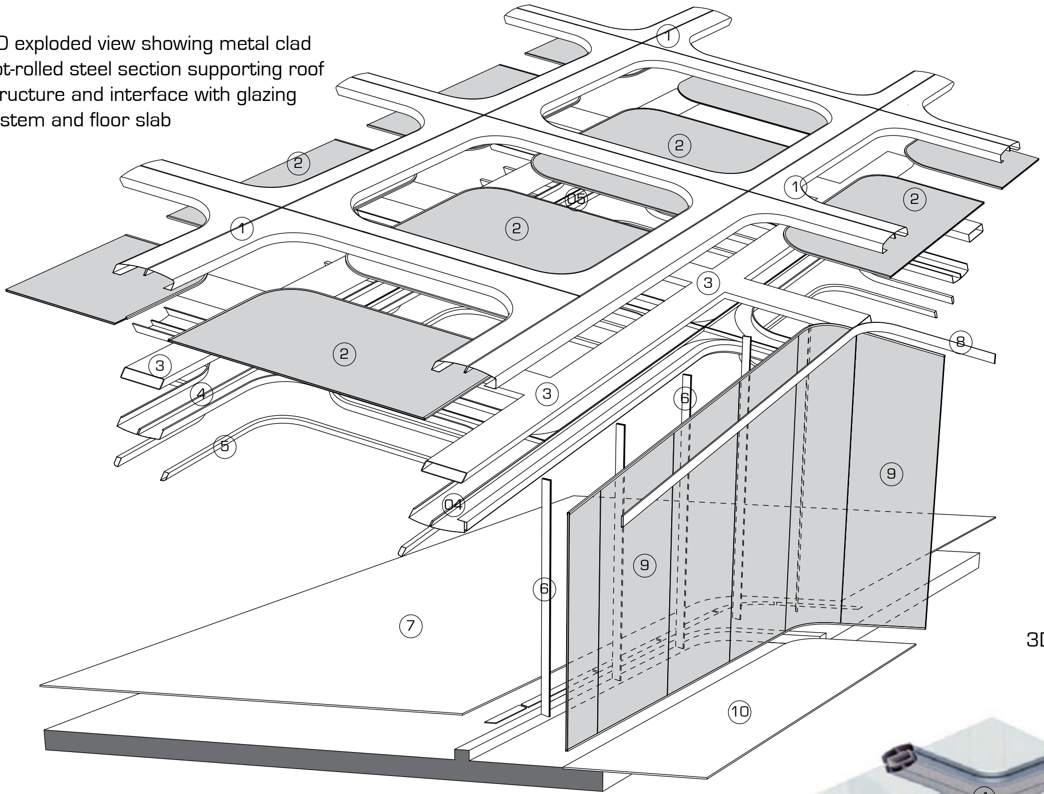
Vertical sections. GRC rainscreen panels fixed to standing seam metal backing and steel primary structure



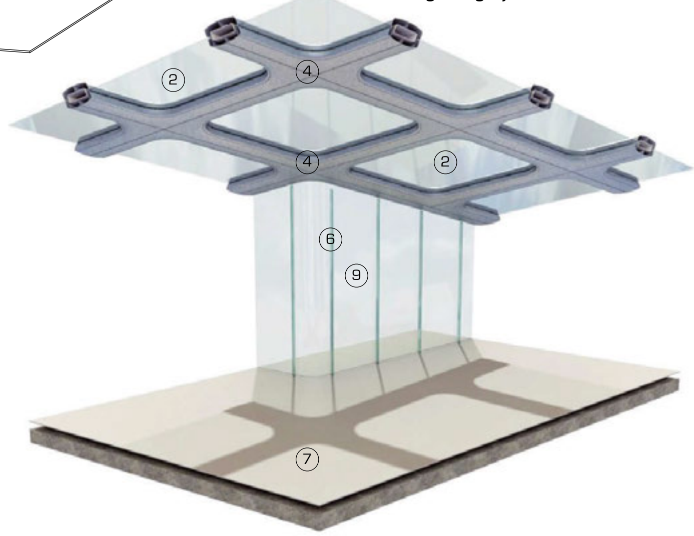
3D detail views showing GRC rainscreen panels fixed to standing seam metal backing and steel primary structure

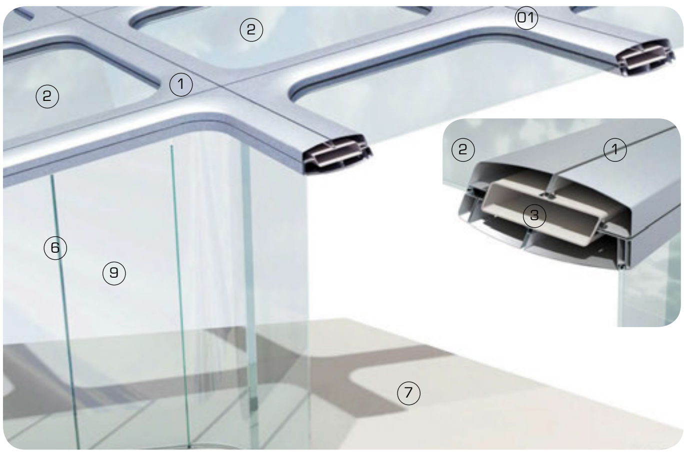
3D exploded view showing metal clad hot-rolled steel section supporting roof structure and interface with glazing system and floor slab

Details
1. Metal outer cladding
2. Double glazed unit
3. Hot-rolled steel section
4. Inner metal cladding
5. Glazing frame
6. Glass fin
7. Internal floor finish
8. Pressure plate
9. Toggle-fixed glazing supported on vertical glass fins
10. External floor finish
11. Concrete slab
12. Precast concrete outer cladding panel
13. Precast fascia panel
14. Supporting steel structure
15. Seal between precast concrete elements

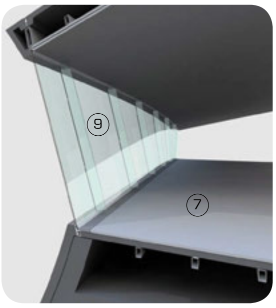


3D sectional view showing metal clad hot-rolled steel section supporting roof structure and interface with glazing system and floor slab

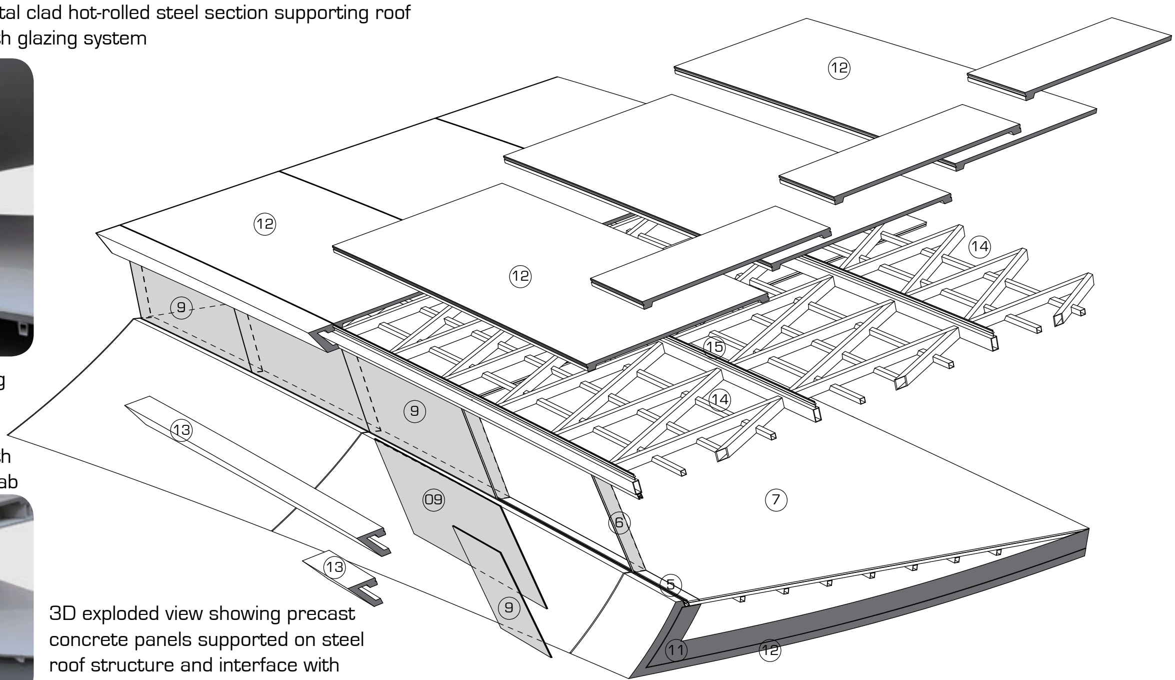




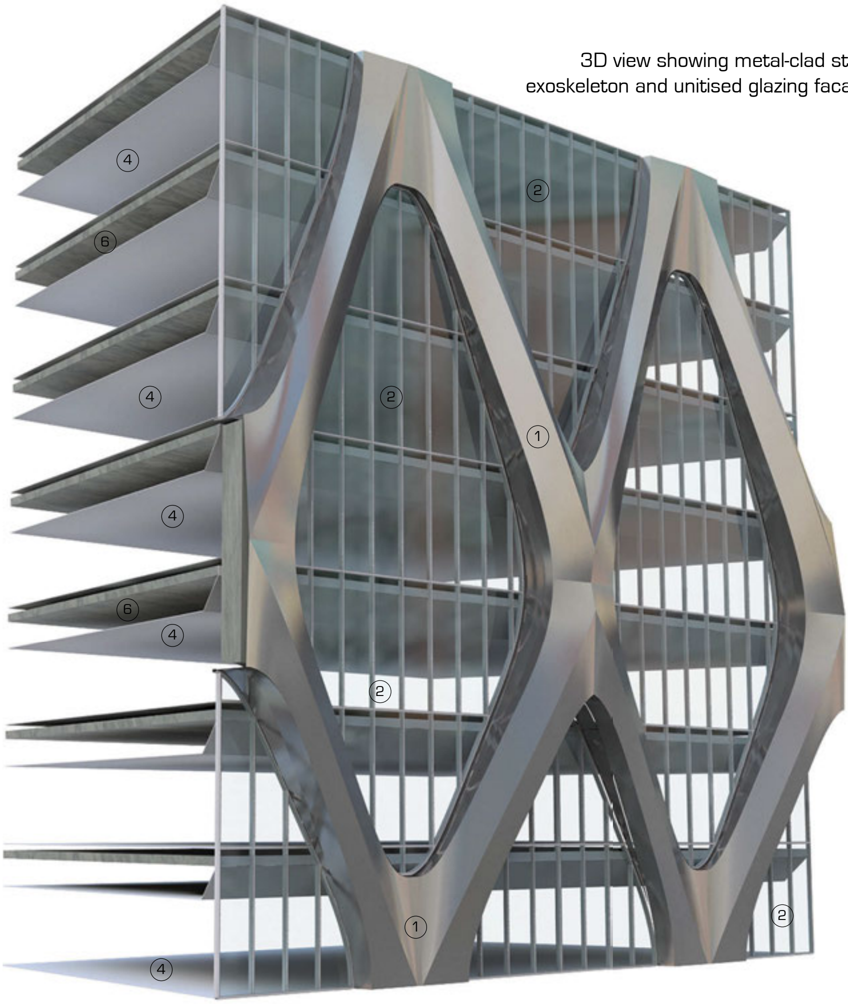
3D detail view showing metal clad hot-rolled steel section supporting roof structure and interface with glazing system



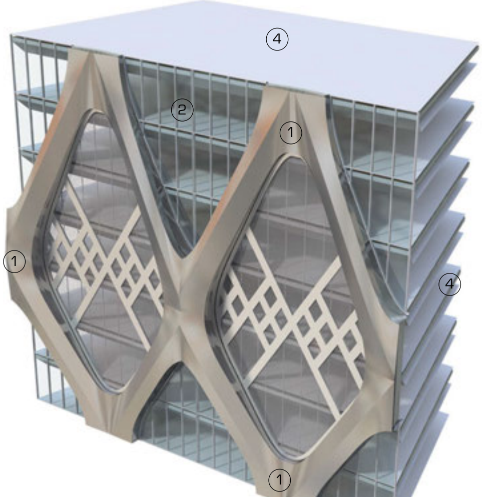
3D sectional views showing precast concrete panels supported on steel roof structure and interface with glazing system and floor slab



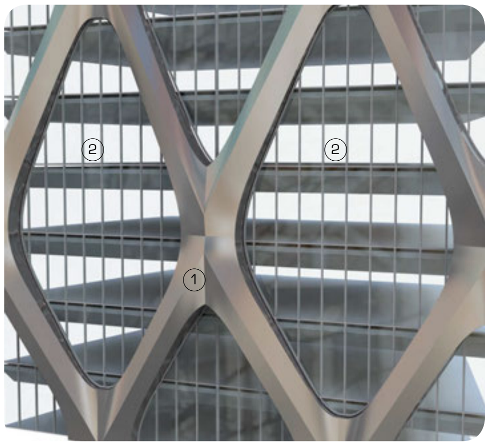
3D exploded view showing precast concrete panels supported on steel roof structure and interface with glazing system and floor slab



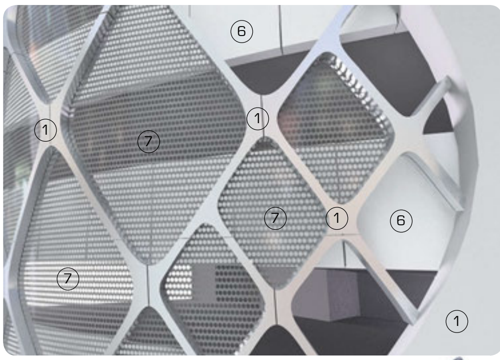
3D view showing metal-clad steel exoskeleton and unitised glazing facade



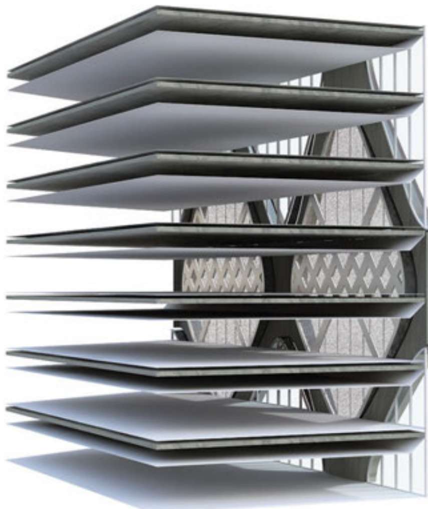
3D views showing metal-clad steel exoskeleton and unitised glazing facade

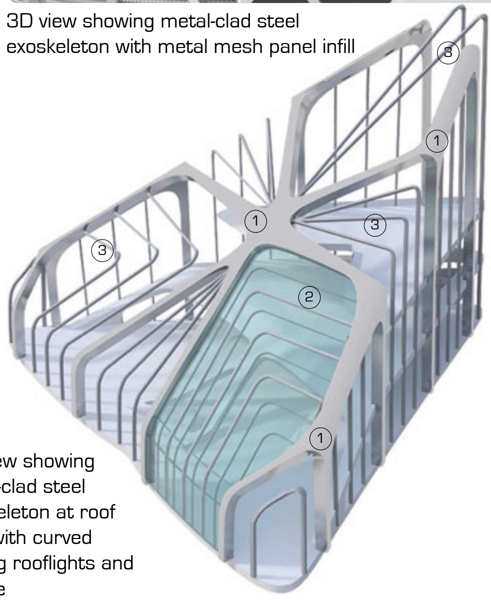


3D view showing GRC-clad steel exoskeleton with metal mesh panel infill



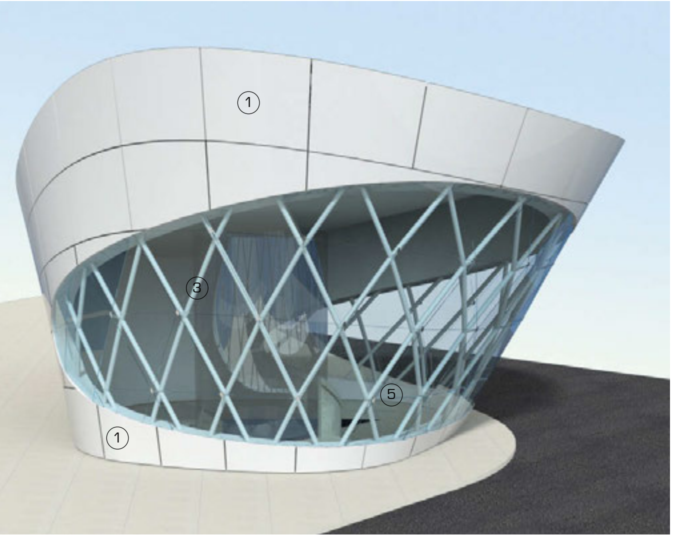
3D view showing metal-clad steel exoskeleton with metal mesh panel infill

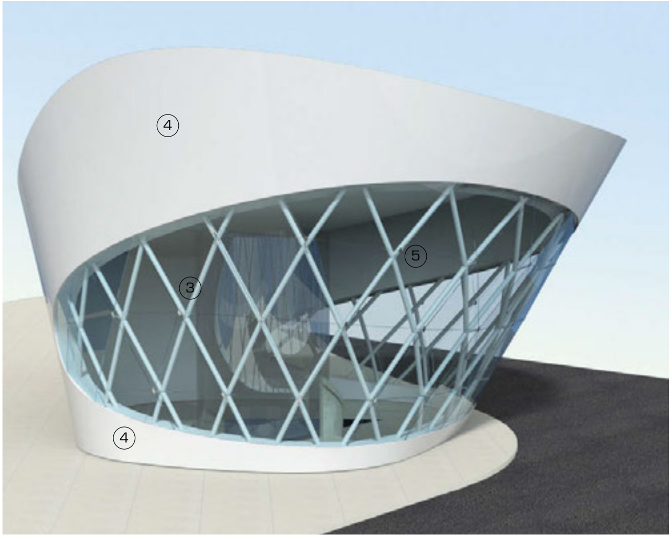


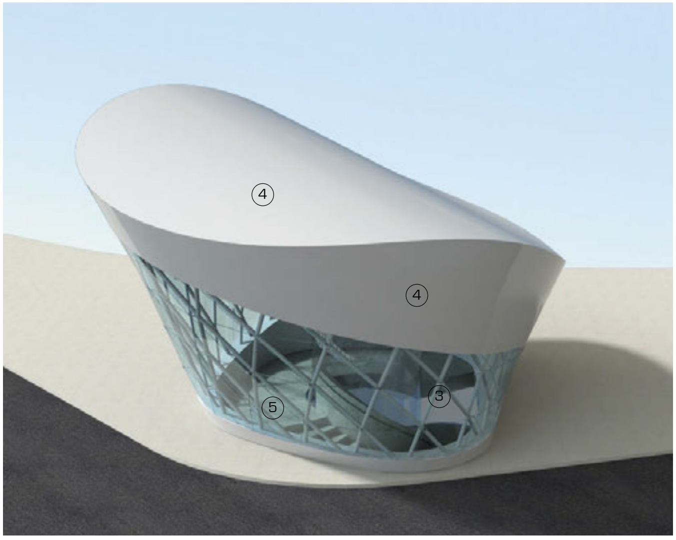


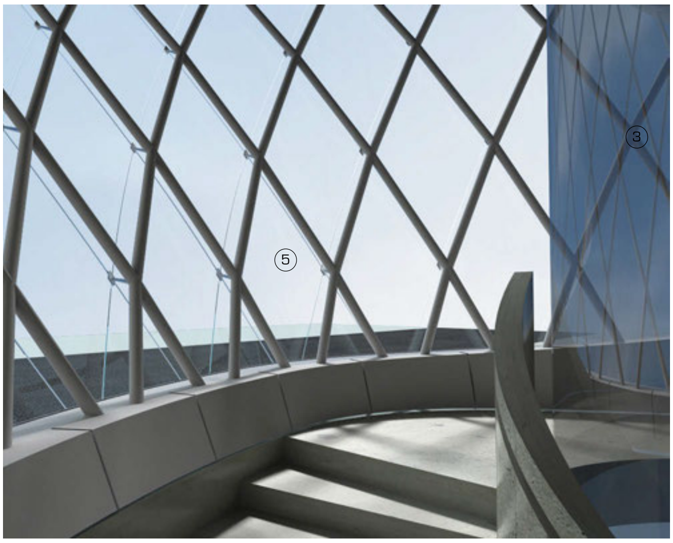
3D view showing metal-clad steel exoskeleton at roof level with curved glazing rooflights and facade

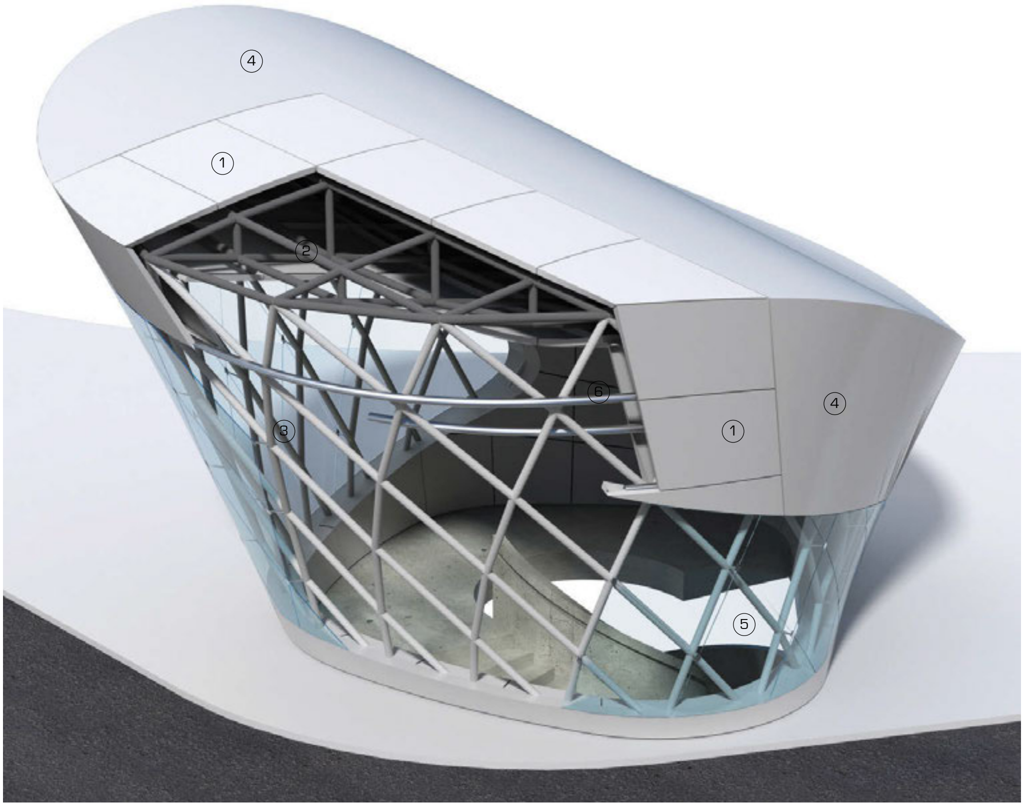
Details
1. Metal outer cladding
2. Double glazed unit
3. Glazing frame
4. Internal finish
5. Internal floor slab
6. Concrete slab
7. Metal mesh panels
8. GRC outer cladding



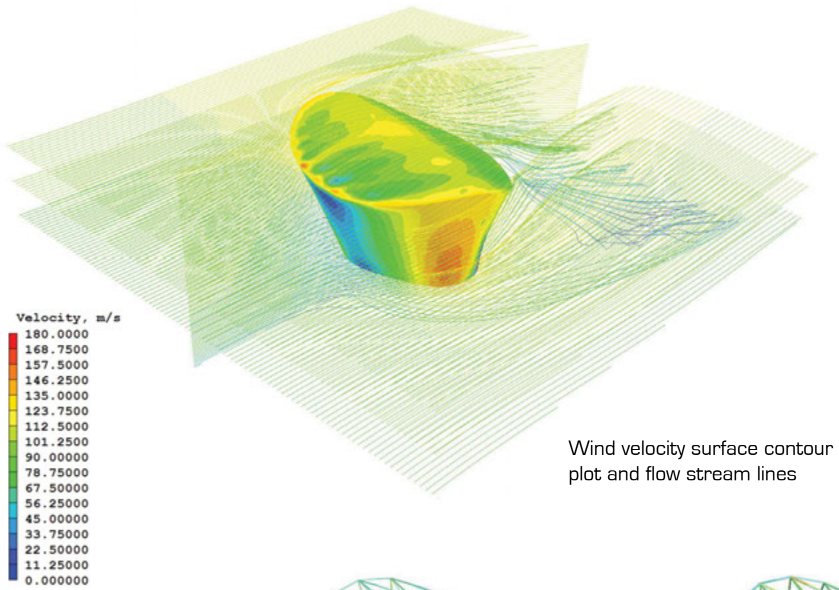




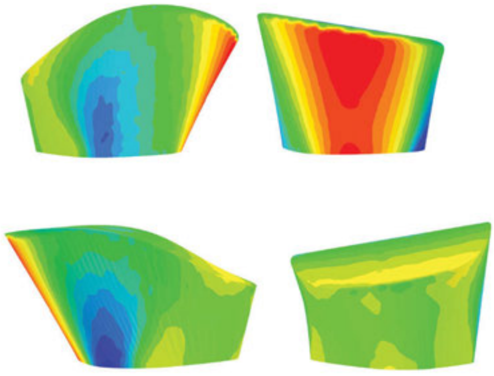




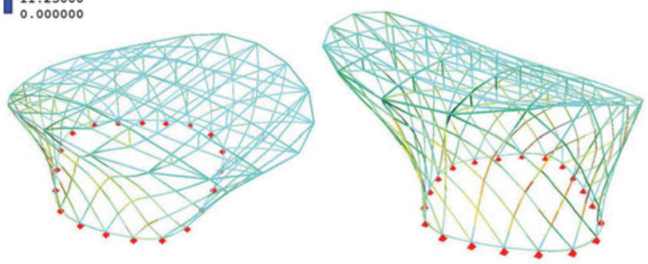
Details
1. Opaque panel
2. Roof structure
3. Wall structure
4. Opaque panels with joints filled and coating applied
5. Secondary structure
6. Glazed panels



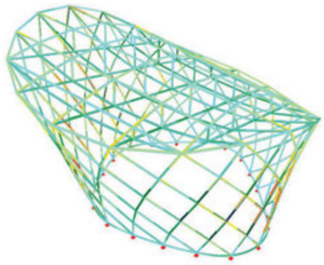
Wind velocity surface contour plot and flow stream lines



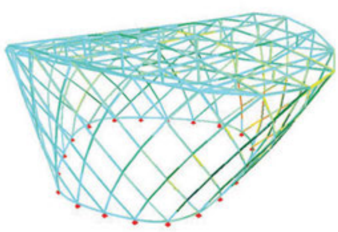
Wind pressure surface contour plot



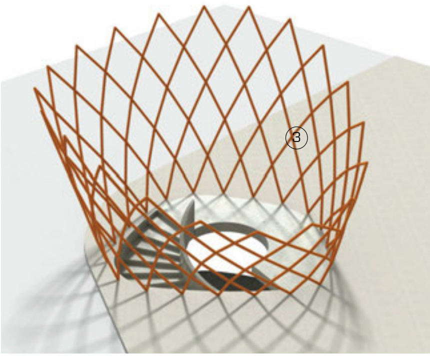
Wind - front on (left) and lateral (right)
The diagrid structure distributes forces through the frame in an even way, reducing peak loads in individual members. The pavilion form reduces the impact of wind uplift since there are no overhanging roof elements.



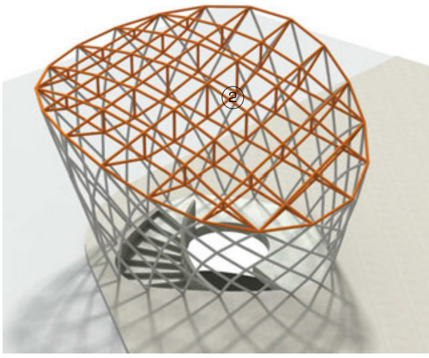
Self weight
The diagrid structure distributes the stresses in an even way which reduces areas of high stress in the frame. The need for ring bracing needs further investigation.



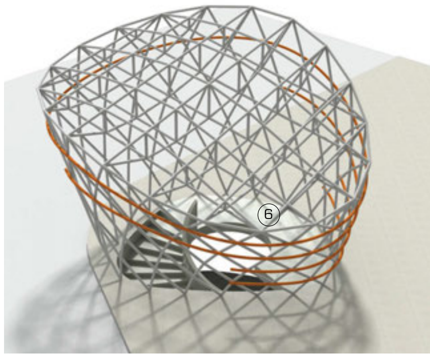
Torsion
The diagrid offers a higher degree of stiffening against torsional moments since the forces are distributed throughout the frame.



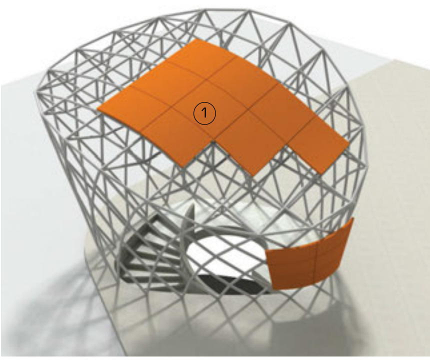
Diagrid structure erected to form rotunda form.



Roof trusses supported on ring beam at top of diagrid.



Secondary steelwork for cladding support fixed to primary structure on inside and outside of pavilion.



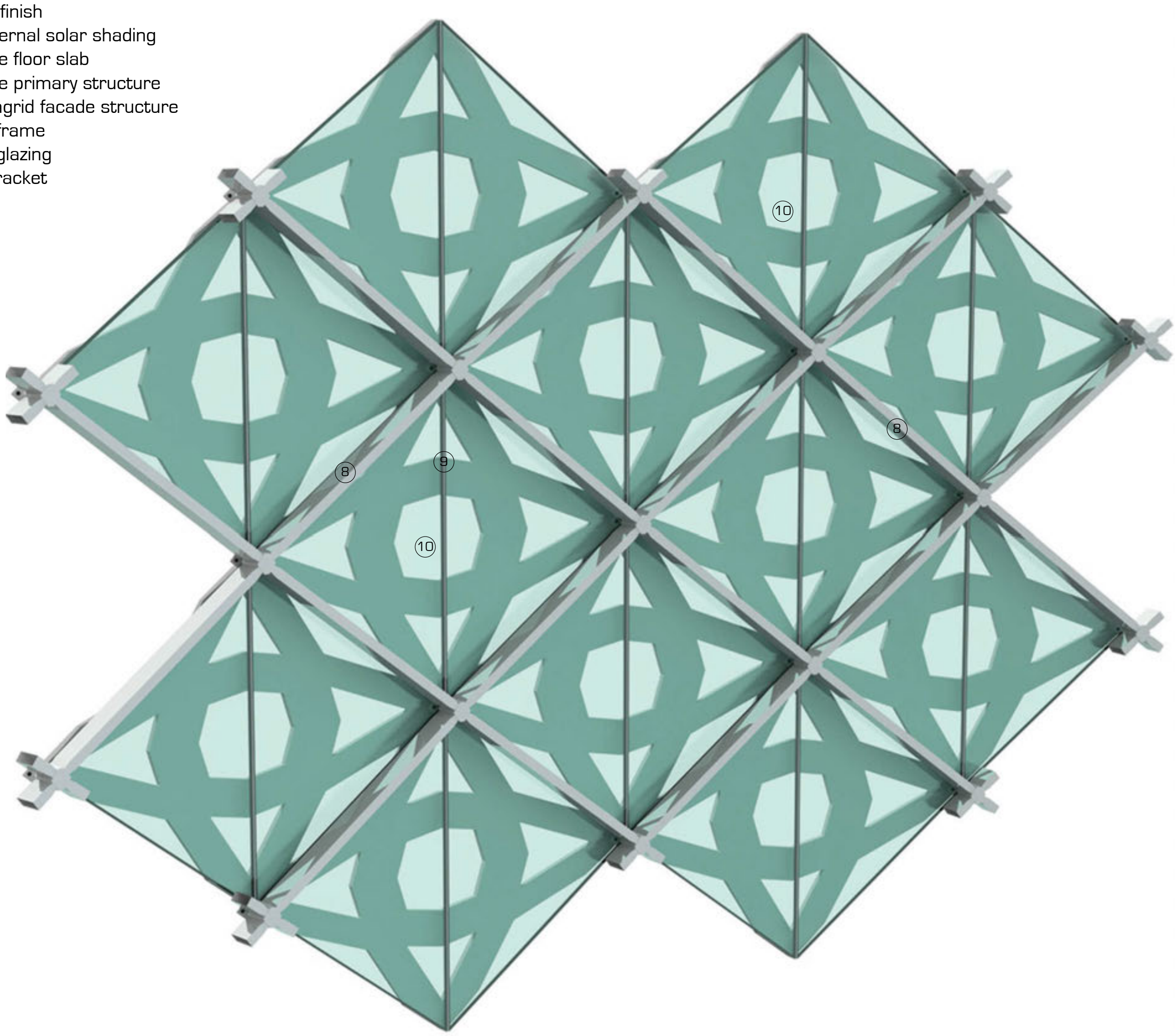
Opaque cladding panels attached to secondary structure

Joints between panels are filled and coated to form a smooth surface

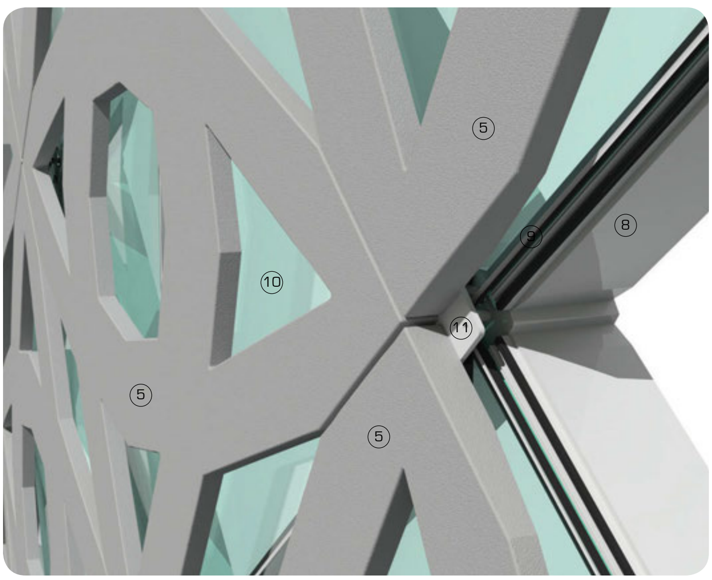
Glazing panels fixed to diagrid structure using point fixings

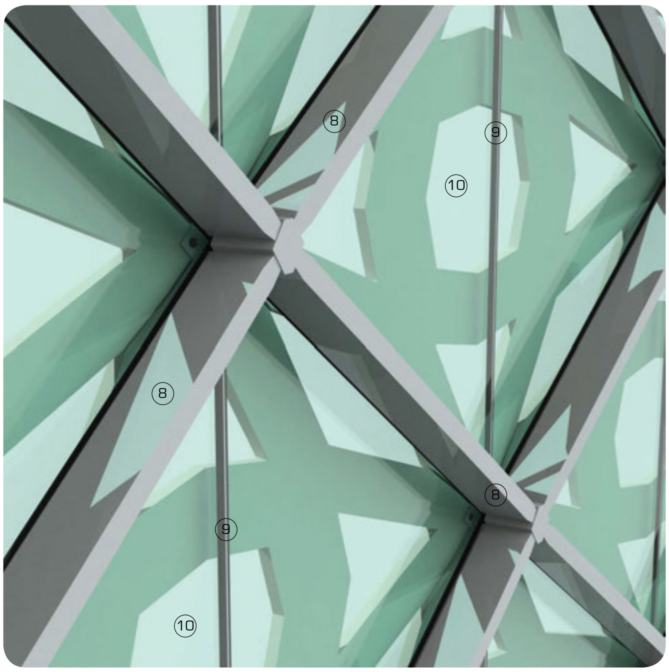
Details
1. GRP rainscreen cladding
2. Thermal insulation
3. Primary steel tube structure
4. Internal finish
5. GRP external solar shading
6. Concrete floor slab
7. Concrete primary structure
8. Steel diagrid facade structure
9. Glazing frame
10. Double glazing
11. Fixing bracket

3D sectional view showing GRP-clad undulating steel tube primary facade structure, and GRP external solar shading fixed to curved glazing supported on steel diagrid structure

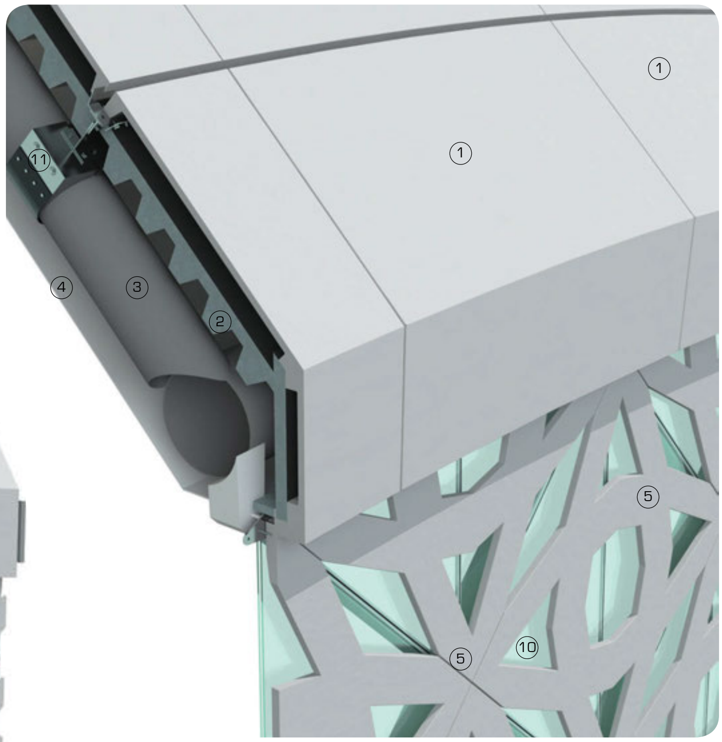


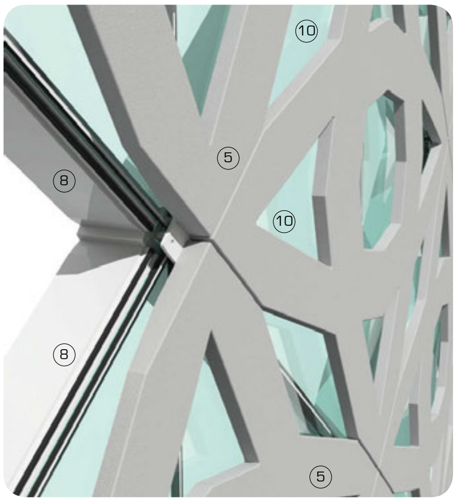
(Below) 3D detail views showing GRP external solar shading fixed to curved glazing supported on steel diagrid structure

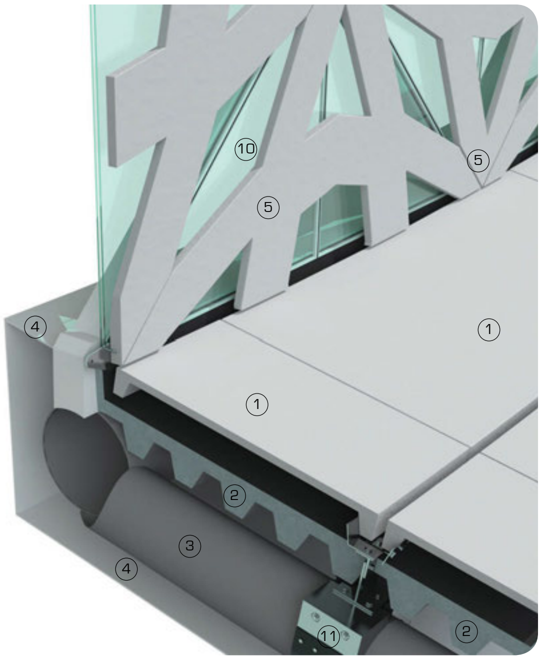


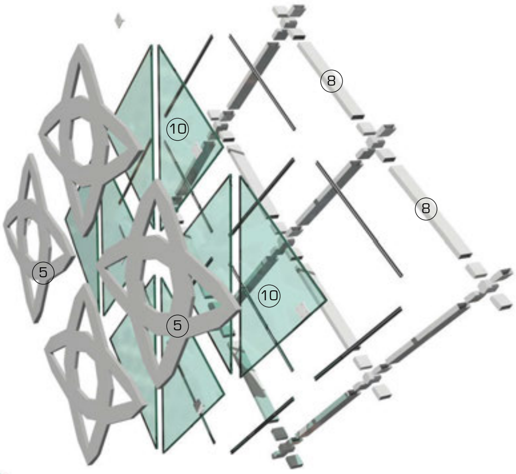


3D sectional detail views showing GRP-clad undulating steel tube primary facade structure, and GRP external solar shading fixed to curved glazing supported on steel diagrid structure

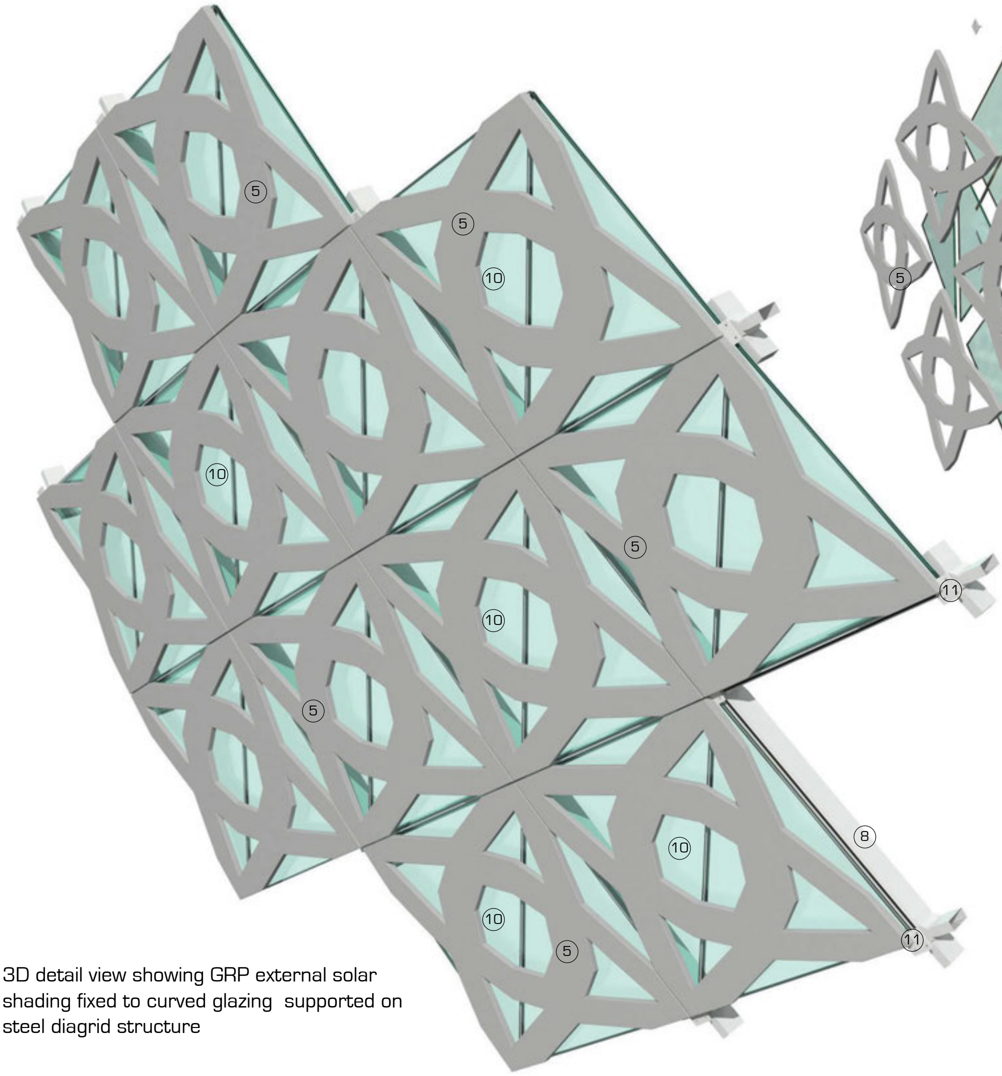






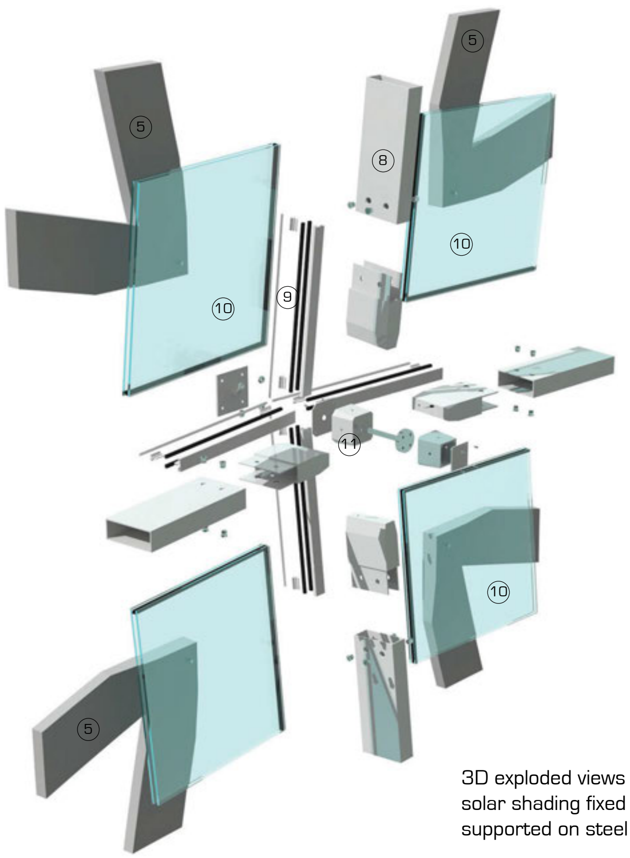


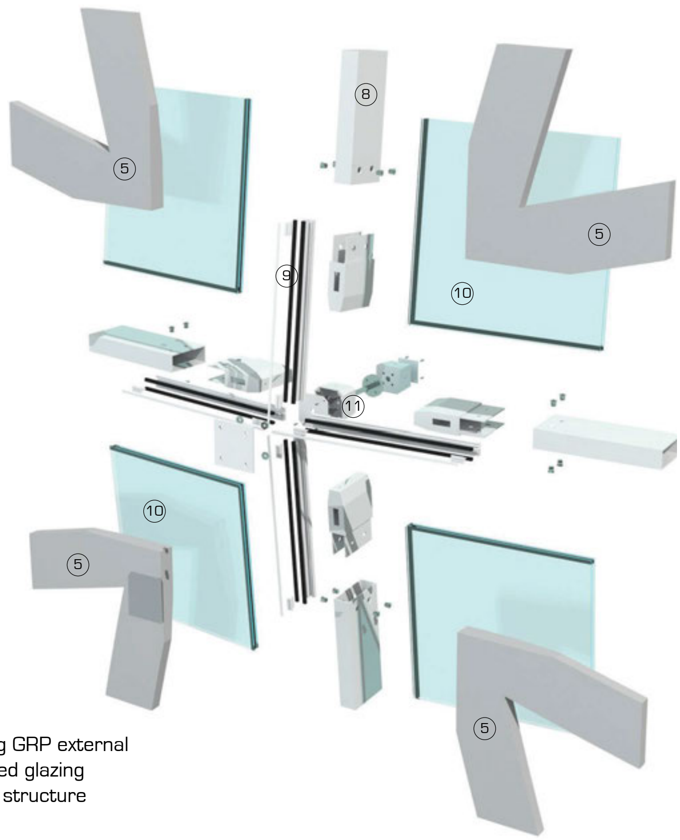
3D exploded views showing GRP external solar shading fixed to curved glazing supported on steel diagrid structure



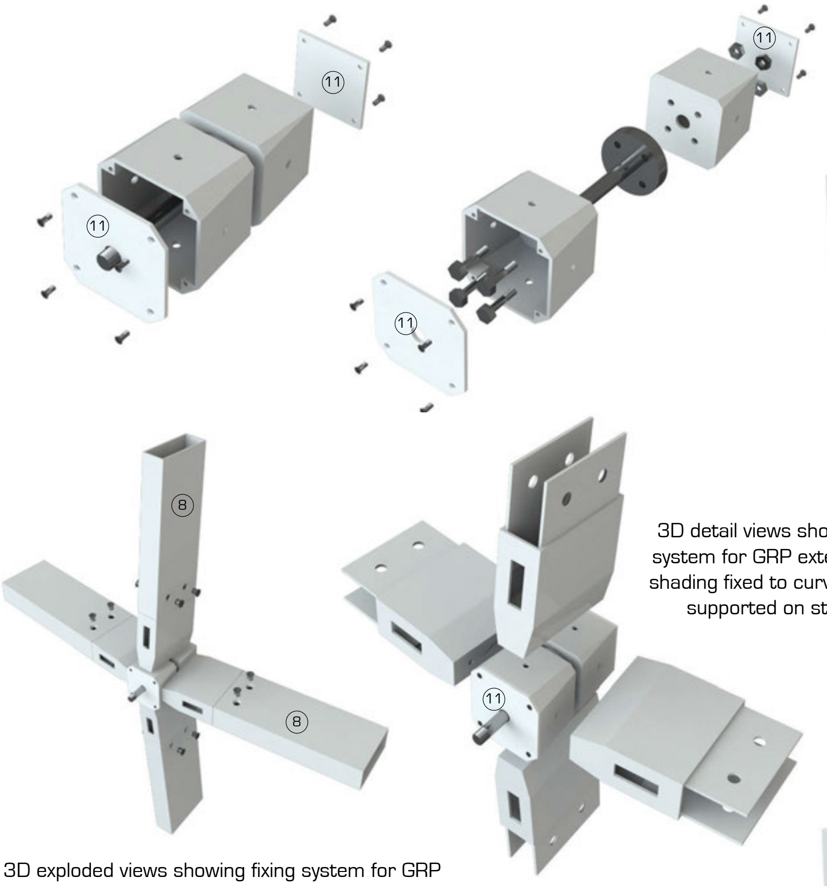
Details
1. GRP rainscreen cladding
2. Thermal insulation
3. Primary steel tube structure
4. Internal finish
5. GRP external solar shading
6. Concrete floor slab
7. Concrete primary structure
8. Steel diagrid facade structure
9. Glazing frame
10. Double glazing
11. Fixing bracket

3D detail view showing GRP external solar shading fixed to curved glazing supported on steel diagrid structure

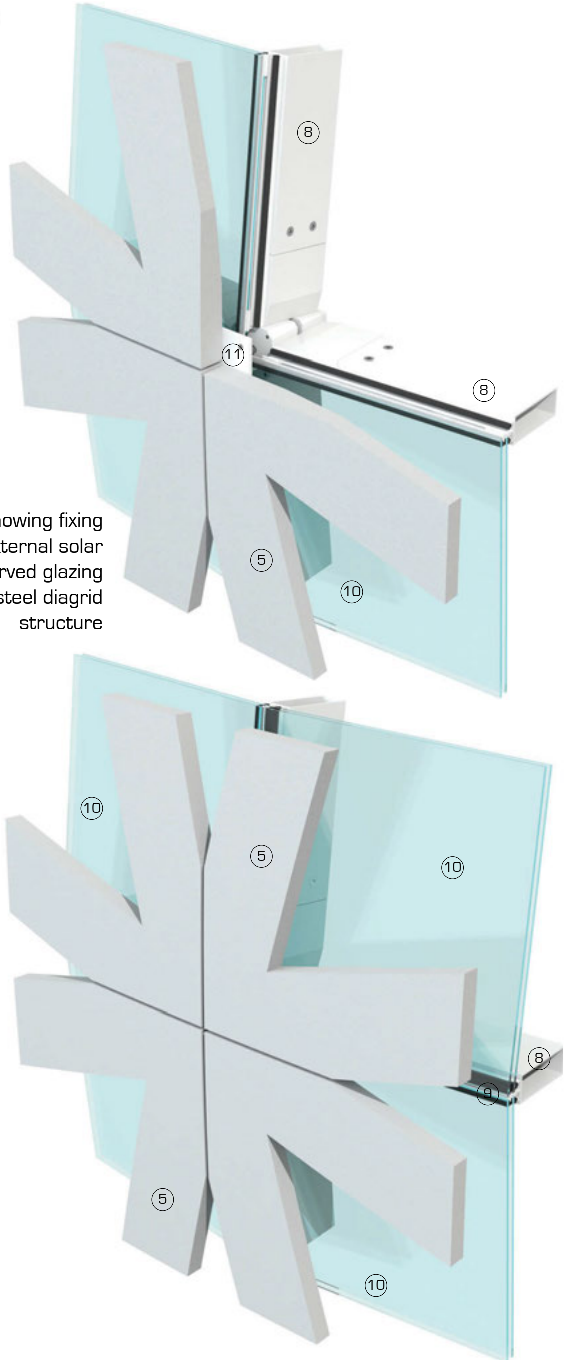




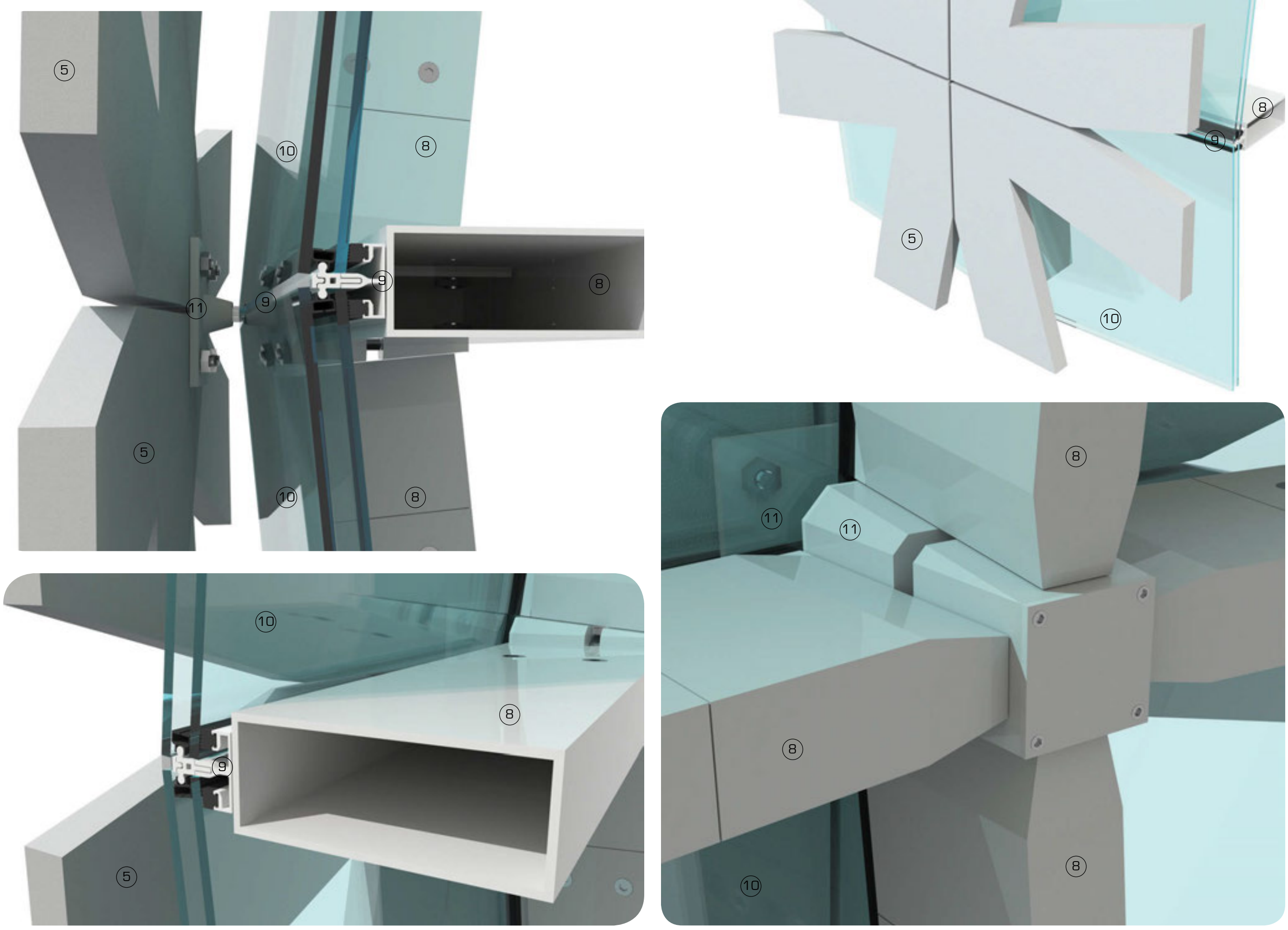
3D exploded views showing GRP external solar shading fixed to curved glazing supported on steel diagrid structure



3D exploded views showing fixing system for GRP external solar shading fixed to curved glazing supported on steel diagrid structure



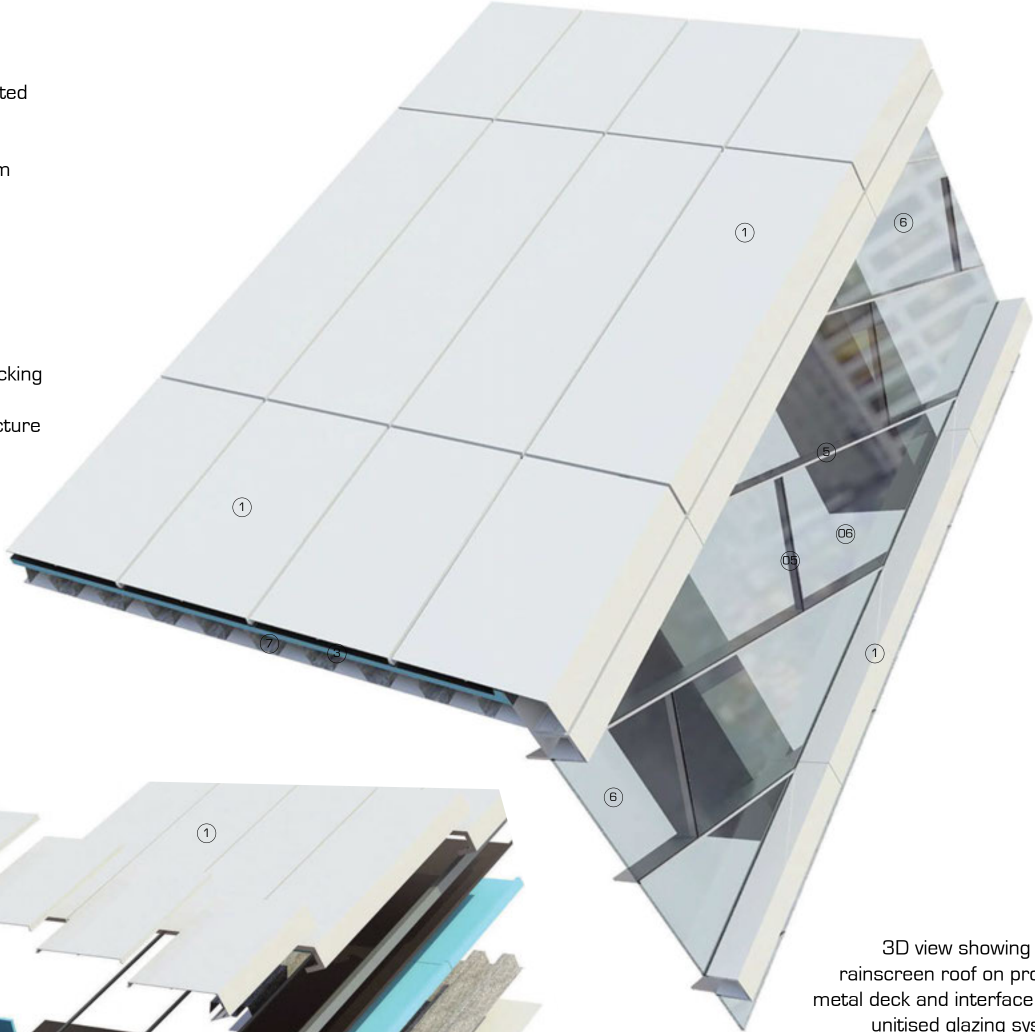
3D detail views showing fixing system for GRP external solar shading fixed to curved glazing supported on steel diagrid structure



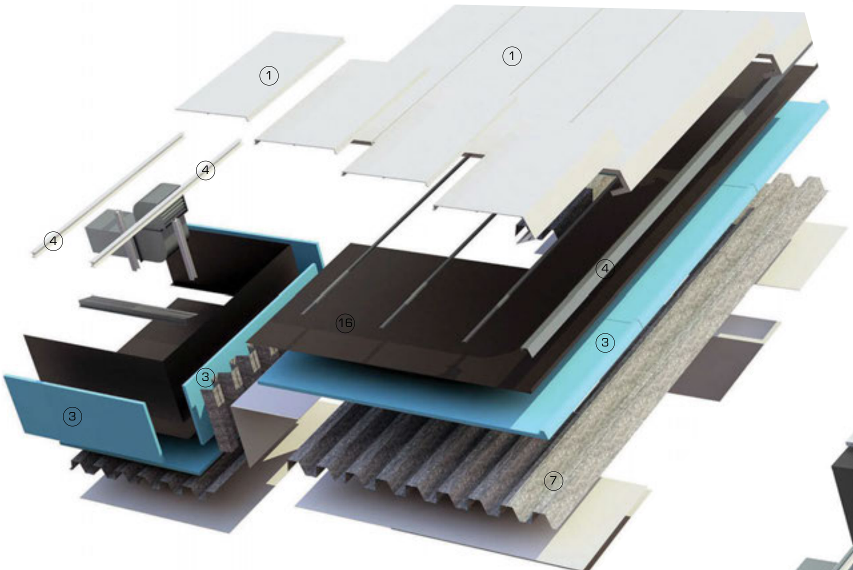
3D detail views showing fixing system for GRP external solar shading fixed to curved glazing supported on steel diagrid structure

Details

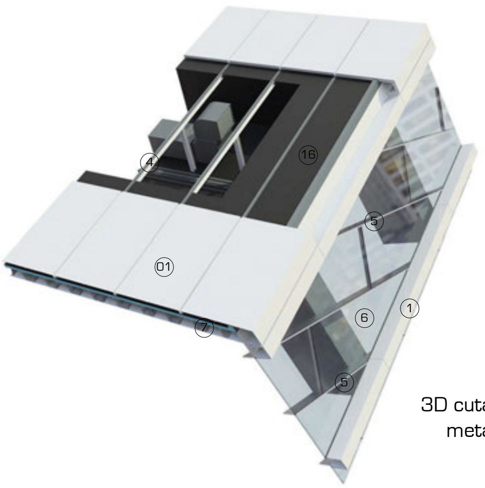
1. GRC rainscreen cladding
2. Primary steel columns (insulated and faced)
3. Thermal insulation
4. Rainscreen panel fixing system
5. Glazing frame
6. Double glazing
7. Profiled metal deck
8. Steel tube secondary facade support structure
9. GRC external shading louvres
10. GRC terrace decking panels
11. Plastic spaces for terrace decking
12. Steel roof truss structure
13. Primary in-situ concrete structure
14. Internal finish
15. Gutter
16. Waterproof membrane

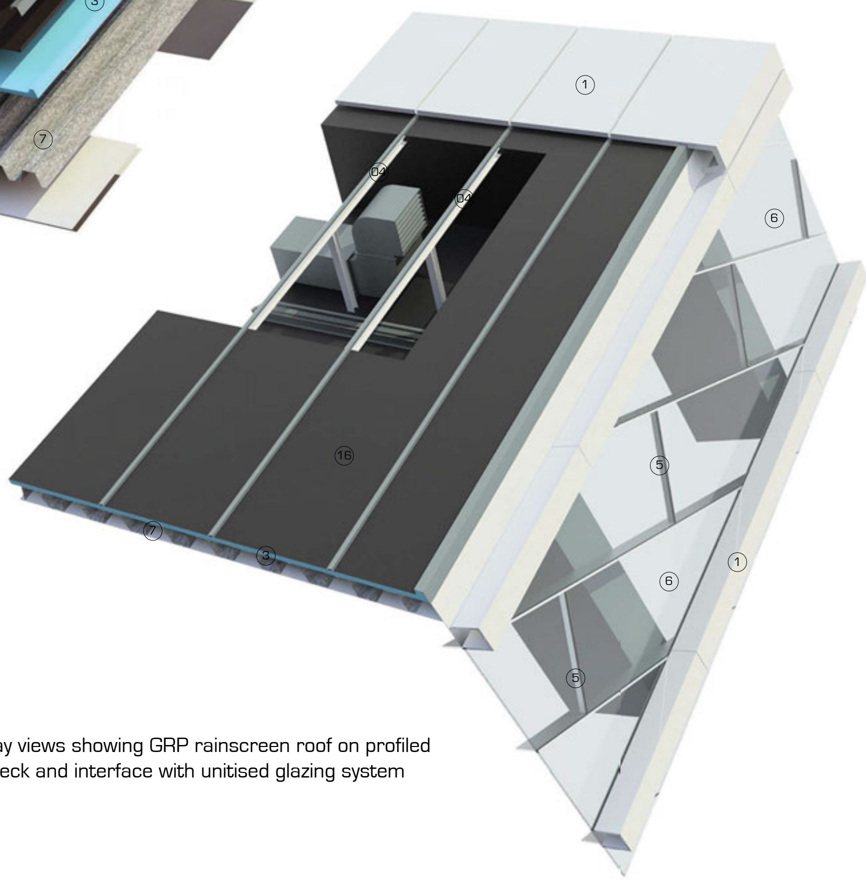


3D view showing GRP rainscreen roof on profiled metal deck and interface with unitised glazing system



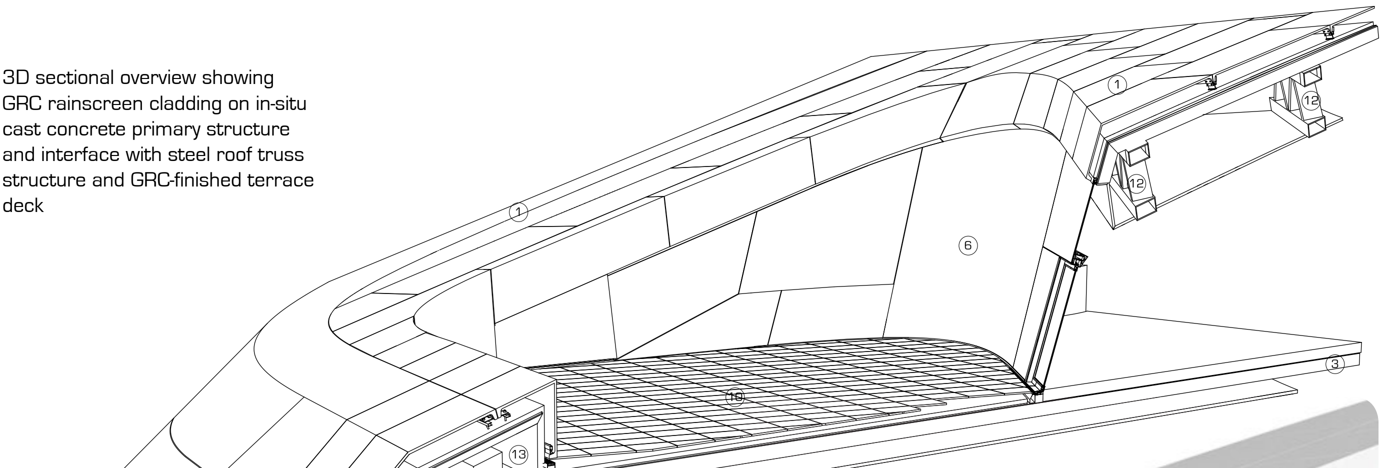
3D exploded fragment view showing GRP rainscreen roof on profiled metal deck

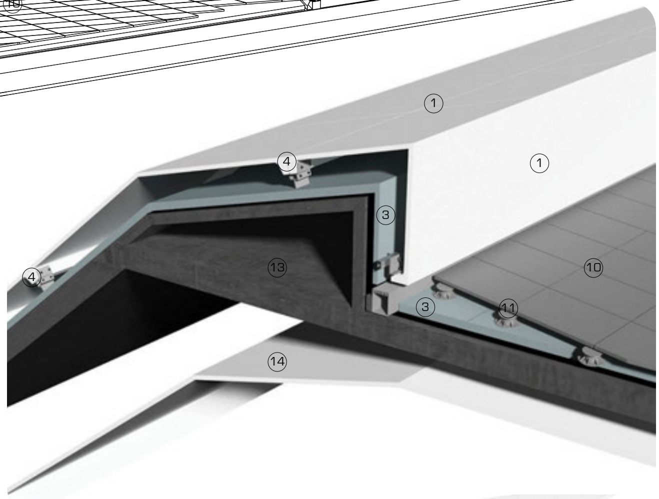




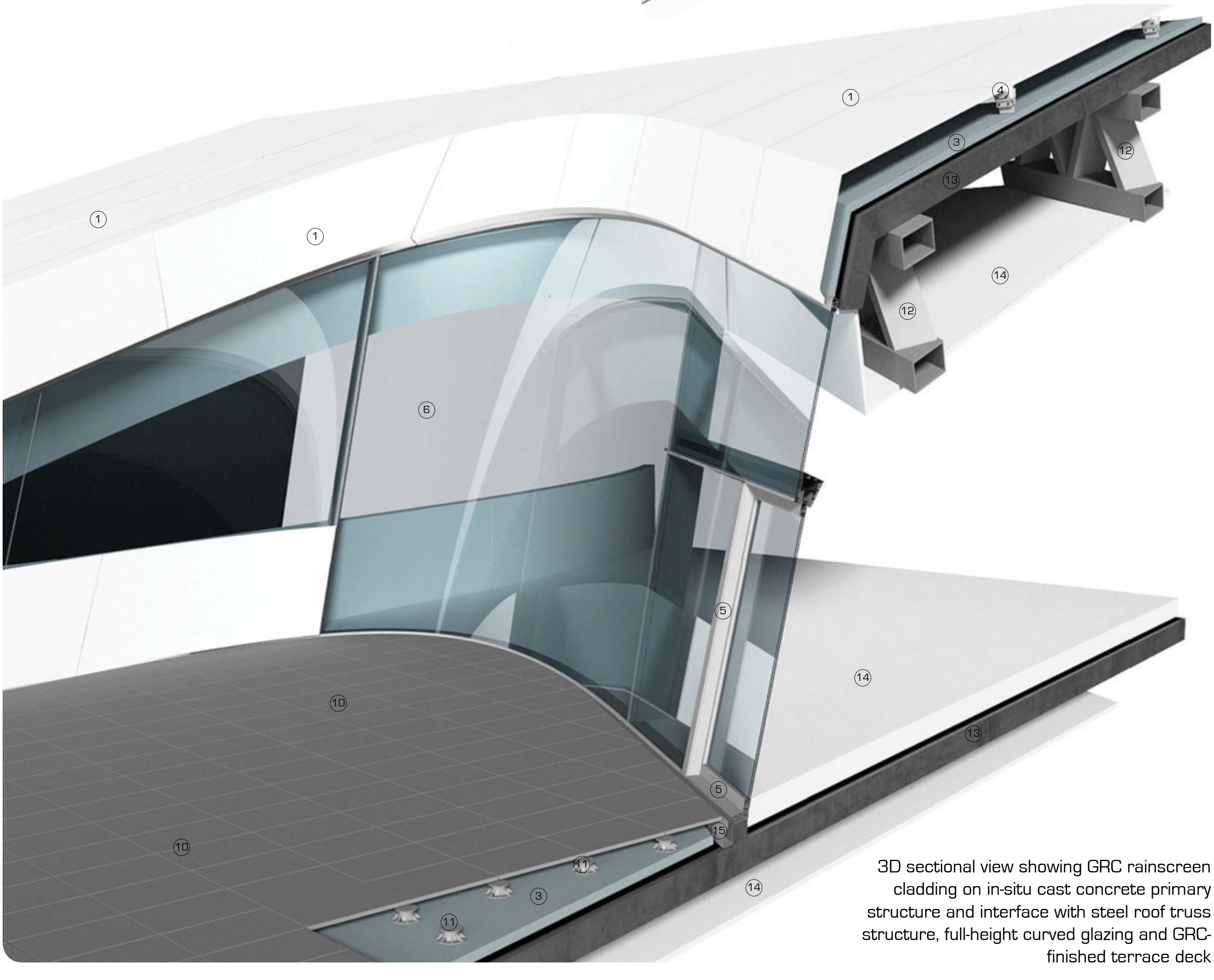
3D cutaway views showing GRP rainscreen roof on profiled metal deck and interface with unitised glazing system

3D sectional overview showing GRC rainscreen cladding on in-situ cast concrete primary structure and interface with steel roof truss structure and GRC-finished terrace deck

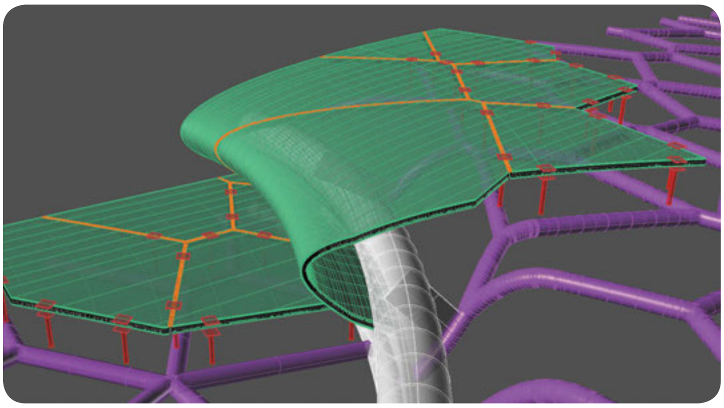




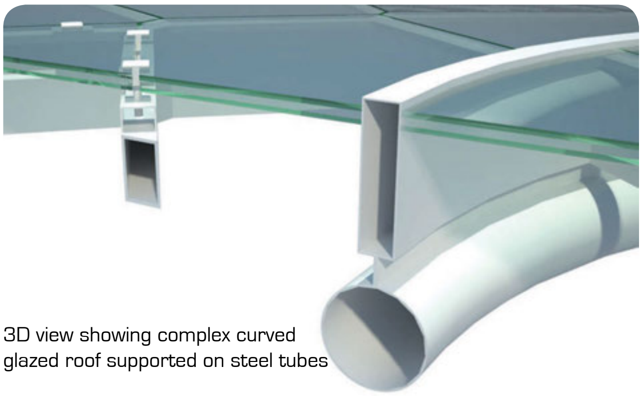
3D detail view showing GRC rainscreen cladding on in-situ cast concrete primary structure and interface with steel roof truss structure and GRC-finished terrace deck



3D sectional view showing GRC rainscreen cladding on in-situ cast concrete primary structure and interface with steel roof truss structure, full-height curved glazing and GRC-finished terrace deck

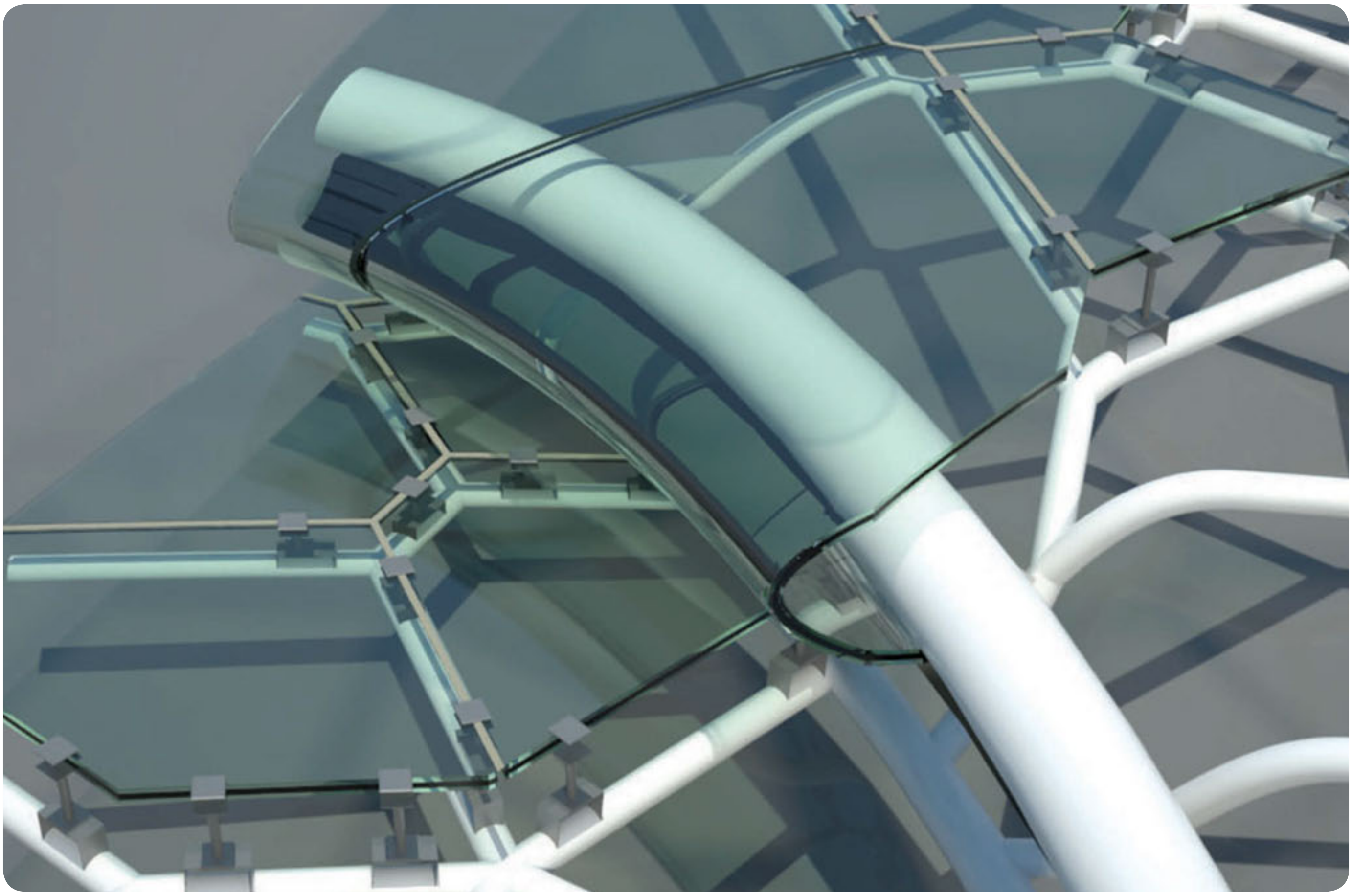


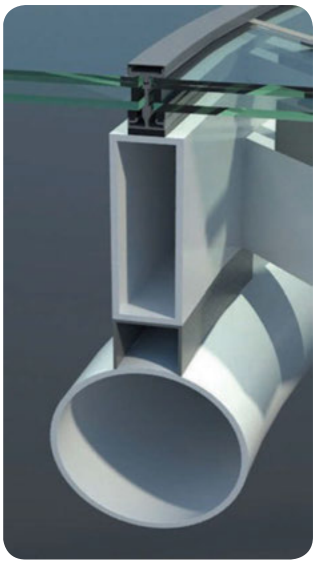
Working digital model of complex curved glazed facade and roof supported on steel tubes



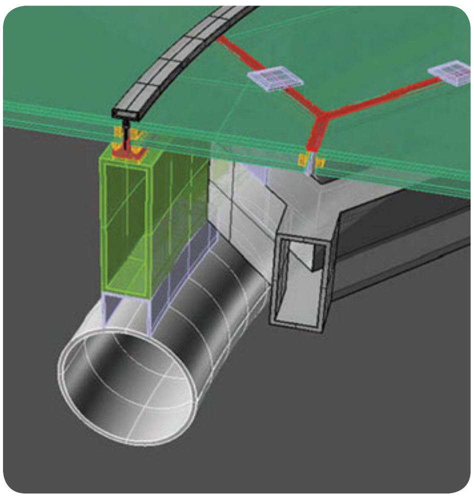
3D view showing complex curved glazed roof supported on steel tubes

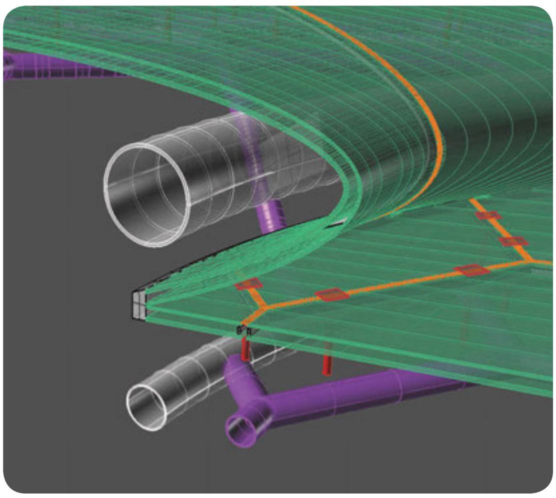
(Below) 3D view showing complex curved glazed facade and roof supported on steel tubes

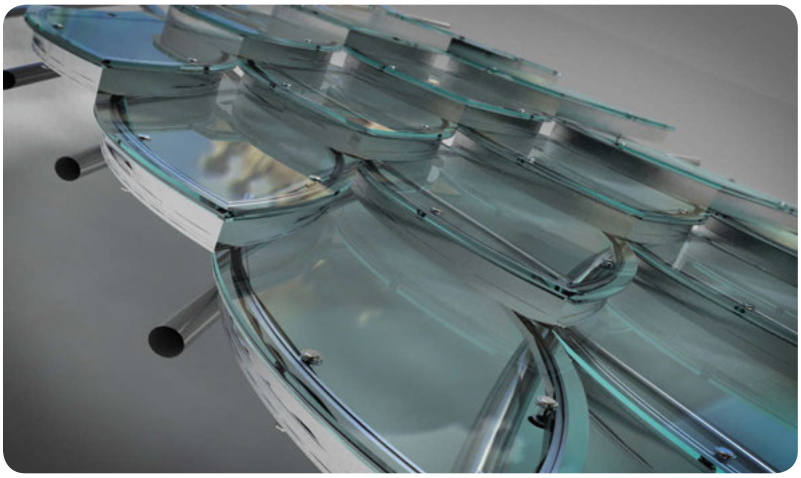


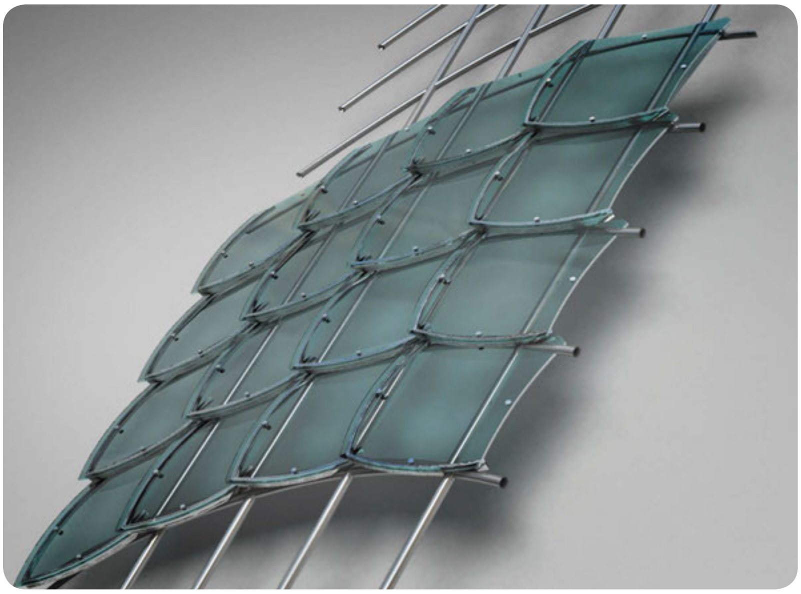


(Right) 3D view showing complex curved glazed roof supported on steel tubes
(Below) Working digital models of complex curved glazed facade and roof supported on steel tubes

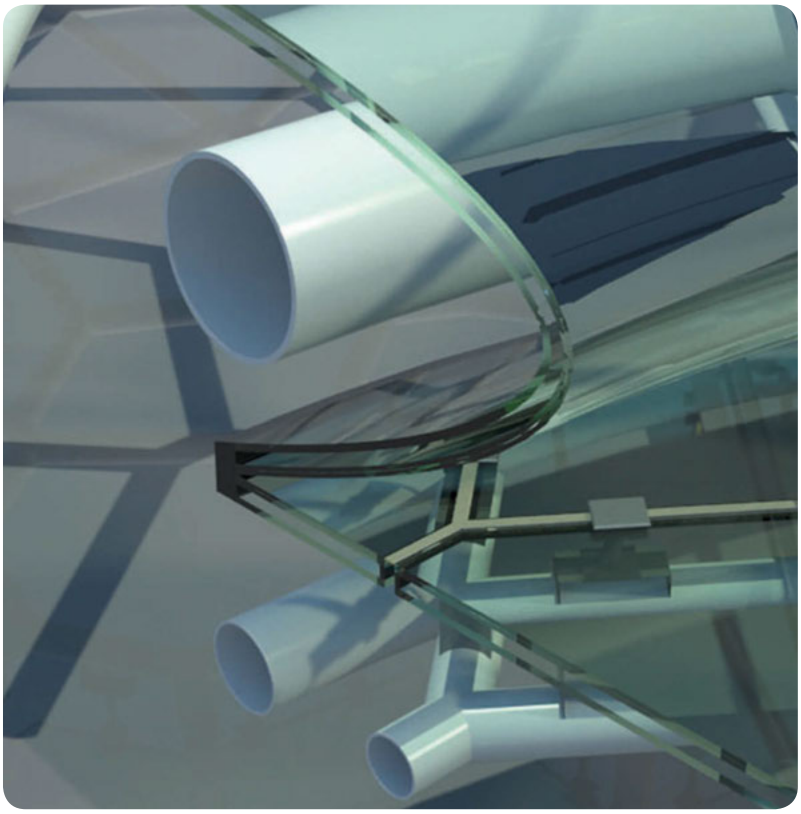




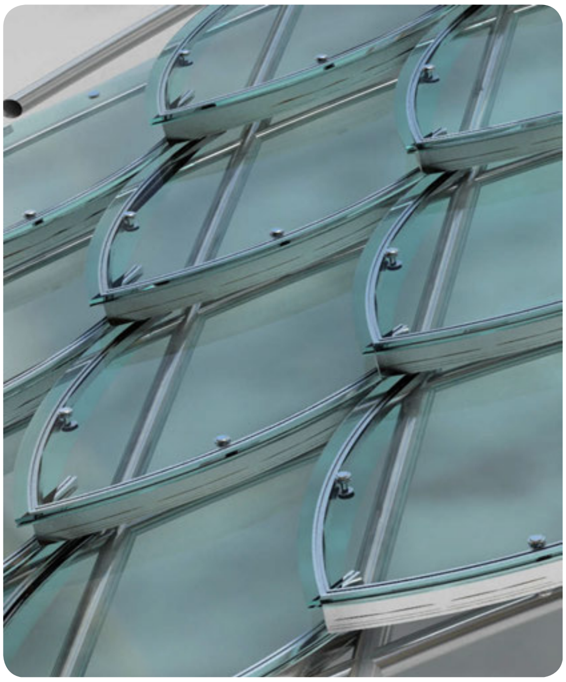




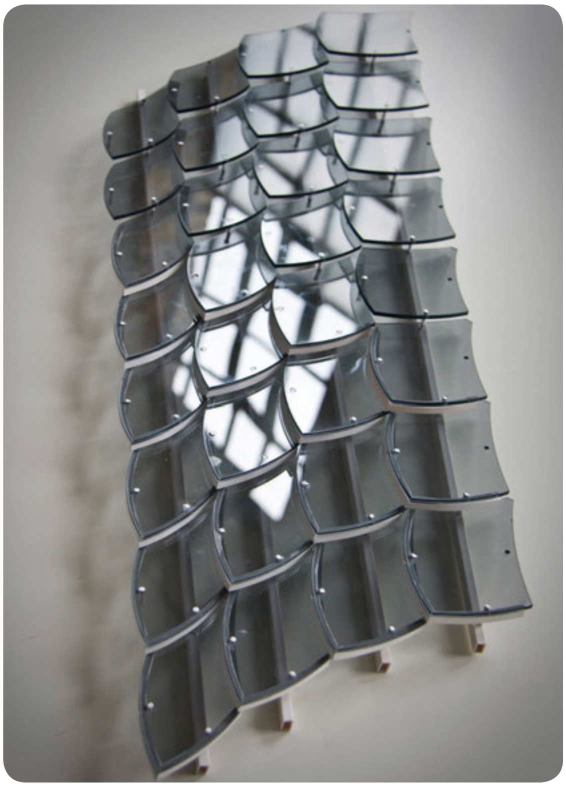
3D views showing shingled glazing system supported on steel tubes



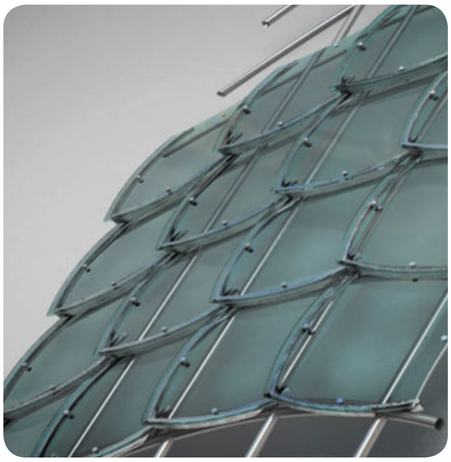
3D views showing complex curved glazed roof supported on steel tubes



3D view showing shingled glazing system supported on steel tubes

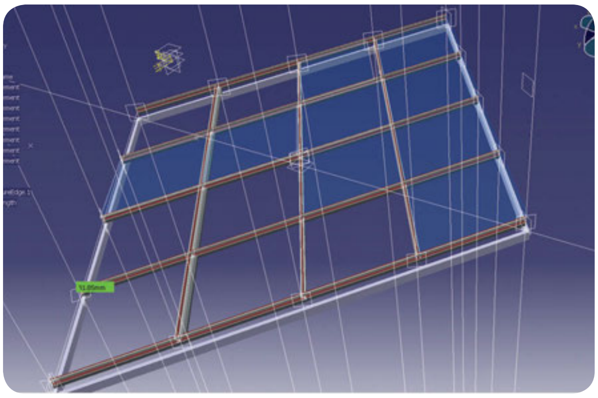


3D physical scale model of shingled glazing system supported on steel tubes

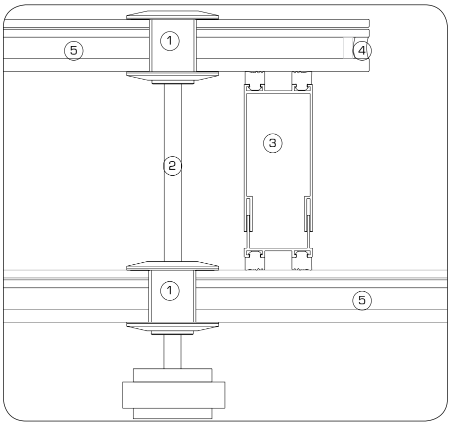


3D views showing shingled glazing system supported on steel tubes

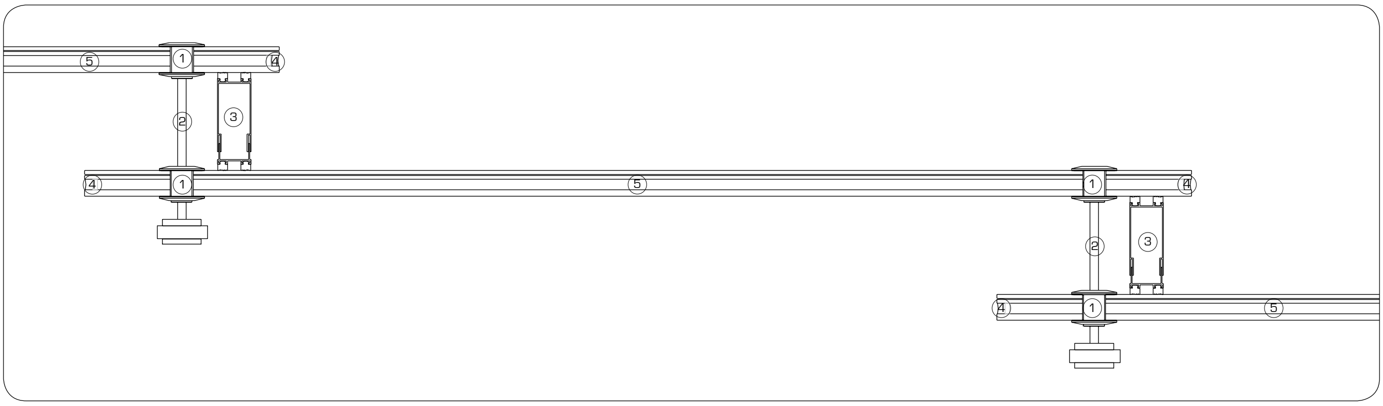
(Right) Working digital model of shingled glazing system supported on steel tubes

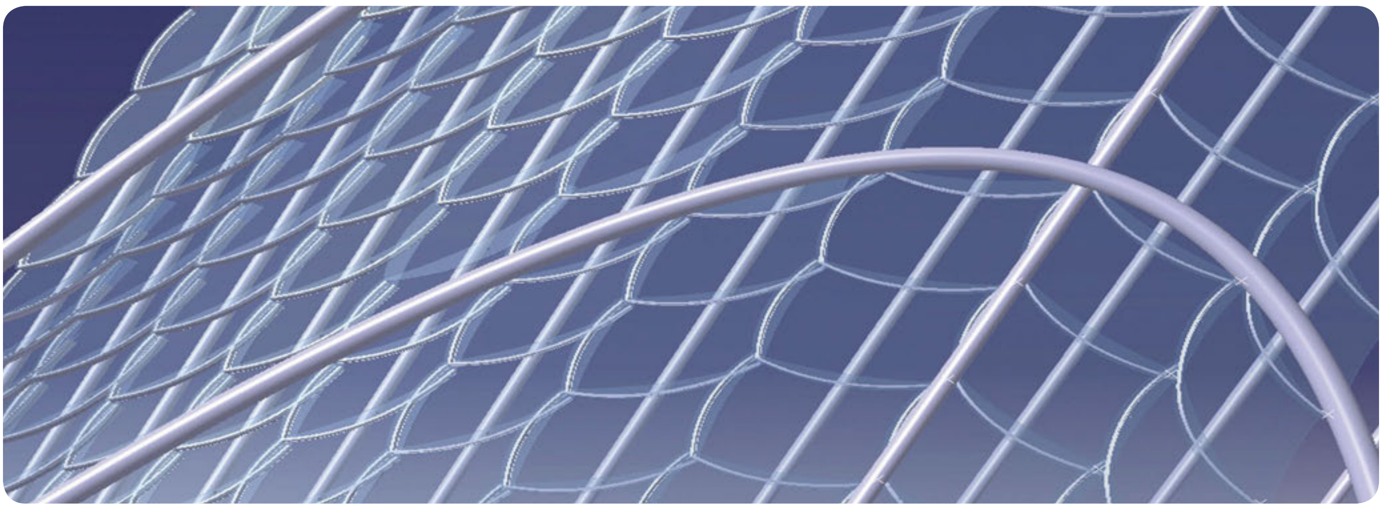


Details
1. Bolt-fixing
2. Steel rod support system
3. Steel box
4. Rubber seal
5. Double glazing

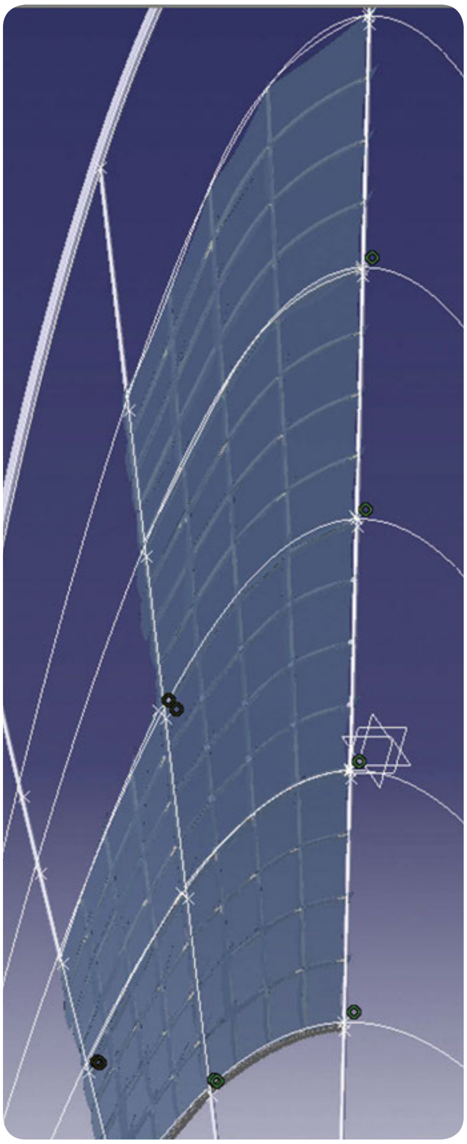


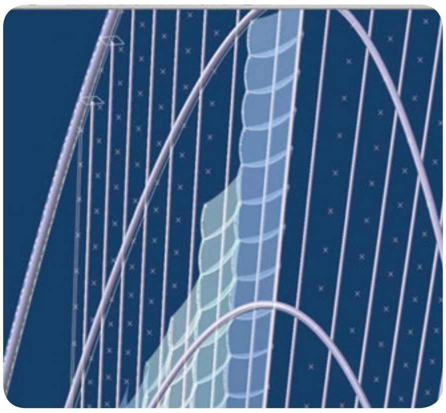
Vertical sections. Detail of shingled glazed roof fixing system

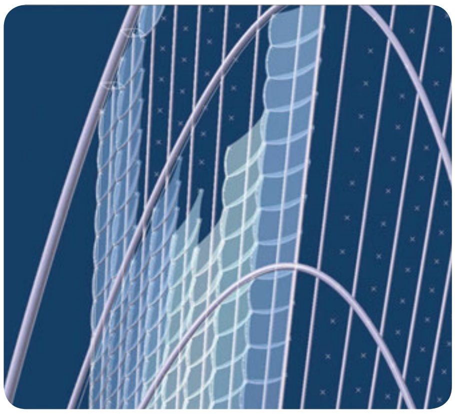


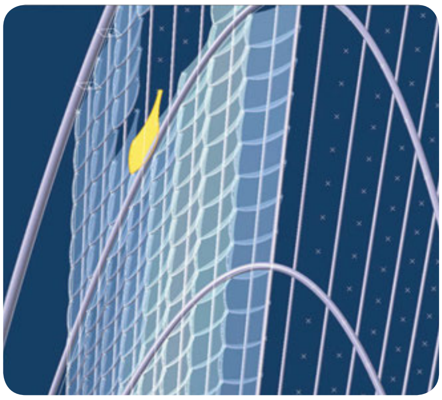


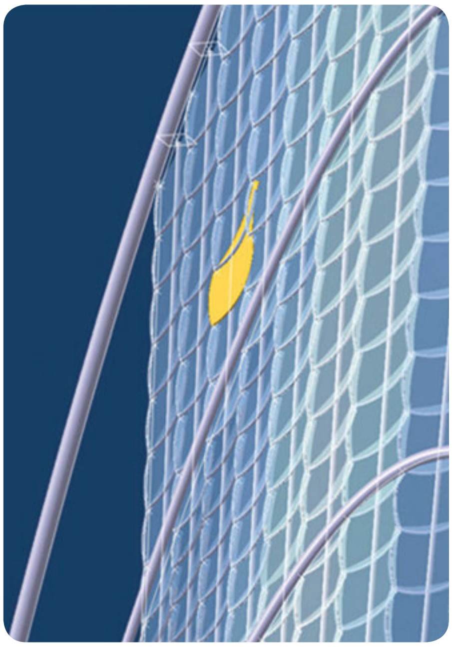
Working digital model of shingled glazing system supported on steel tubes

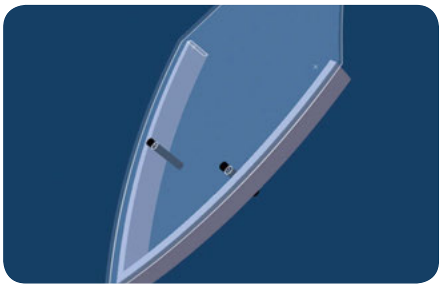




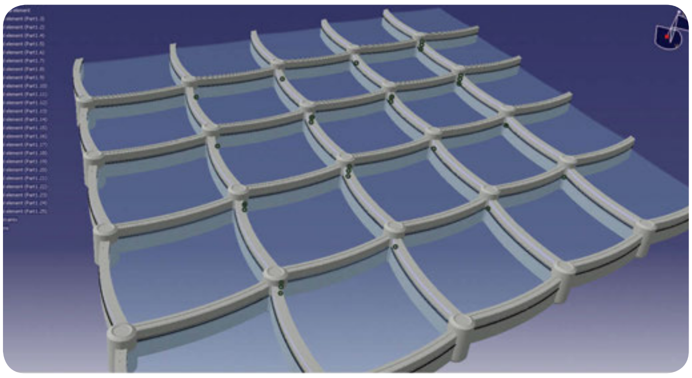


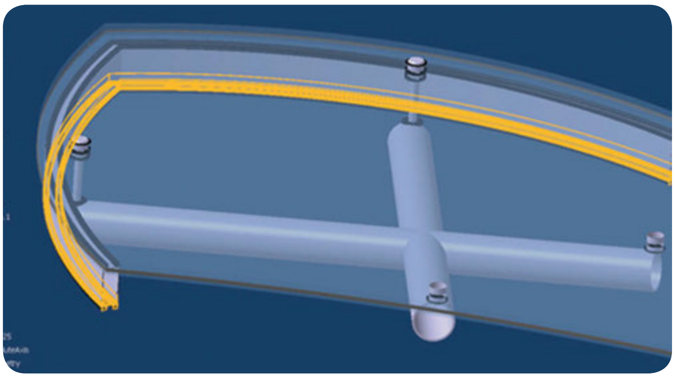


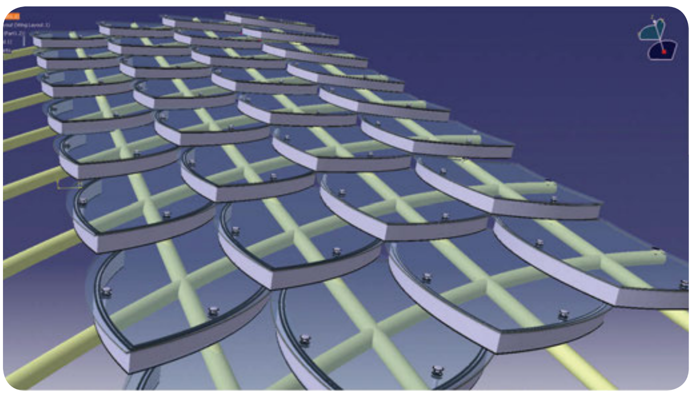


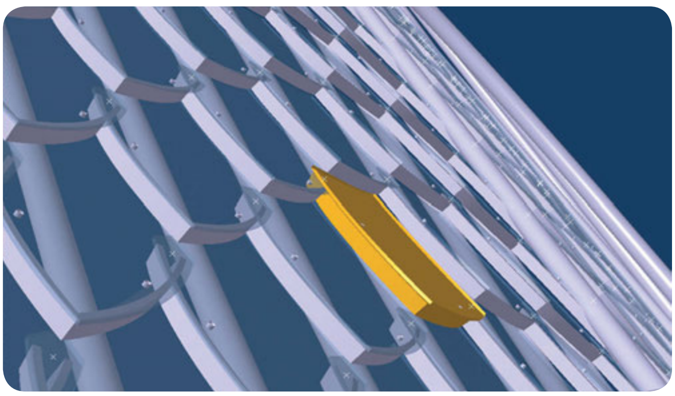


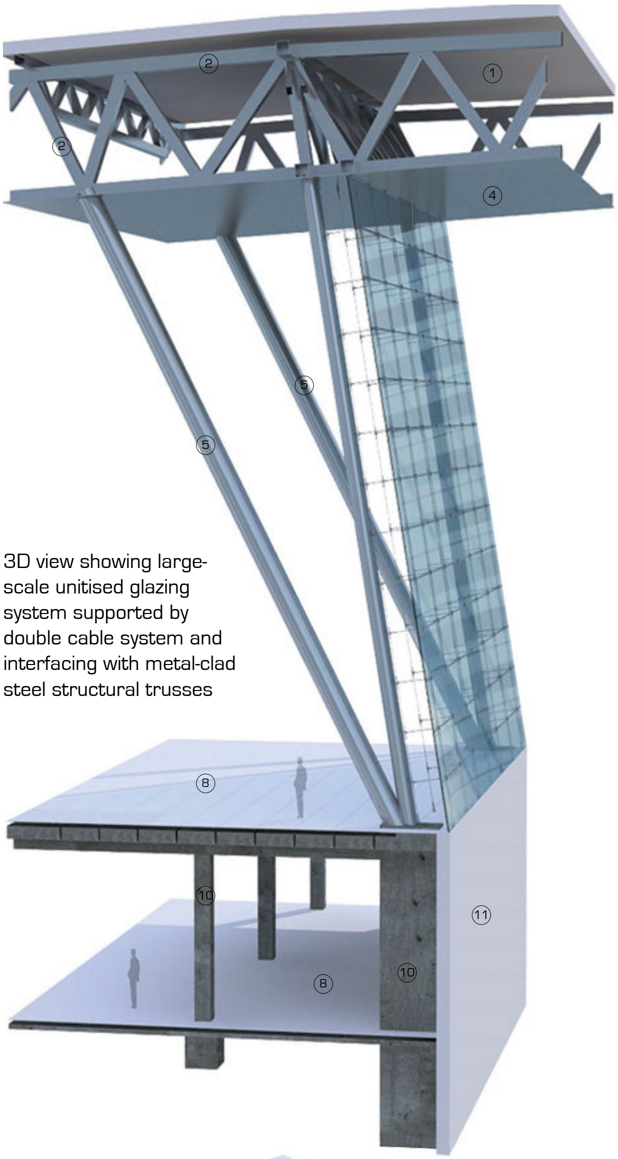
Working digital models of shingled glazing system supported on steel tubes



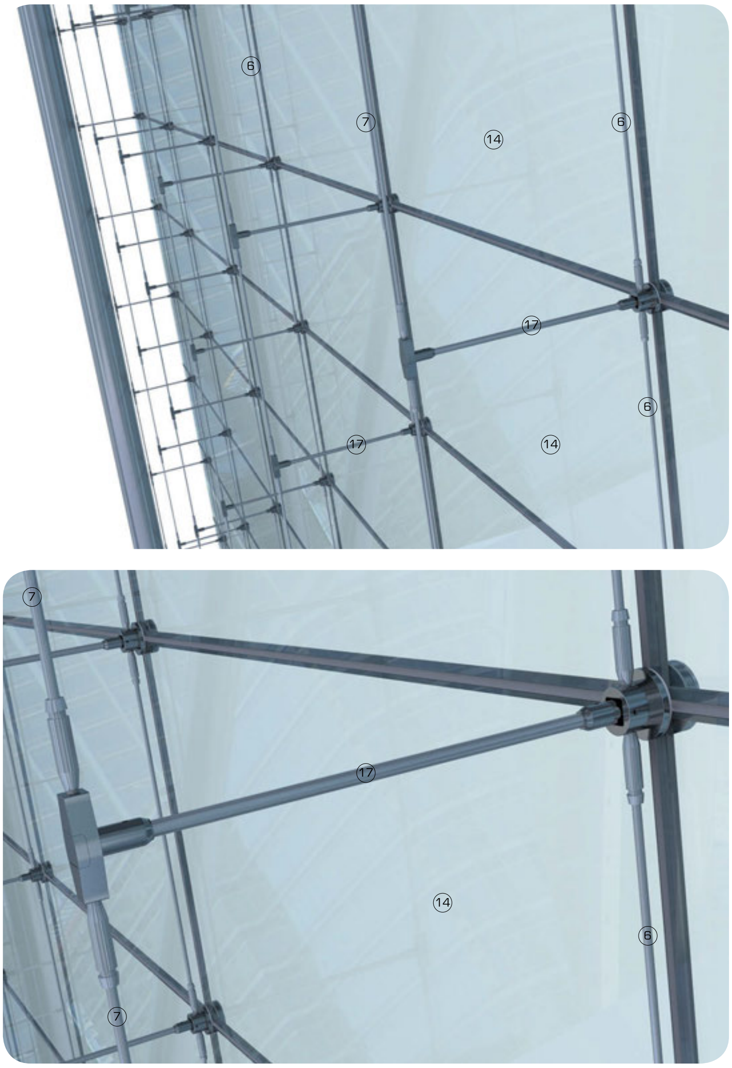




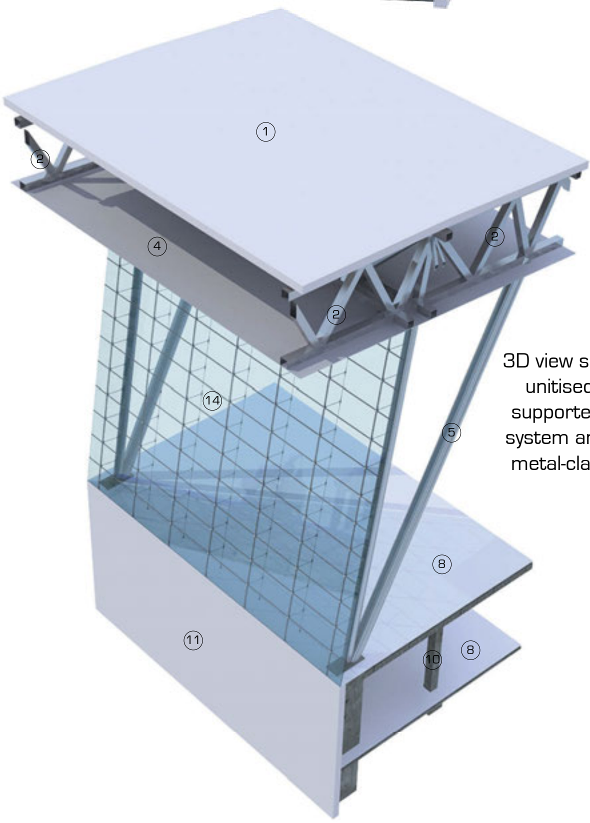




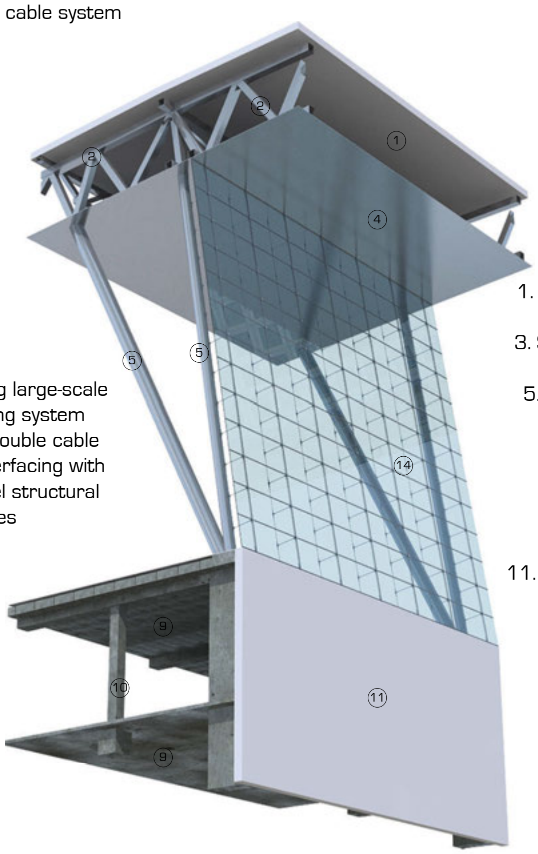
3D view showing large-scale unitised glazing system supported by double cable system and interfacing with metal-clad steel structural trusses



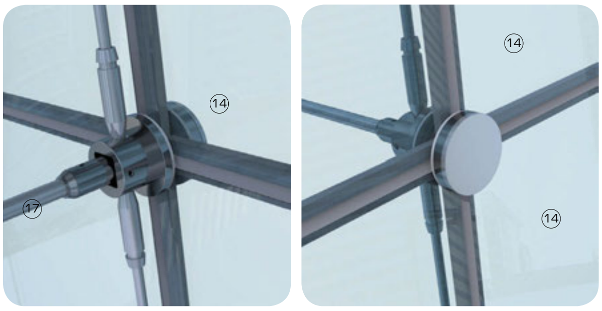
3D detail views showing large-scale unitised glazing system supported by double cable system



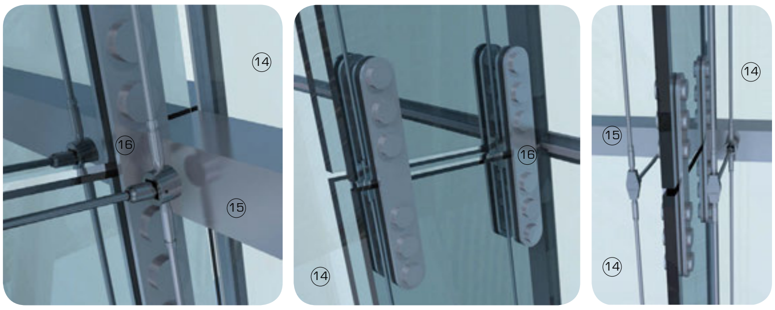
3D view showing large-scale unitised glazing system supported by double cable system and interfacing with metal-clad steel structural trusses



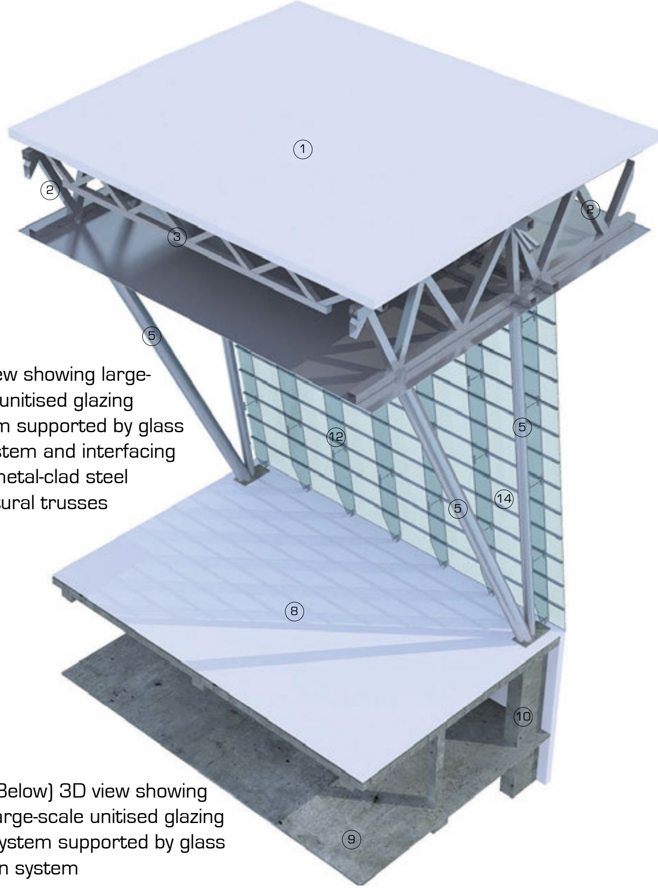
Details
1. External roof cladding
2. Primary roof truss
3. Secondary steel truss
4. Soffit panel
5. Inclined steel column
6. Inner cable
7. Outer cable
8. Internal floor finish
9. Floor slab
10. Concrete primary structure
11. External wall cladding
12. Glass fin
13. Double glass fin
14. Double glazing
15. Horizontal glazing frame
16. Steel clamp
17. Steel support rod



3D detail views showing cable-supported glazing system at glass clamp

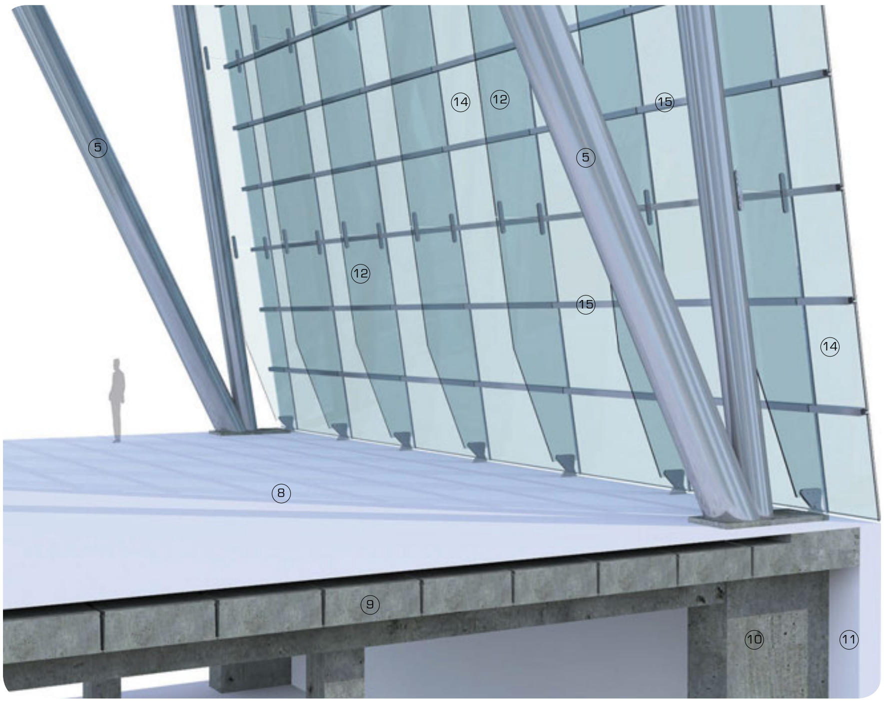


3D detail views showing glass fin-supported glazing system in various configurations

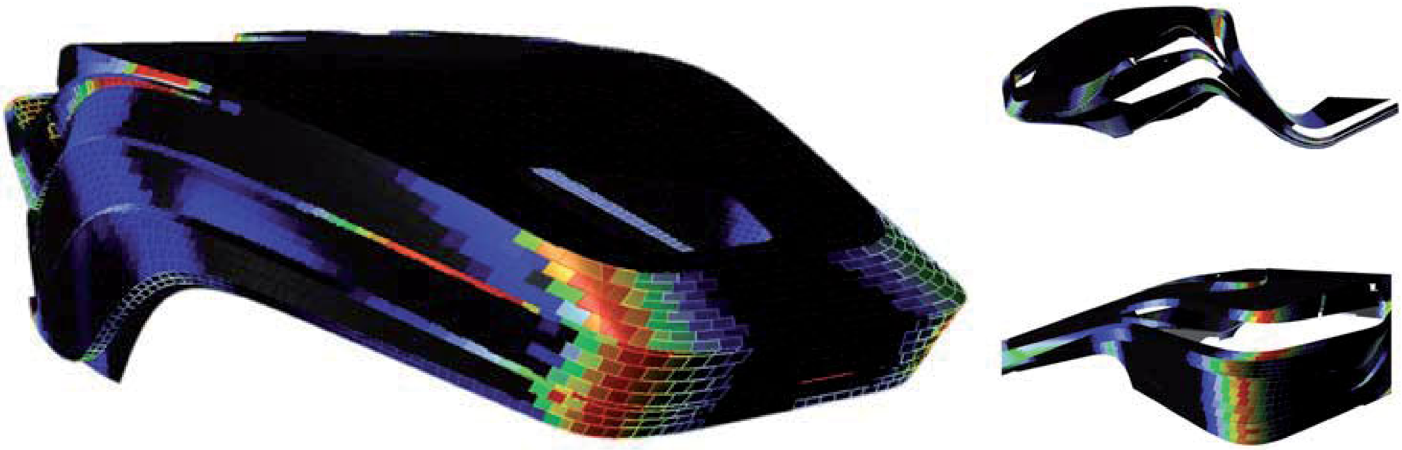


3D view showing large-scale unitised glazing system supported by glass fin system and interfacing with metal-clad steel structural trusses

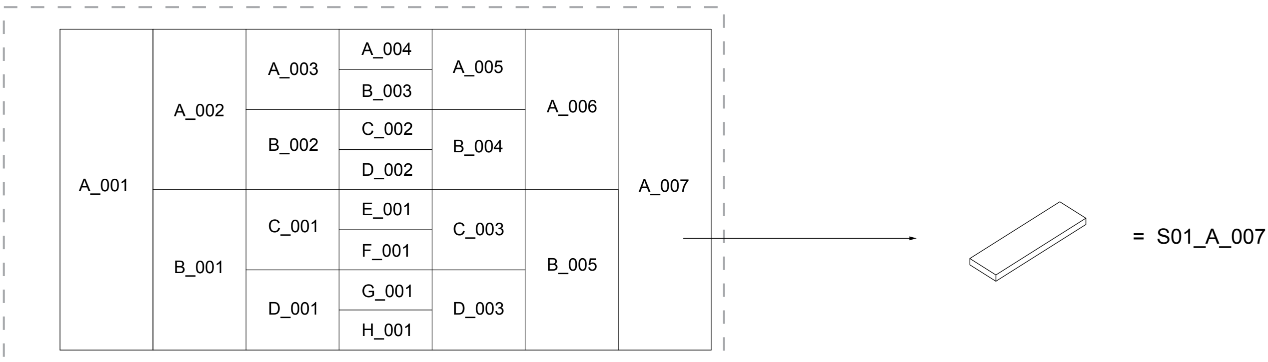
(Below) 3D view showing large-scale unitised glazing system supported by glass fin system



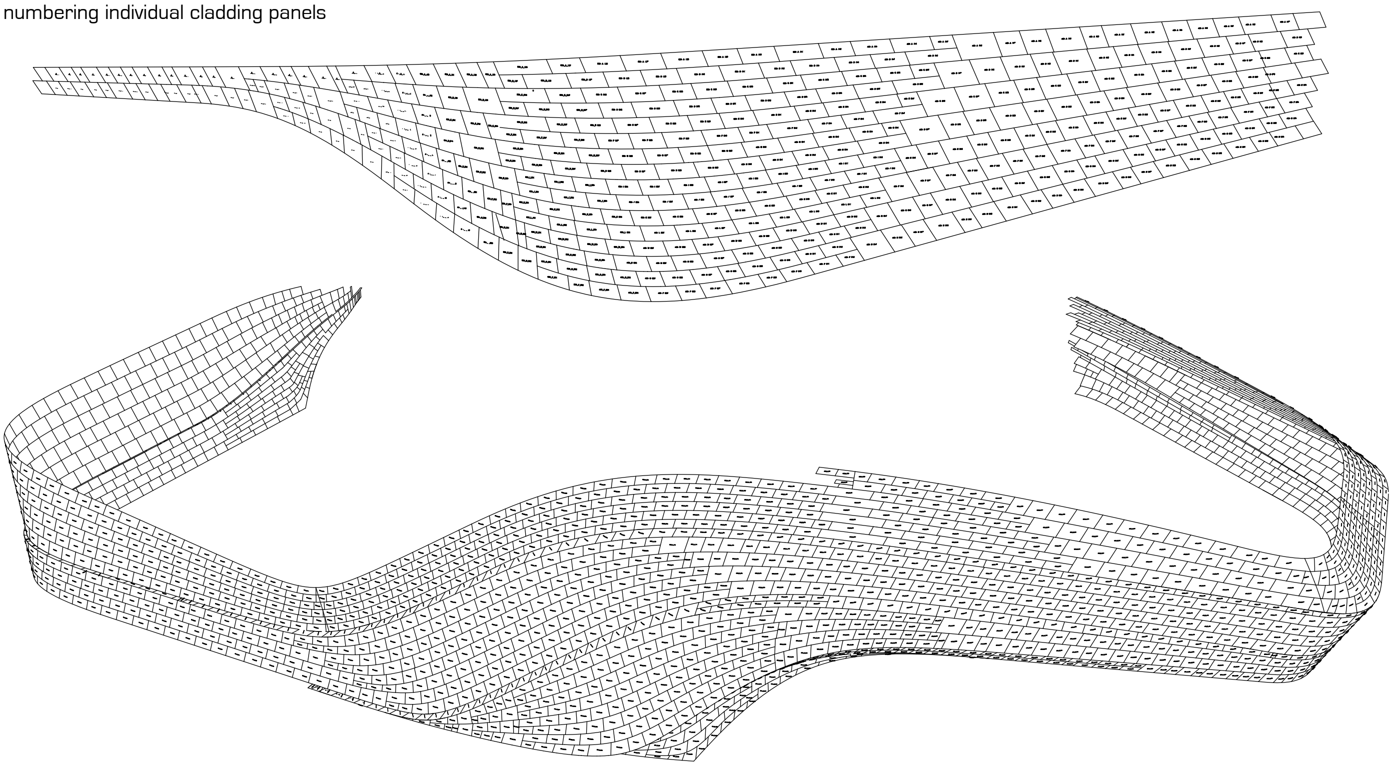
3D view showing large-scale unitised glazing system supported by glass fin and double cable hybrid system

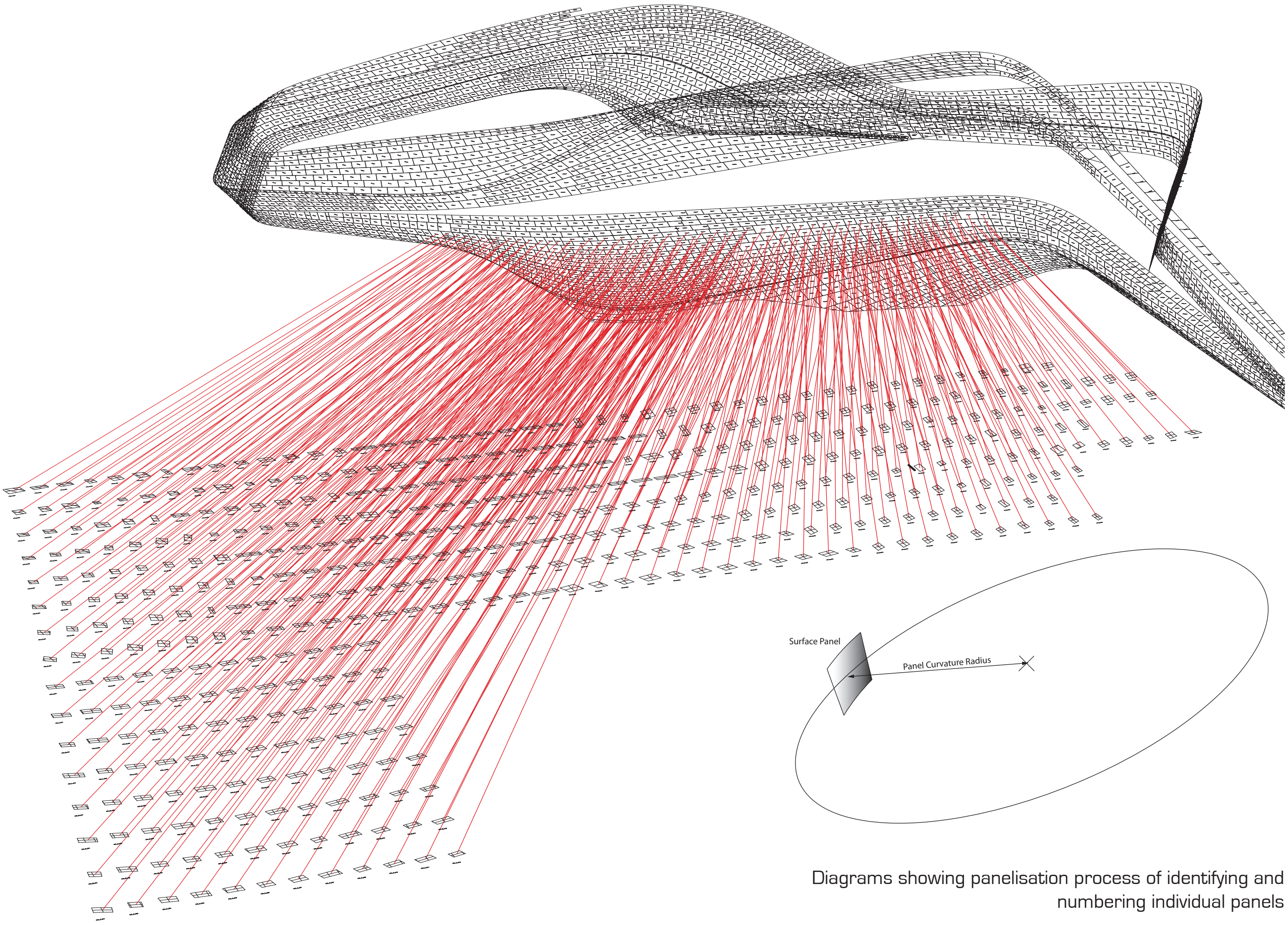


3D views showing curvature analysis of individual panels model for facade of complex geometry

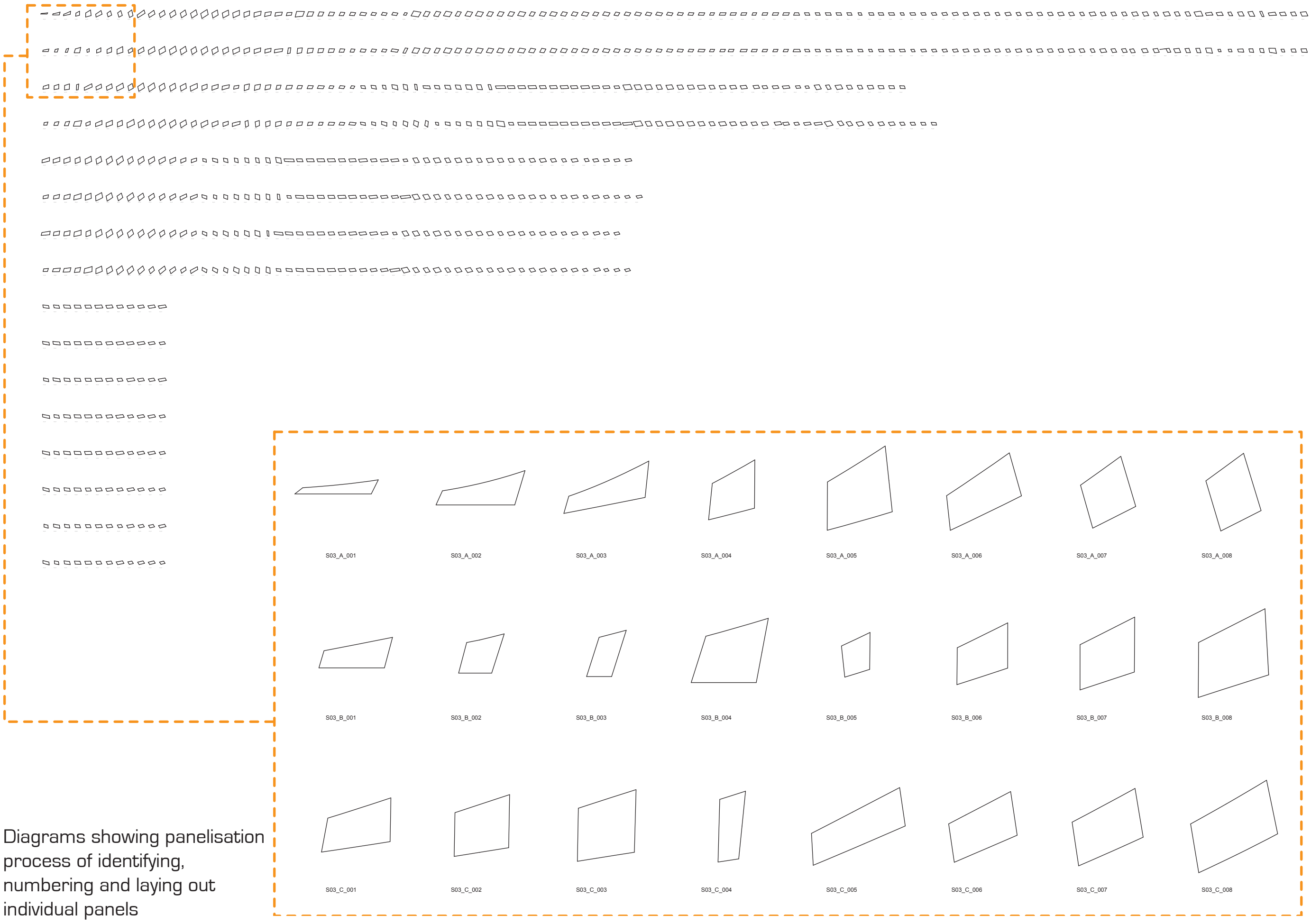


Diagrams showing panelisation process of identifying and numbering individual cladding panels



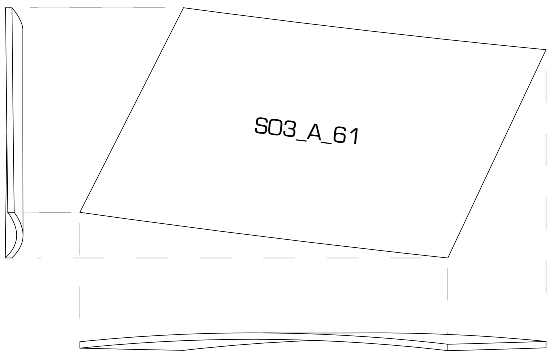


Diagrams showing panelisation process of identifying and numbering individual panels

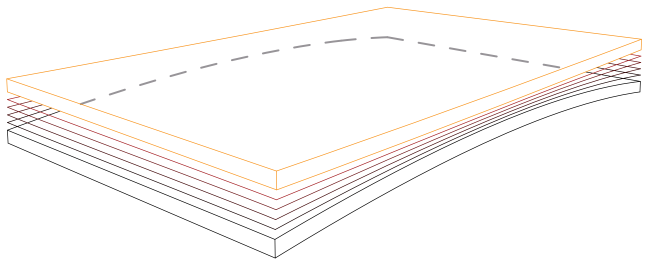


Diagrams showing panelisation process of identifying, numbering and laying out individual panels

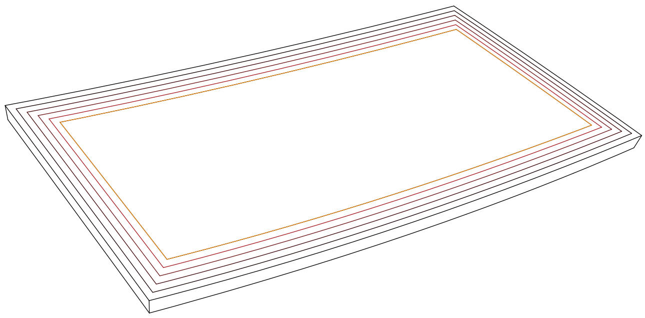
S03_A_61

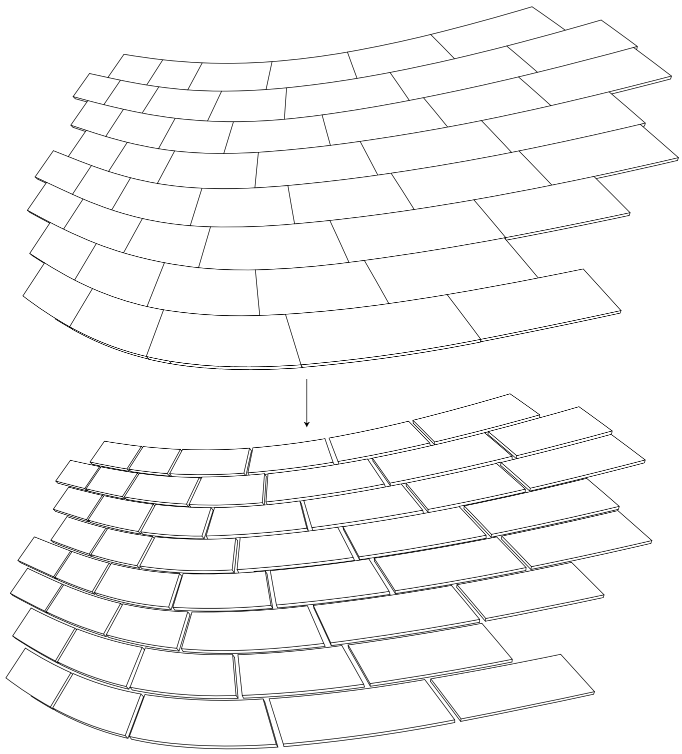


Inset panel edges for joints

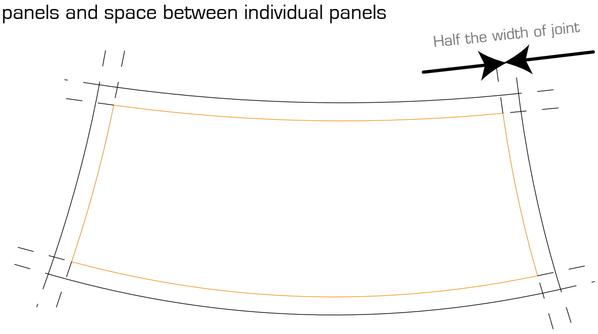


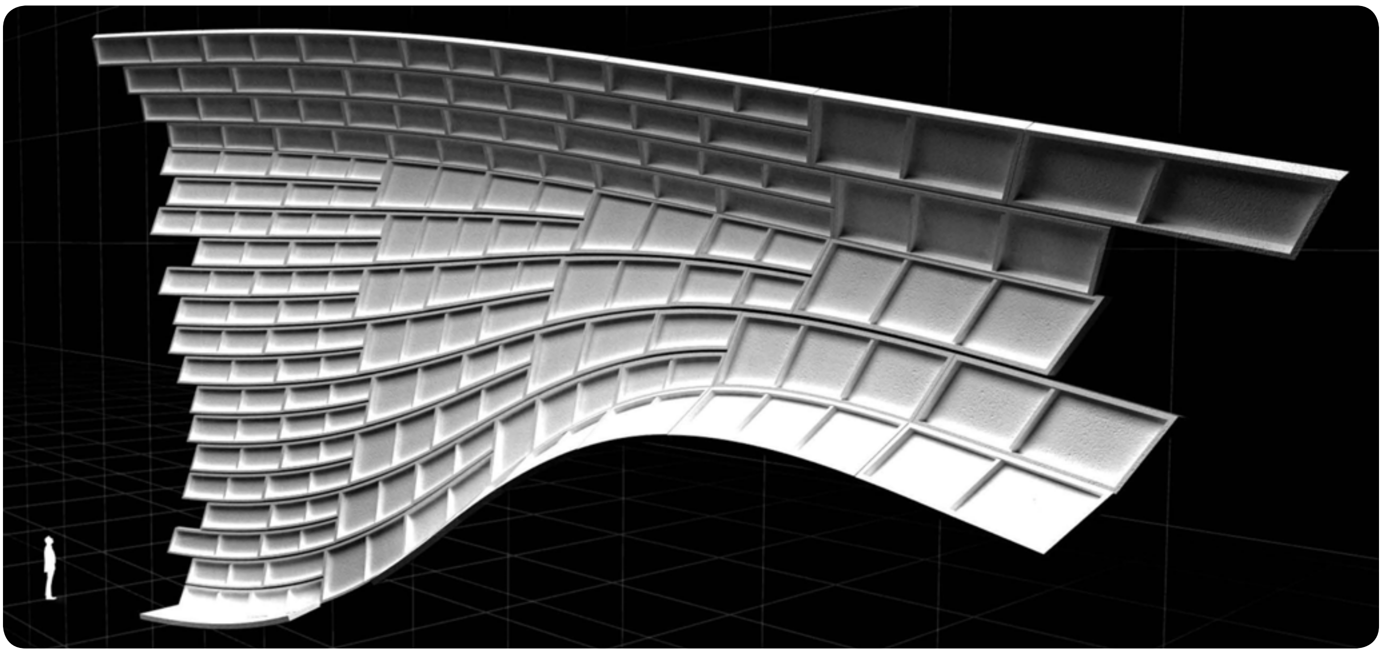
Geometry is unrolled to a flat surface so it can be bent into the mould for fabrication



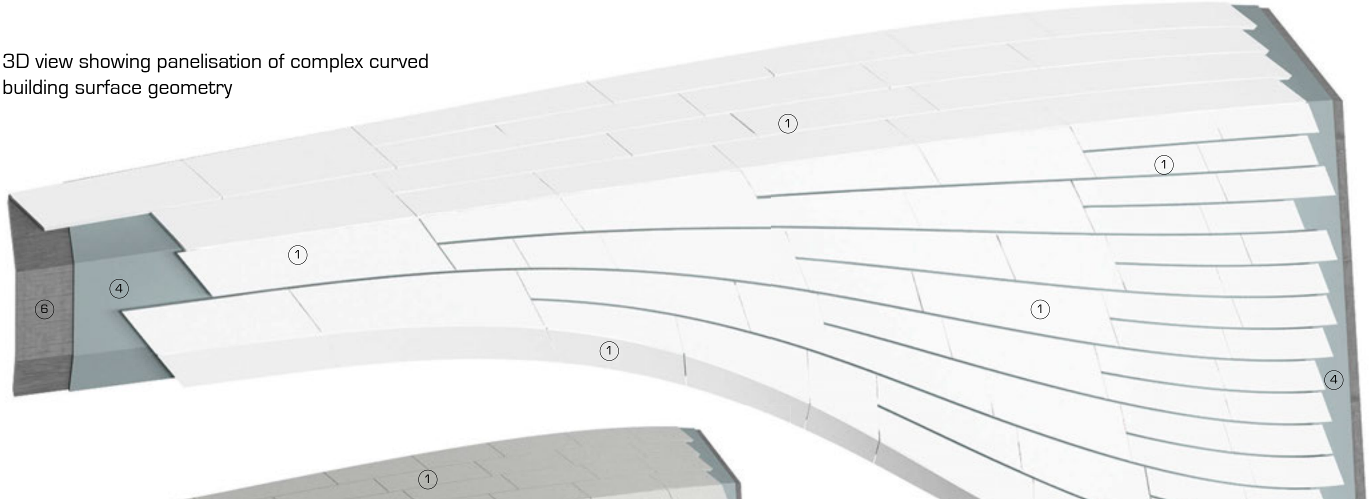


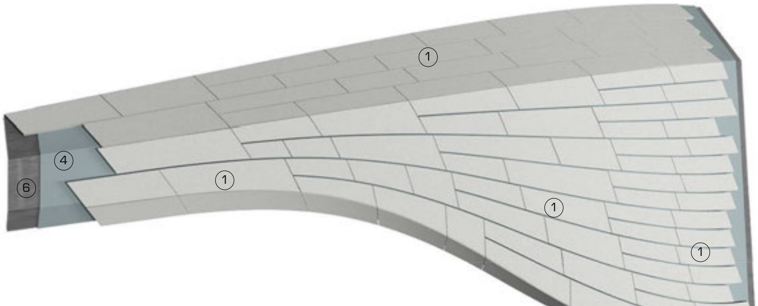
Diagrams showing panelisation process of identifying, numbering and laying out individual panels and space between individual panels



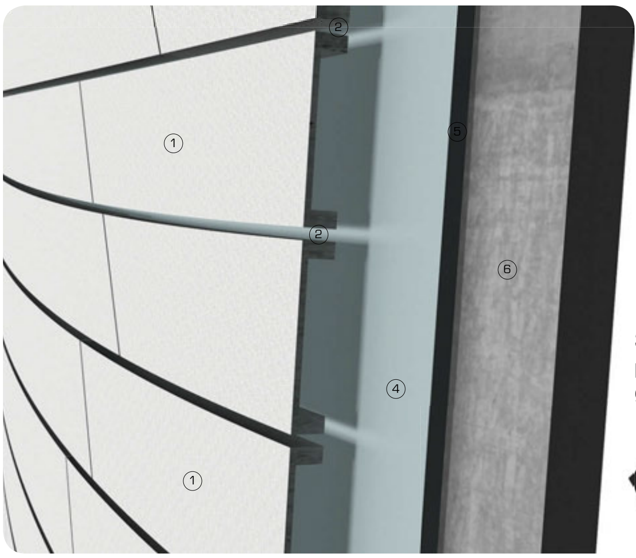


3D view showing panelisation of complex curved building surface geometry

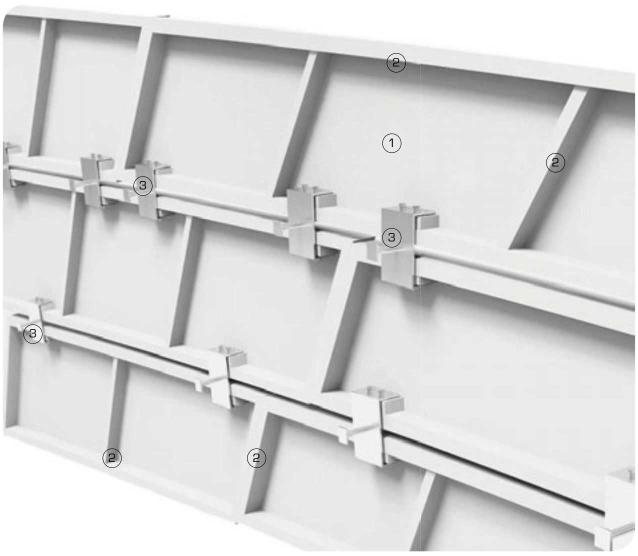




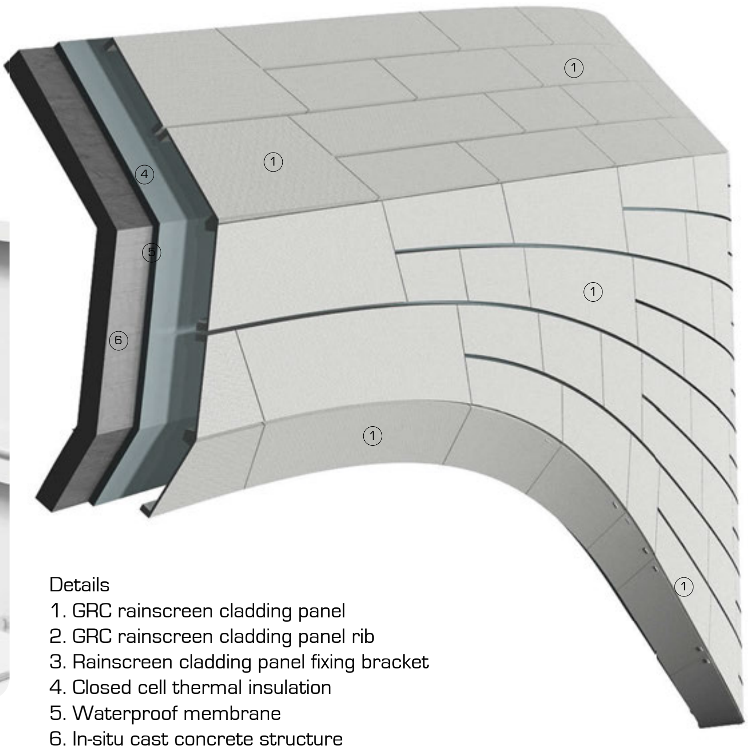
3D view showing panelisation of complex curved building surface geometry



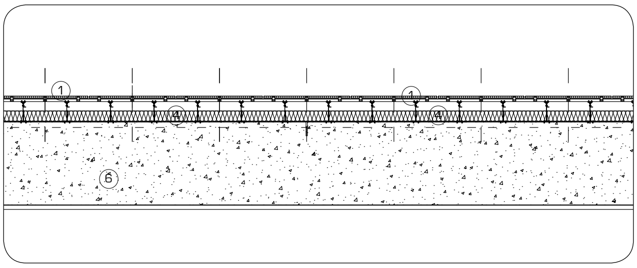
3D views showing fixing method for individual GRC panels fixed to complex curved building surface geometry

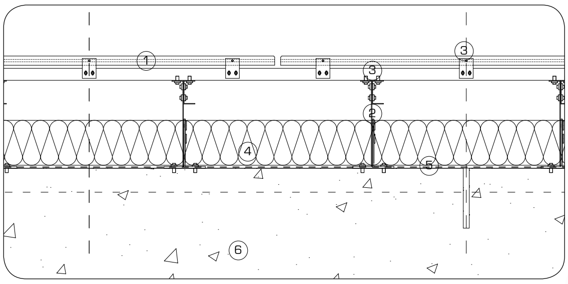


3D view showing panelisation of complex curved building surface geometry

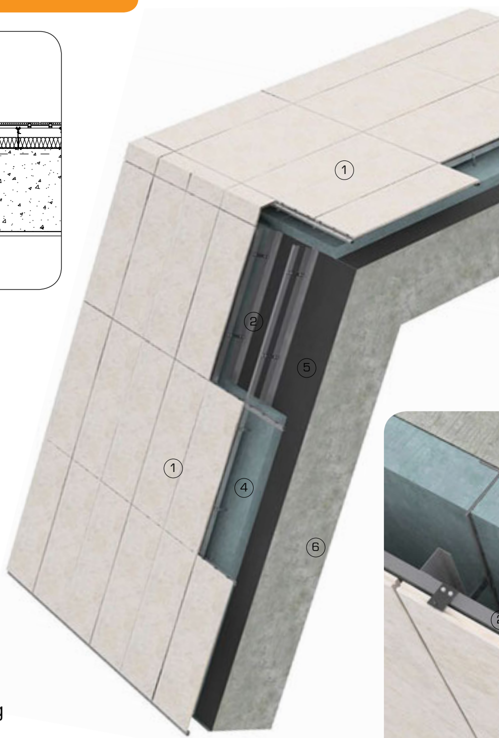


Details
1. GRC rainscreen cladding panel
2. GRC rainscreen cladding panel rib
3. Rainscreen cladding panel fixing bracket
4. Closed cell thermal insulation
5. Waterproof membrane
6. In-situ cast concrete structure

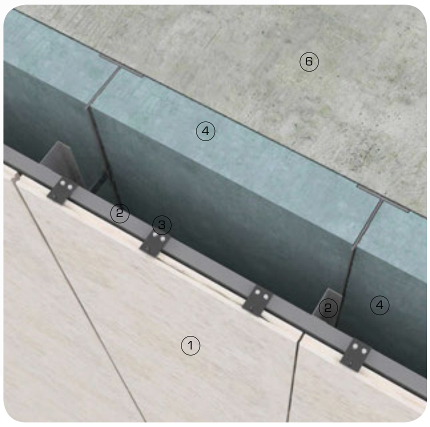




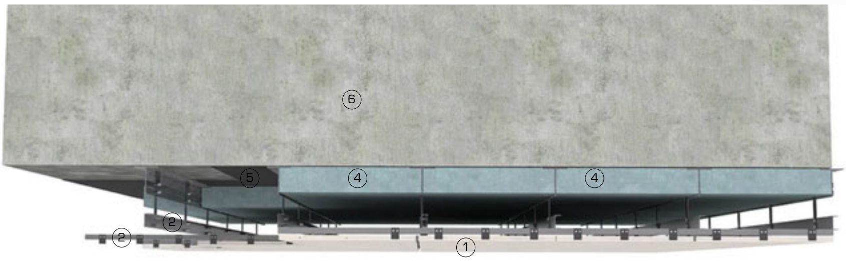
Vertical sections. Stone rainscreen cladding panels fixed to in-situ cast concrete primary structure



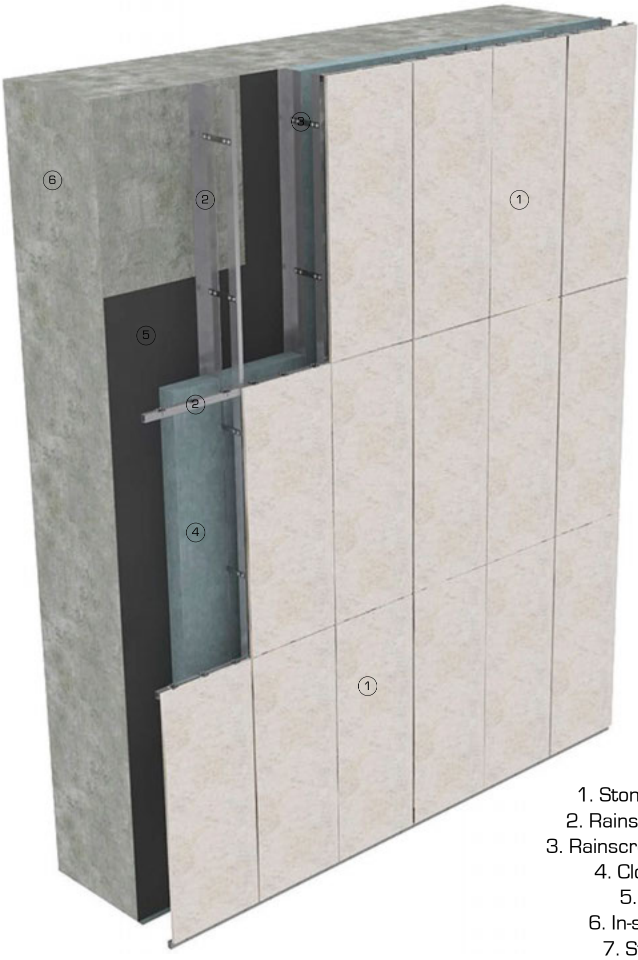
3D view showing stone rainscreen cladding panels fixed to in-situ cast concrete primary structure

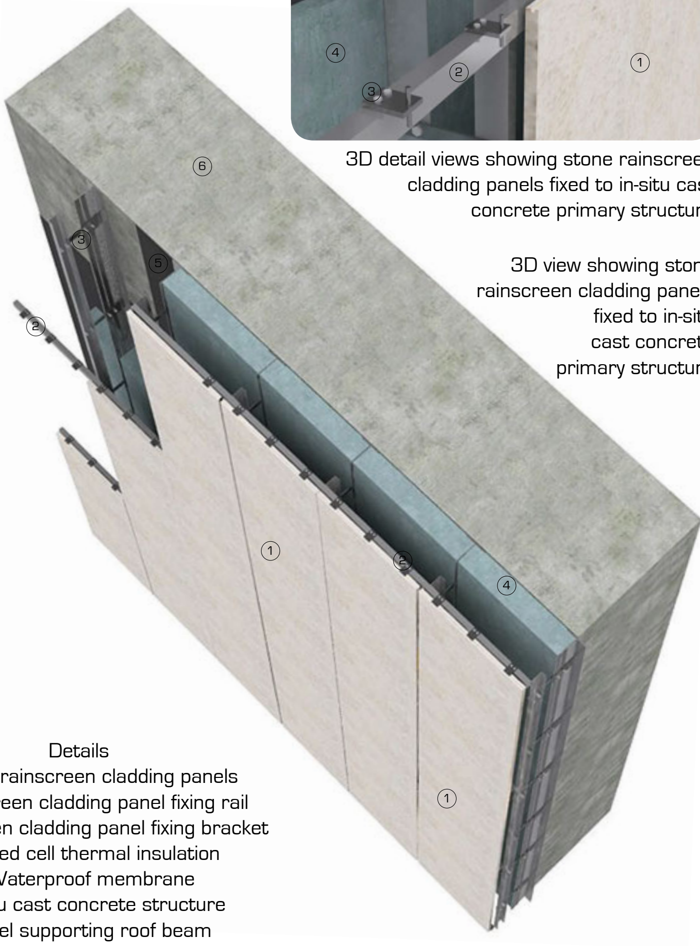


(Below) 3D detail views showing stone rainscreen cladding panels fixed to in-situ cast concrete primary structure



3D detail views showing stone rainscreen cladding panels fixed to in-situ cast concrete primary structure

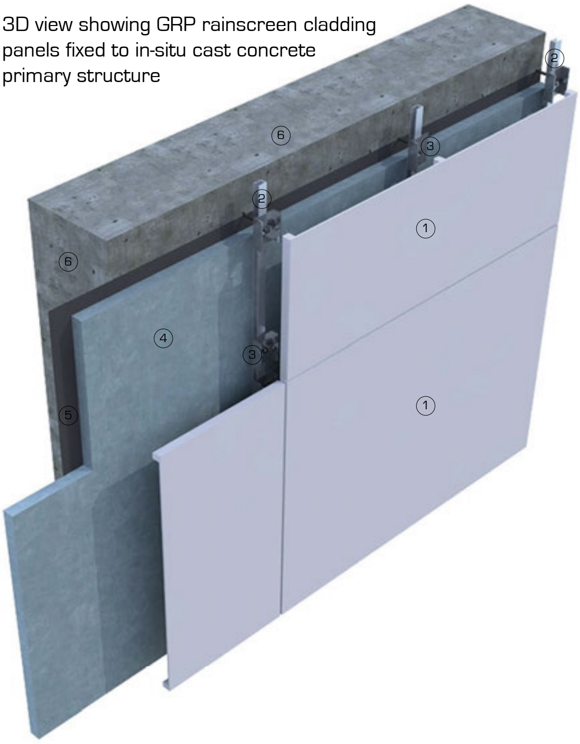


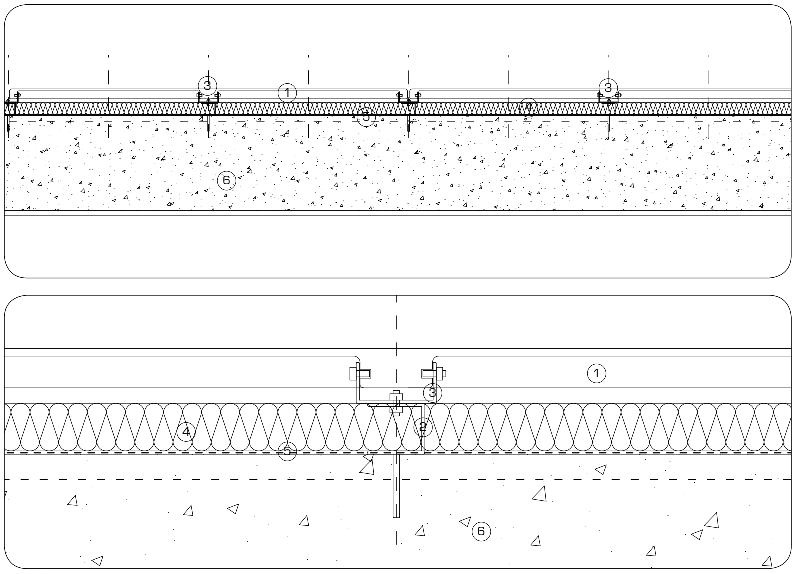


3D view showing stone rainscreen cladding panels fixed to in-situ cast concrete primary structure

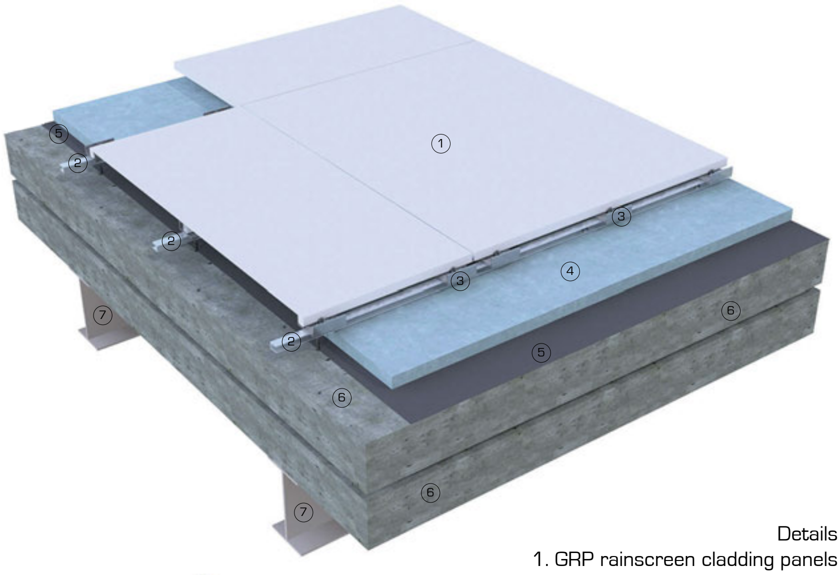
Details
1. Stone rainscreen cladding panels
2. Rainscreen cladding panel fixing rail
3. Rainscreen cladding panel fixing bracket
4. Closed cell thermal insulation
5. Waterproof membrane
6. In-situ cast concrete structure
7. Steel supporting roof beam

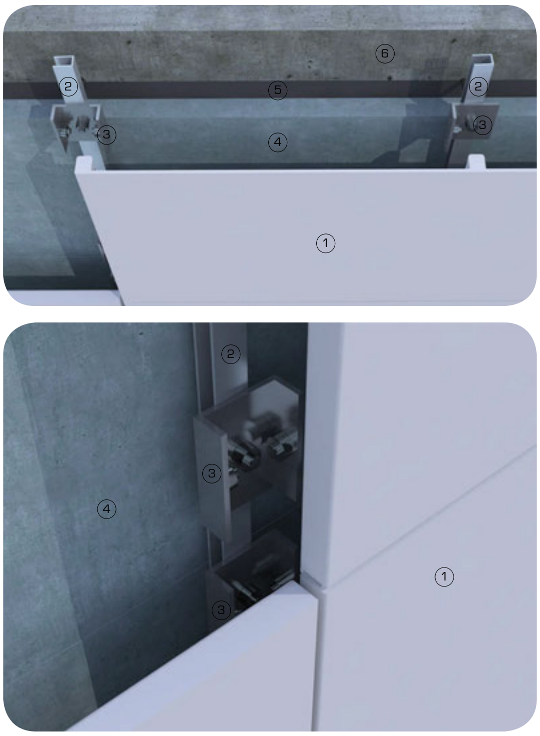
3D view showing GRP rainscreen cladding panels fixed to in-situ cast concrete primary structure





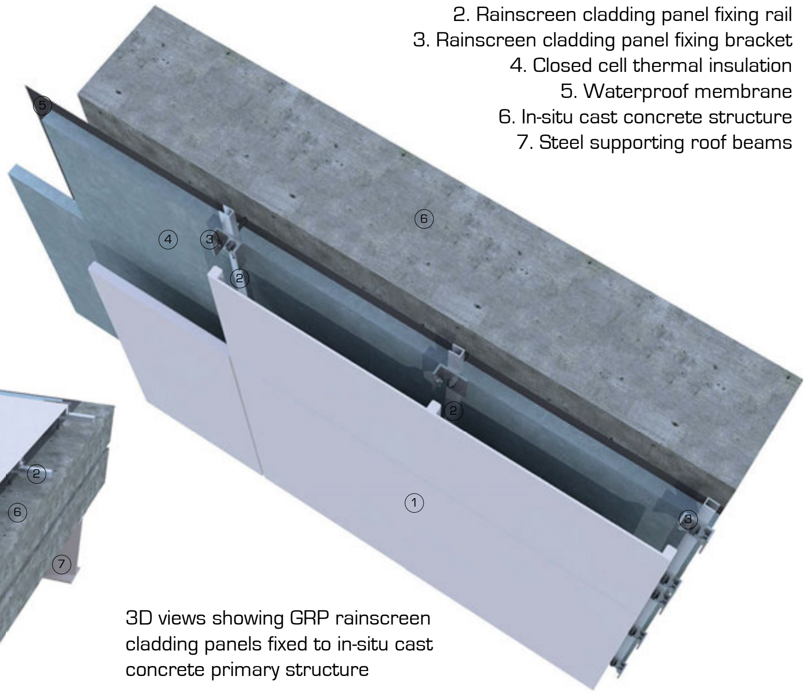
Vertical sections. GRP rainscreen cladding panels fixed to in-situ cast concrete primary roof structure



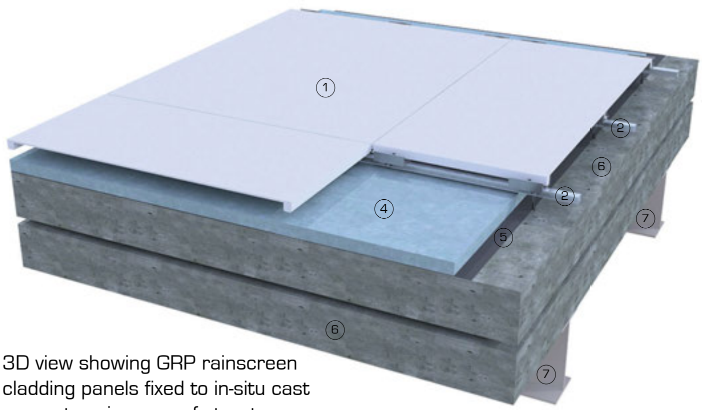


3D detail views showing GRP rainscreen cladding panels fixed to in-situ cast concrete primary structure

Details
1. GRP rainscreen cladding panels
2. Rainscreen cladding panel fixing rail
3. Rainscreen cladding panel fixing bracket
4. Closed cell thermal insulation
5. Waterproof membrane
6. In-situ cast concrete structure
7. Steel supporting roof beams



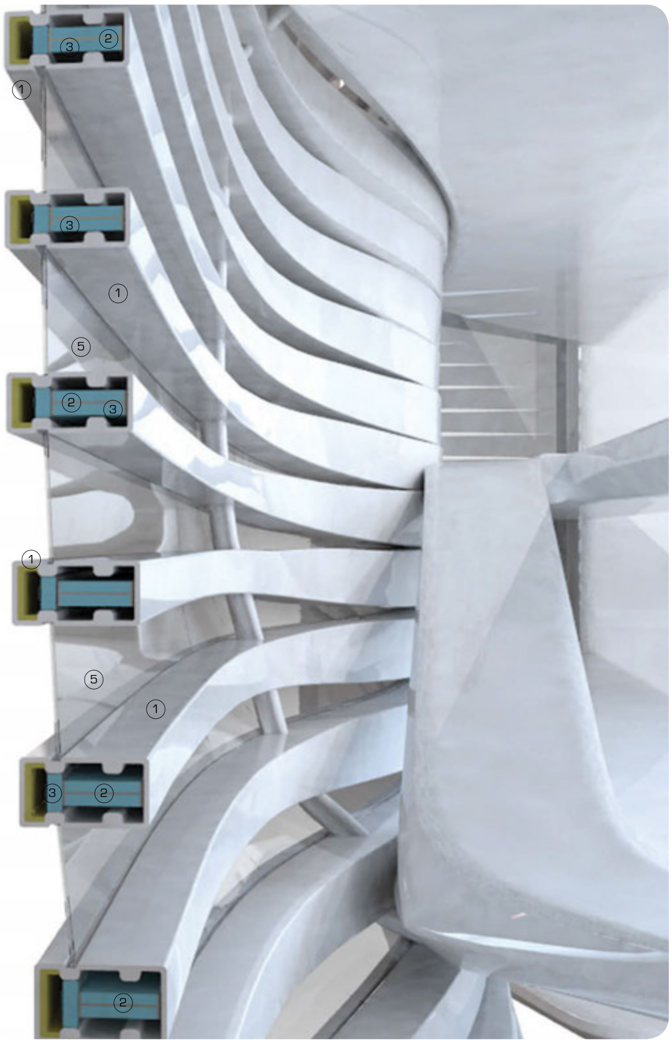
3D views showing GRP rainscreen cladding panels fixed to in-situ cast concrete primary structure



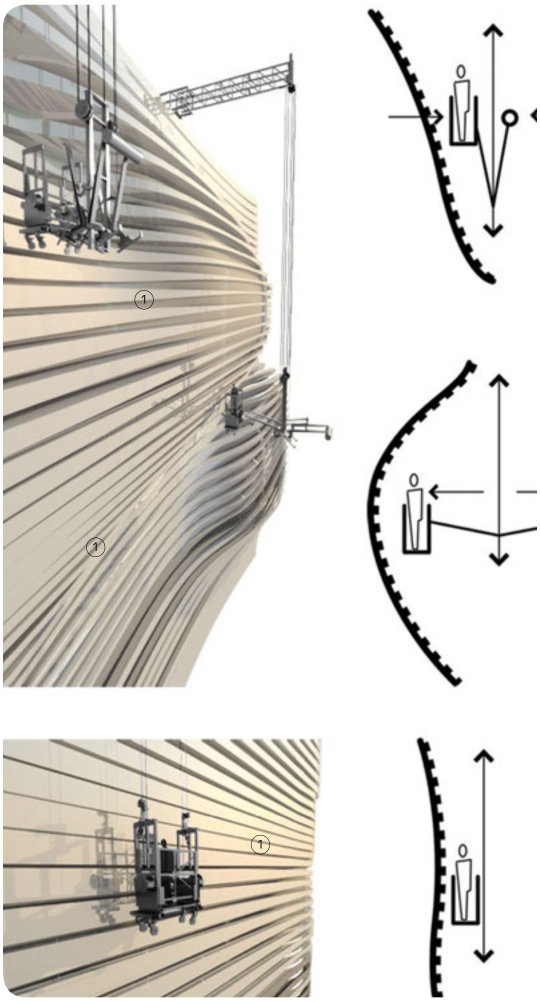
3D view showing GRP rainscreen cladding panels fixed to in-situ cast concrete primary roof structure

15 Full-height glazing with GRP-clad structural frame

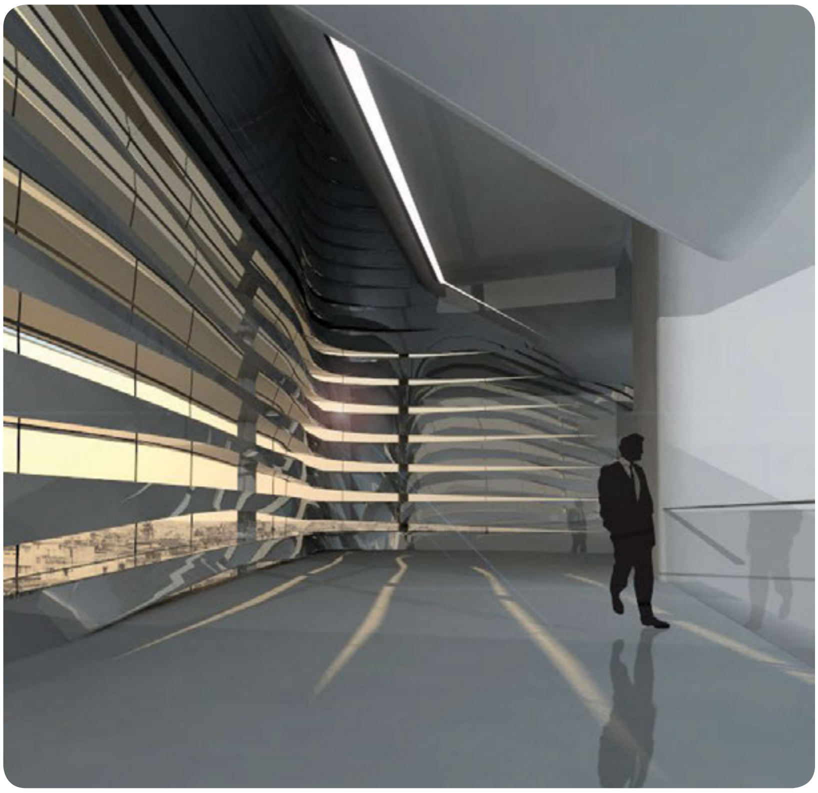
3D internal view showing full-height glazed facade with external GRP cladding over primary steel structure



3D sectional detail view showing full-height glazed facade with external GRP cladding over primary steel structure



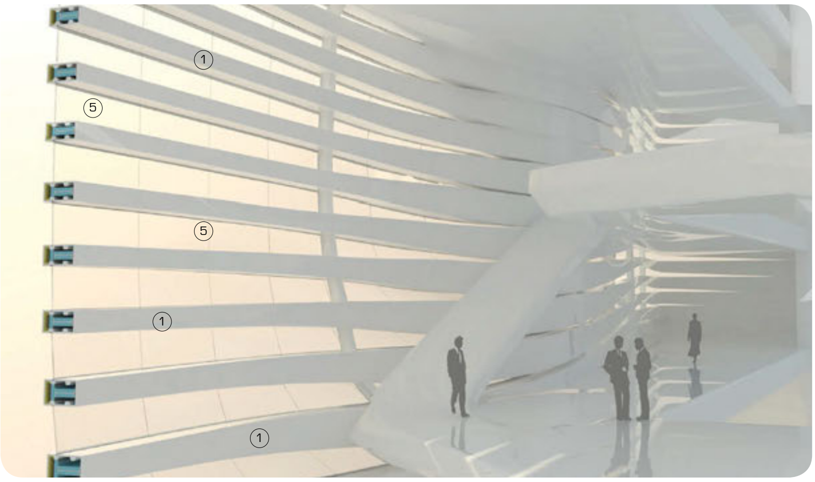
Diagrams showing cleaning method for full-height glazed facade with external GRP cladding over primary steel structure



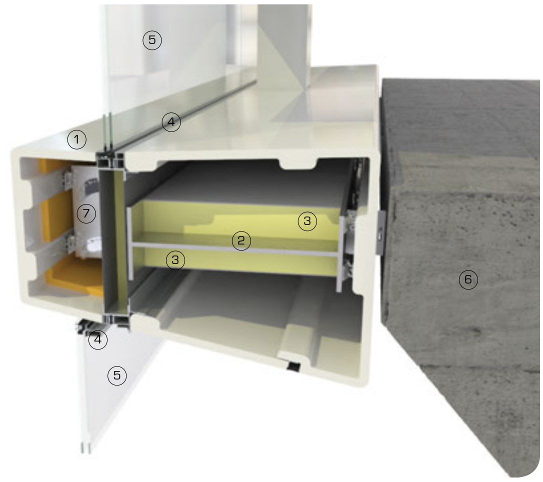
3D internal view showing full-height glazed facade with external GRP cladding over primary steel structure

Details
1. GRP cladding
2. Primary steel structure
3. Thermal insulation
4. Glazing frame
5. Double glazing
6. Concrete floor slab
7. GRP fixing bracket

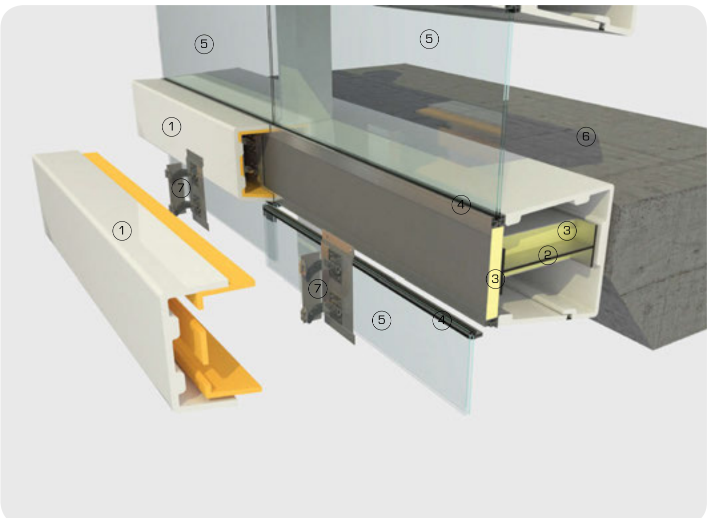
3D sectional detail view showing full-height glazed facade with external GRP cladding over primary steel structure

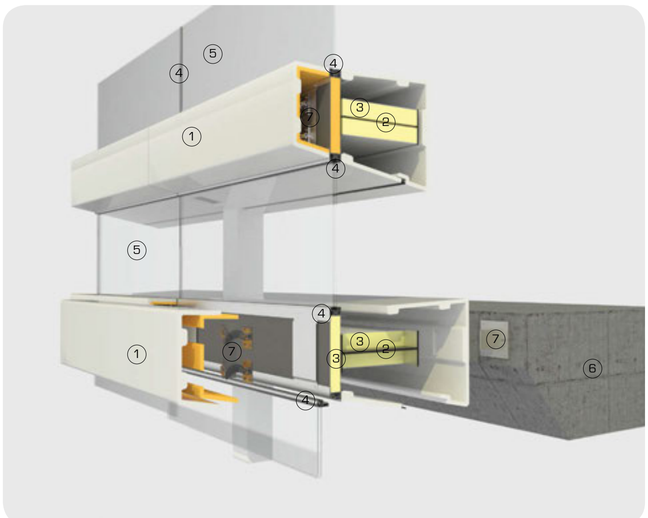


3D sectional detail view showing full-height glazed facade with external GRP cladding over primary steel structure



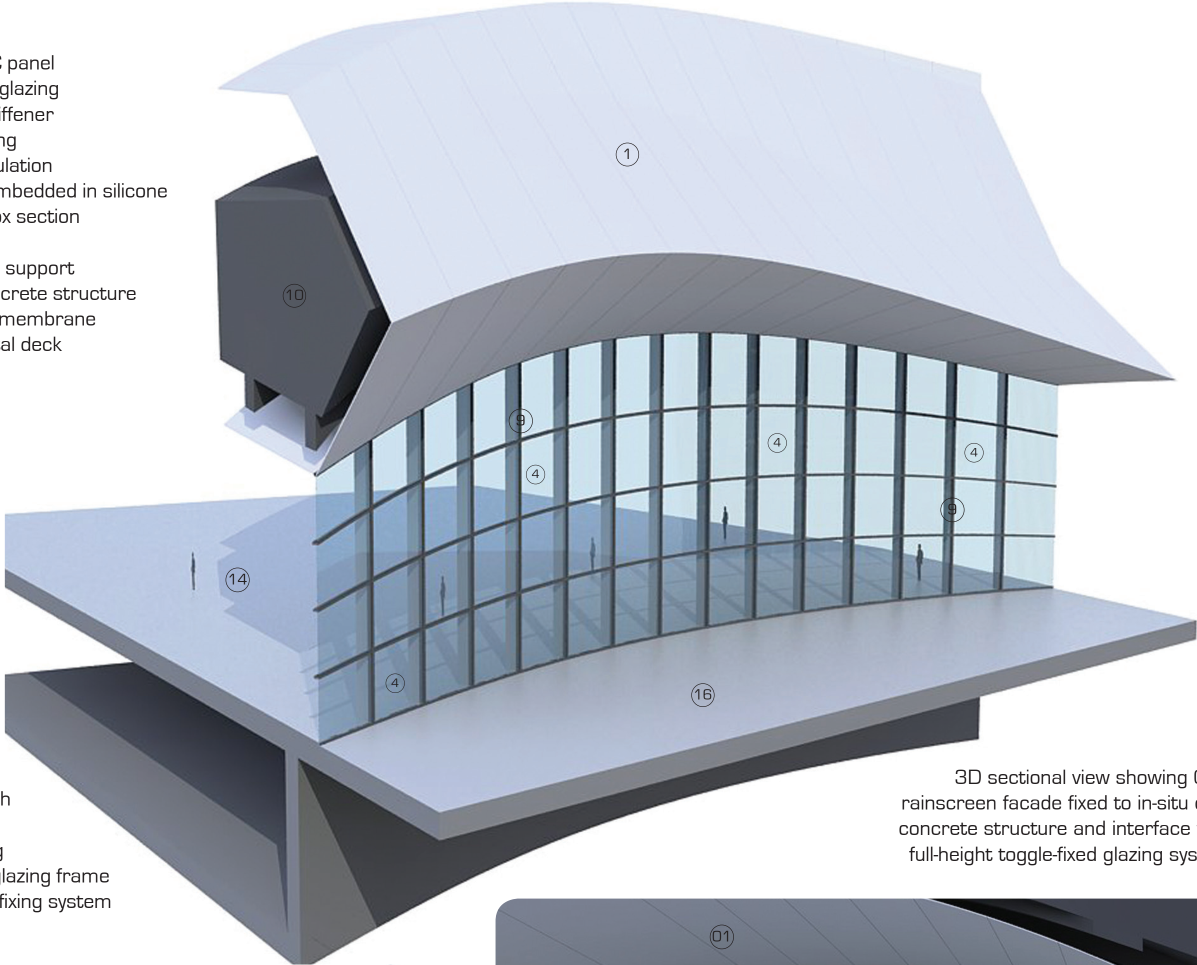
3D detail view showing full-height glazed facade with external GRP cladding over primary steel structure



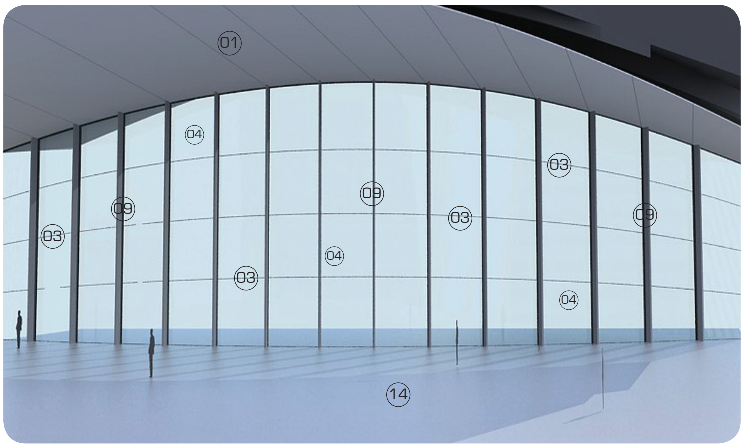


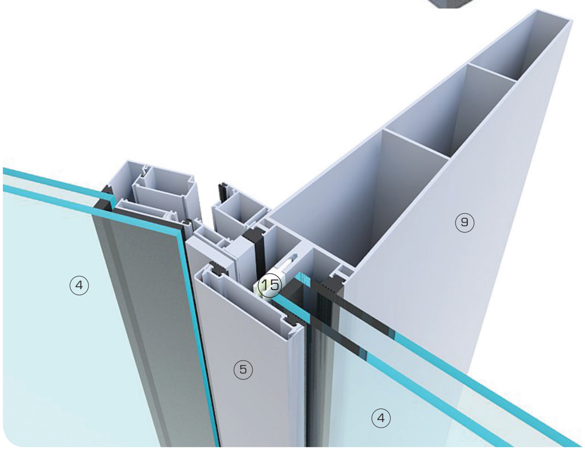
3D exploded detail views showing full-height glazed facade with external GRP cladding over primary steel structure

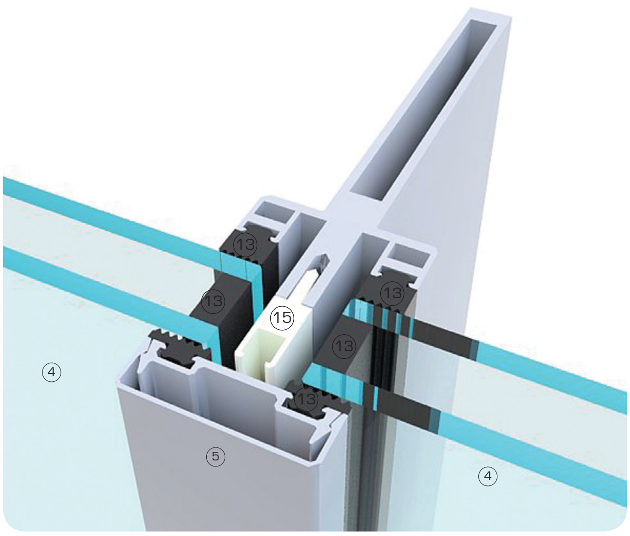
Details
1. Opaque GRC panel
2. Toggle fixed glazing
3. Mild steel stiffener
4. Double glazing
5. Thermal insulation
6. Metal cap embedded in silicone
7. Mild steel box section
8. Gutter
9. Steel glazing support
10. Primary concrete structure
11. Single layer membrane
12. Profiled metal deck
13. Silicone seal
14. Internal finish
15. Toggle-fixing
16. Landscaping
17. Aluminium glazing frame
18. Rainscreen fixing system

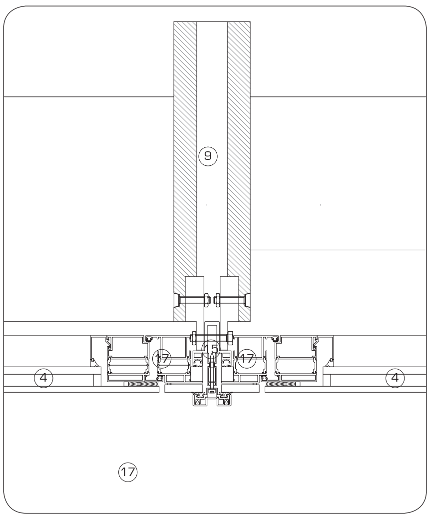


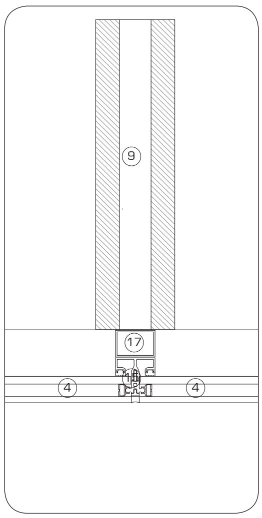
3D sectional view showing GRC rainscreen facade fixed to in-situ cast concrete structure and interface with full-height toggle-fixed glazing system



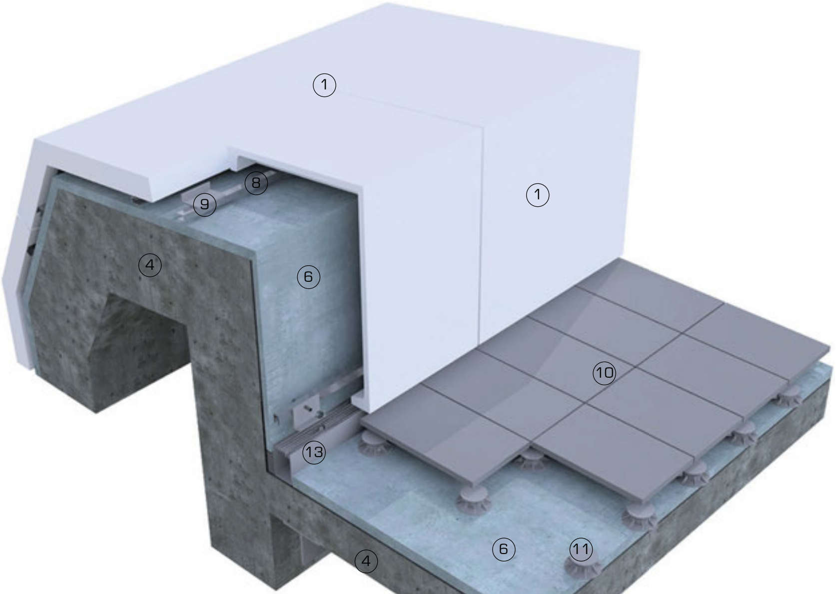




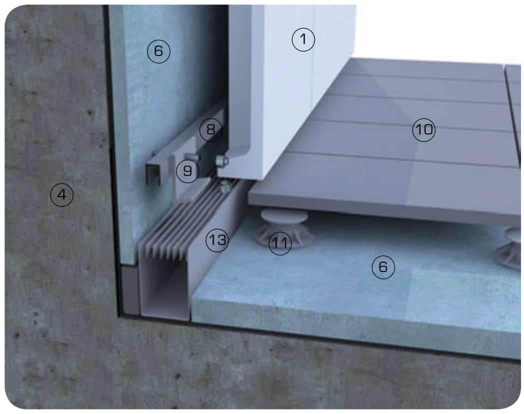




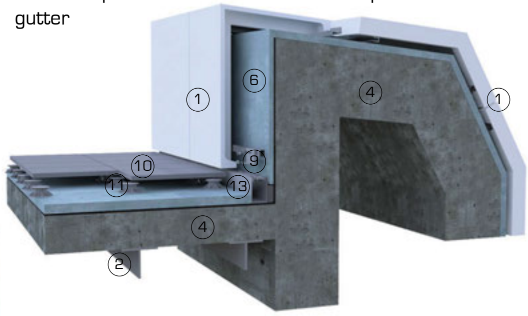
(Above) Horizontal section. Toggle-fixed glazing system (opening light and fixed light configurations)
(Left) 3D detail views showing toggle-fixed glazing system

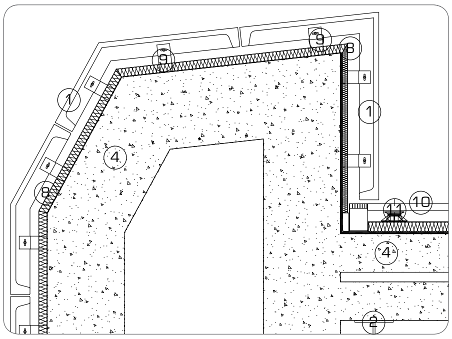


3D detail fragment view showing GRC rainscreen cladding interface with GRC pavers on terrace deck build-up

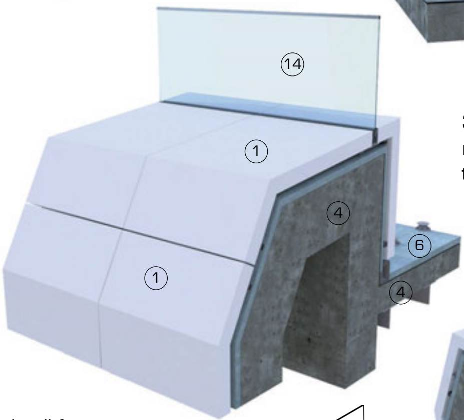


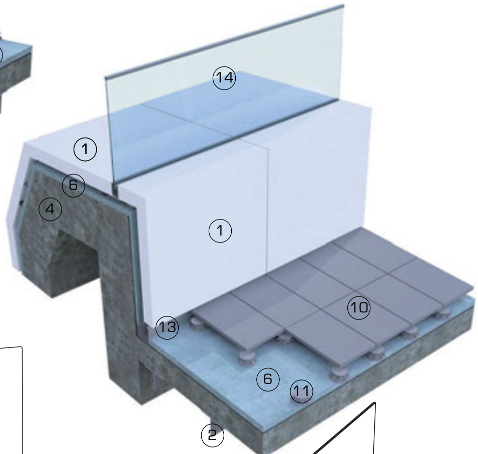
3D detail view showing GRC rainscreen cladding interface with GRC pavers on terrace deck build-up and concealed gutter



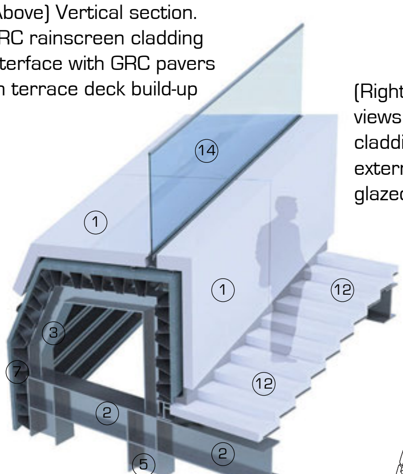


(Above) Vertical section. GRC rainscreen cladding interface with GRC pavers on terrace deck build-up

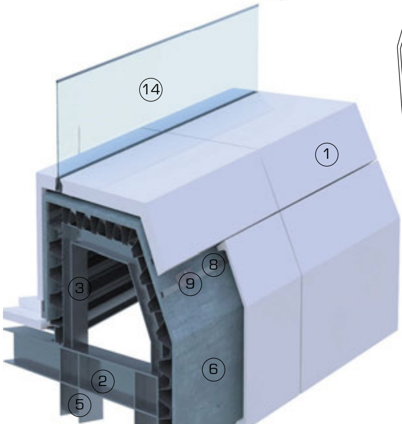


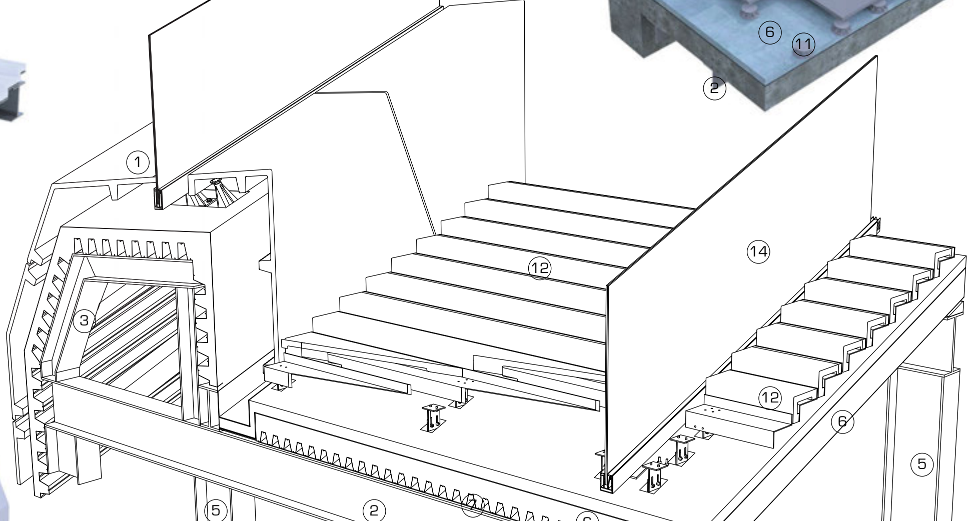


3D detail fragment views showing GRC rainscreen cladding interface with GRC pavers on terrace deck build-up and glazed balustrade



(Right) 3D detail fragment views showing GRC rainscreen cladding interface with GRC clad external steel staircase and glazed balustrade

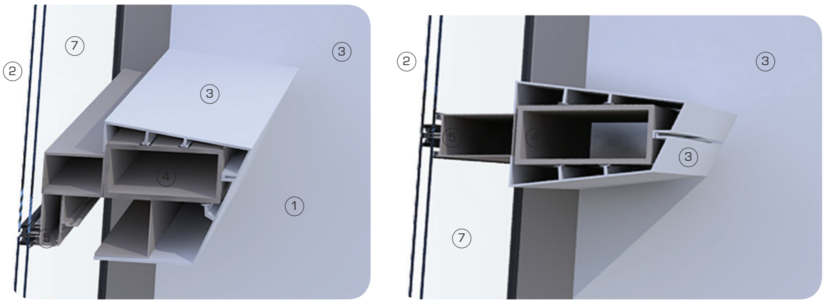




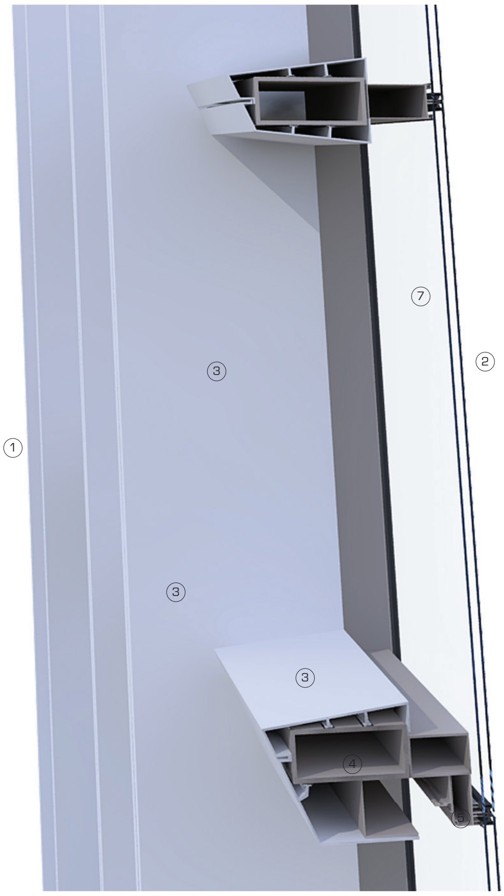
3D detail fragment view showing GRC rainscreen cladding interface with GRC-clad external steel staircase and glazed balustrade

Details
1. GRC rainscreen cladding
2. Primary steel roof structure
3. Secondary steel structure
4. Concrete primary structure
5. Primary steel column
6. Closed cell thermal insulation
7. Profiled metal deck
8. Rainscreen cladding fixing rail
9. Rainscreen cladding fixing bracket
10. GRC paver
11. GRC paver plastic spacers
12. GRC steel staircase cladding
13. Gutter
14. Glazed balustrade

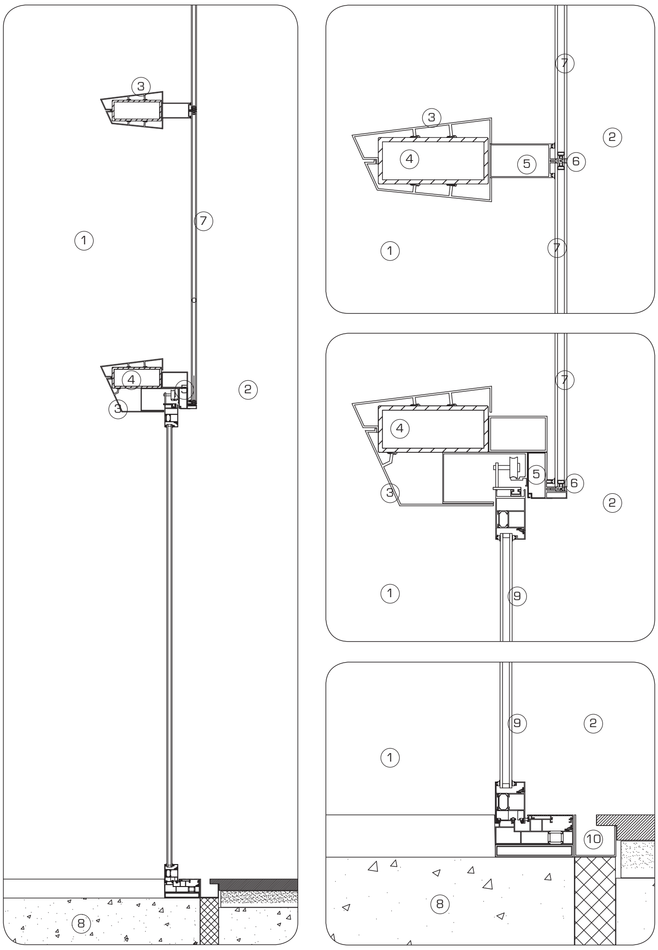
3D sectional view showing GRP-clad steel support structure with full-height toggle-fixed glazing



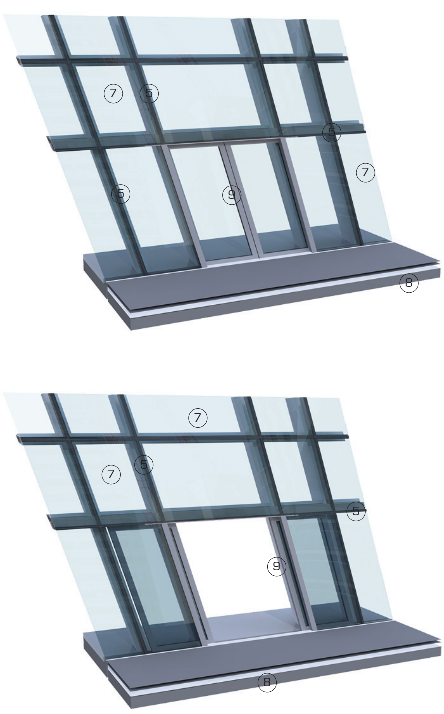
3D detail views showing GRP-clad steel support structure with full-height toggle-fixed glazing



3D sectional view showing GRP-clad steel support structure with full-height toggle-fixed glazing



Vertical sections. GRP-clad steel support structure with full-height toggle-fixed glazing, sliding door and interface with ground

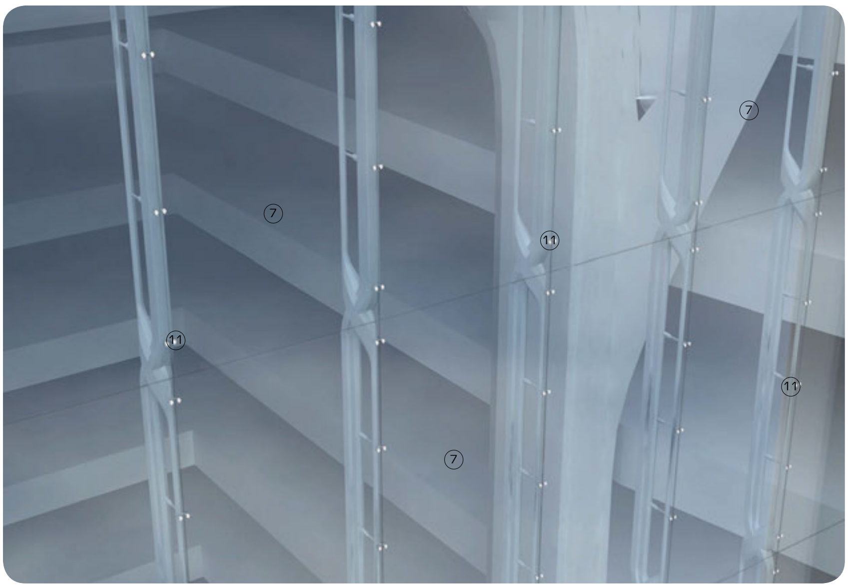


(Above) 3D views showing sliding door within GRP-clad steel support structure and toggle-fixed glazing, in closed and open positions

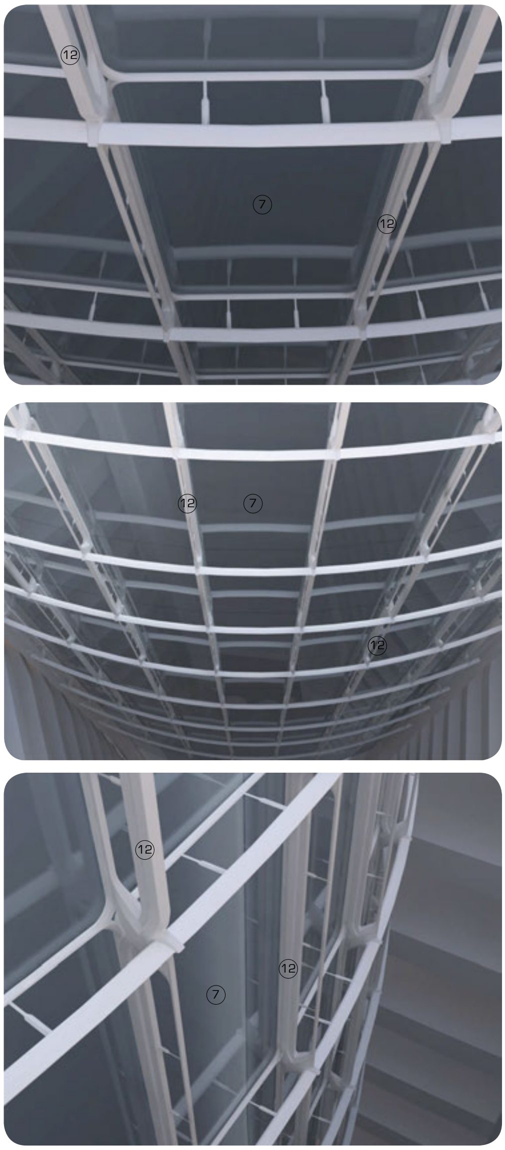
(Right) 3D sectional view showing GRP-clad steel support structure with full-height toggle-fixed glazing

3D views showing cast aluminium glazing frames supporting full-height glazing

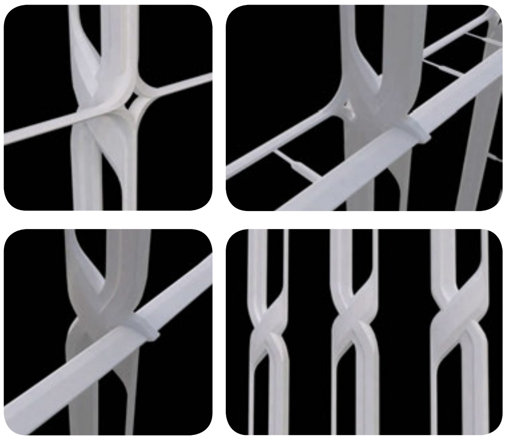
3D views showing cast aluminium glazing frames supporting full-height glazing with cap piece



3D view showing cast aluminium glazing frames supporting full-height clamped glazing



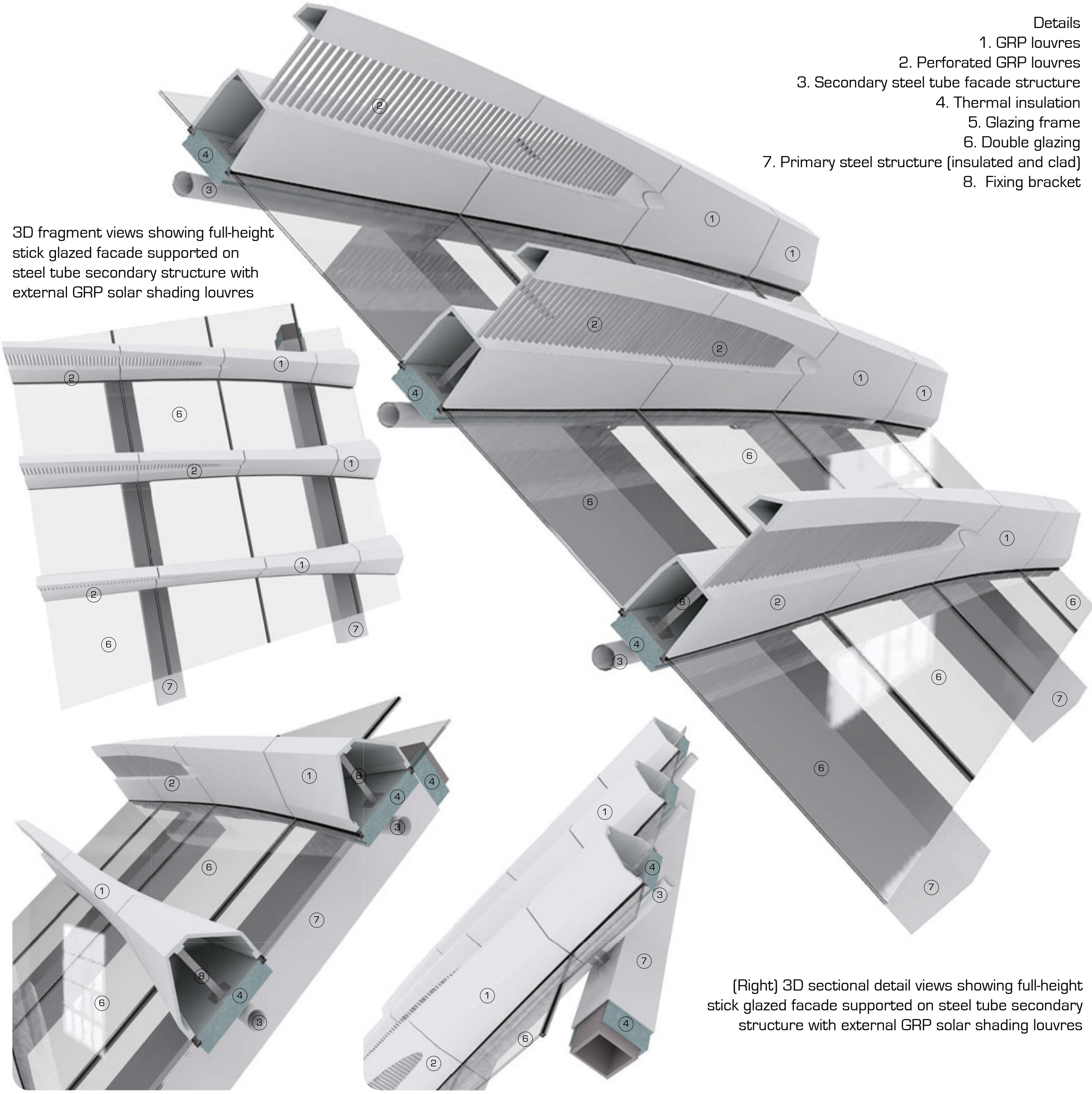
3D internal views showing cast aluminium glazing frames with double-layer rod support


3D views showing cast aluminium glazing frames, in various configurations

Details

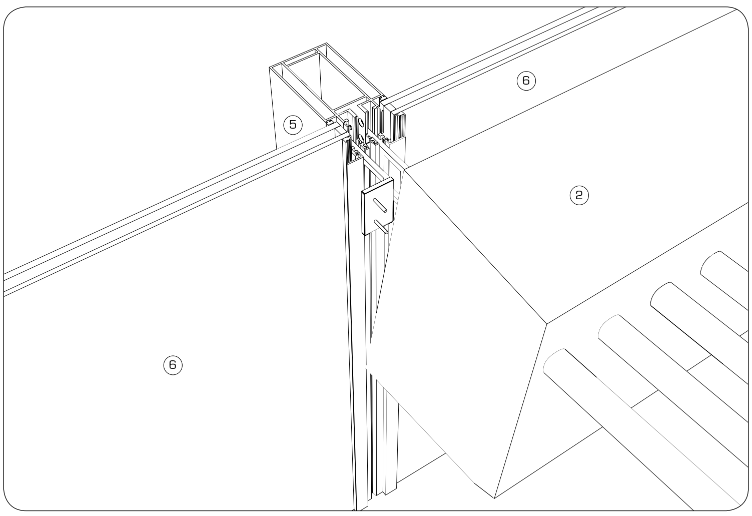
1. Internal
2. External
3. Metal cladding to glazing support structure
4. Steel support structure
5. Glazing frame
6. Toggle-fixing
7. Double glazing
8. Ground
9. Sliding door
10. Gutter
11. Clamped glazing fixing
12. Cast aluminium glazing frame

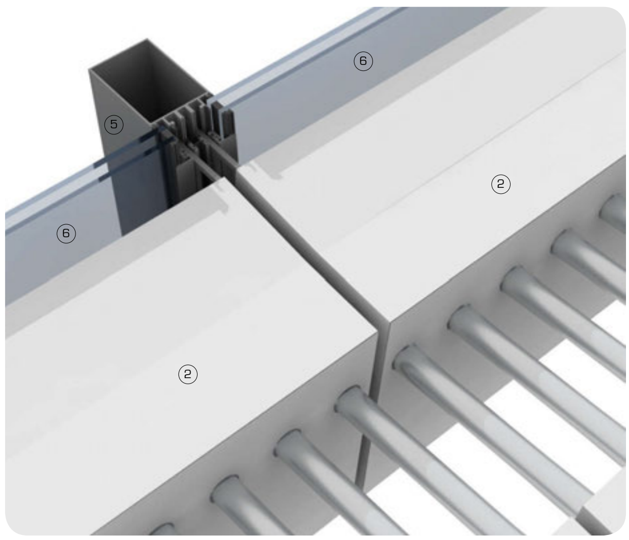
Details
1. GRP louvres
2. Perforated GRP louvres
3. Secondary steel tube facade structure
4. Thermal insulation
5. Glazing frame
6. Double glazing
7. Primary steel structure (insulated and clad)
8. Fixing bracket



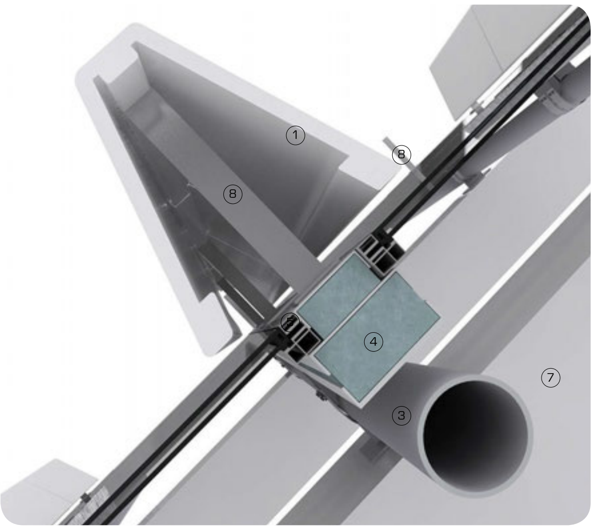
3D fragment views showing full-height stick glazed facade supported on steel tube secondary structure with external GRP solar shading louvres

(Right) 3D sectional detail views showing full-height stick glazed facade supported on steel tube secondary structure with external GRP solar shading louvres

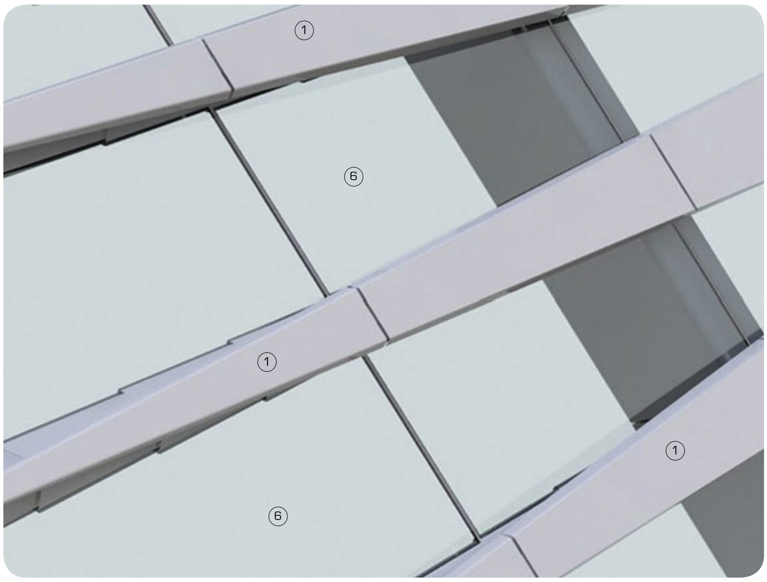




3D detail views showing stick glazed facade with external GRP solar shading louvres

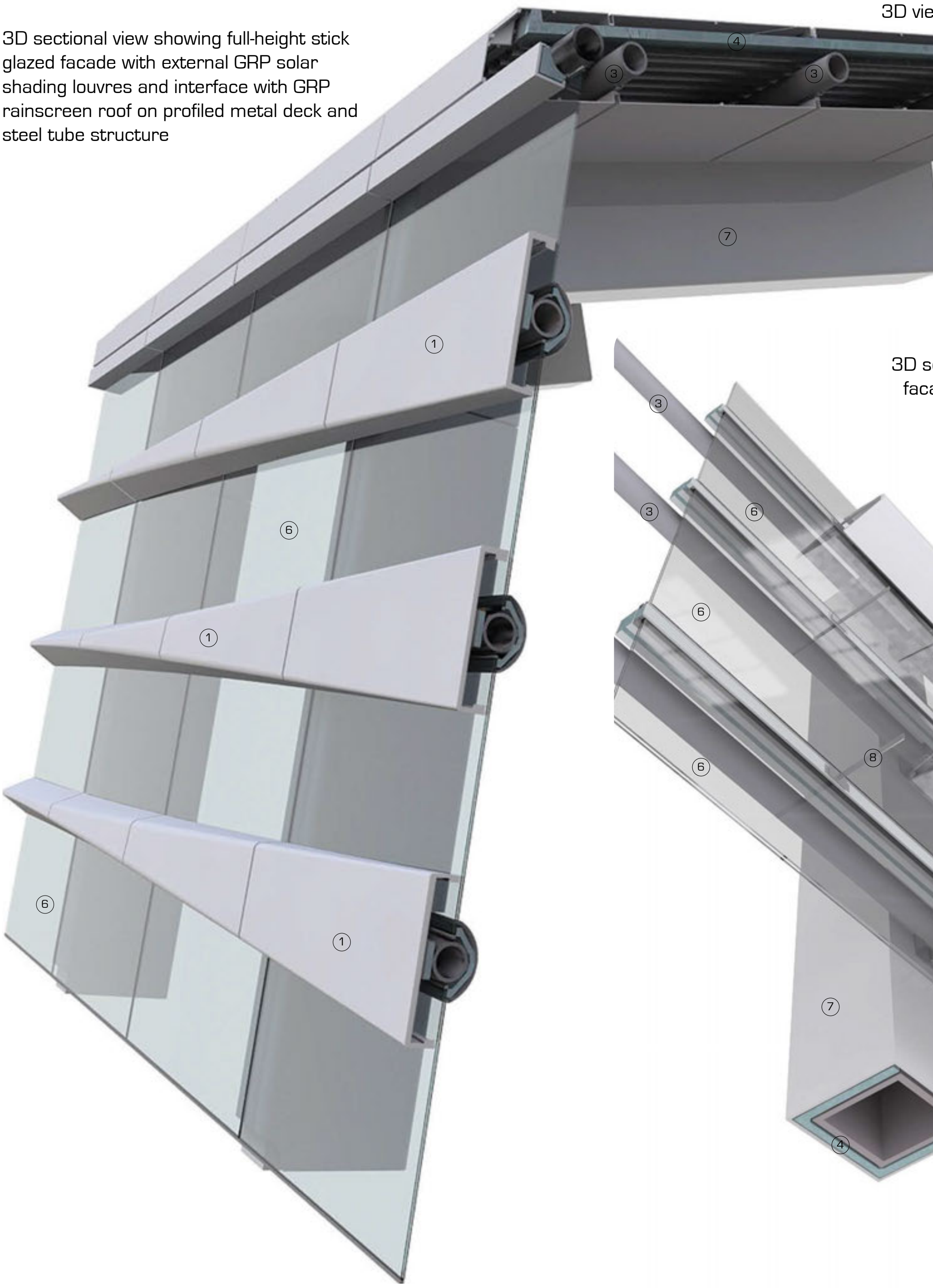


3D detail view showing stick glazed facade supported on steel tube secondary structure with external GRP solar shading louvres



3D view showing stick glazed facade with external GRP solar shading louvres

3D sectional view showing full-height stick glazed facade with external GRP solar shading louvres and interface with GRP rainscreen roof on profiled metal deck and steel tube structure



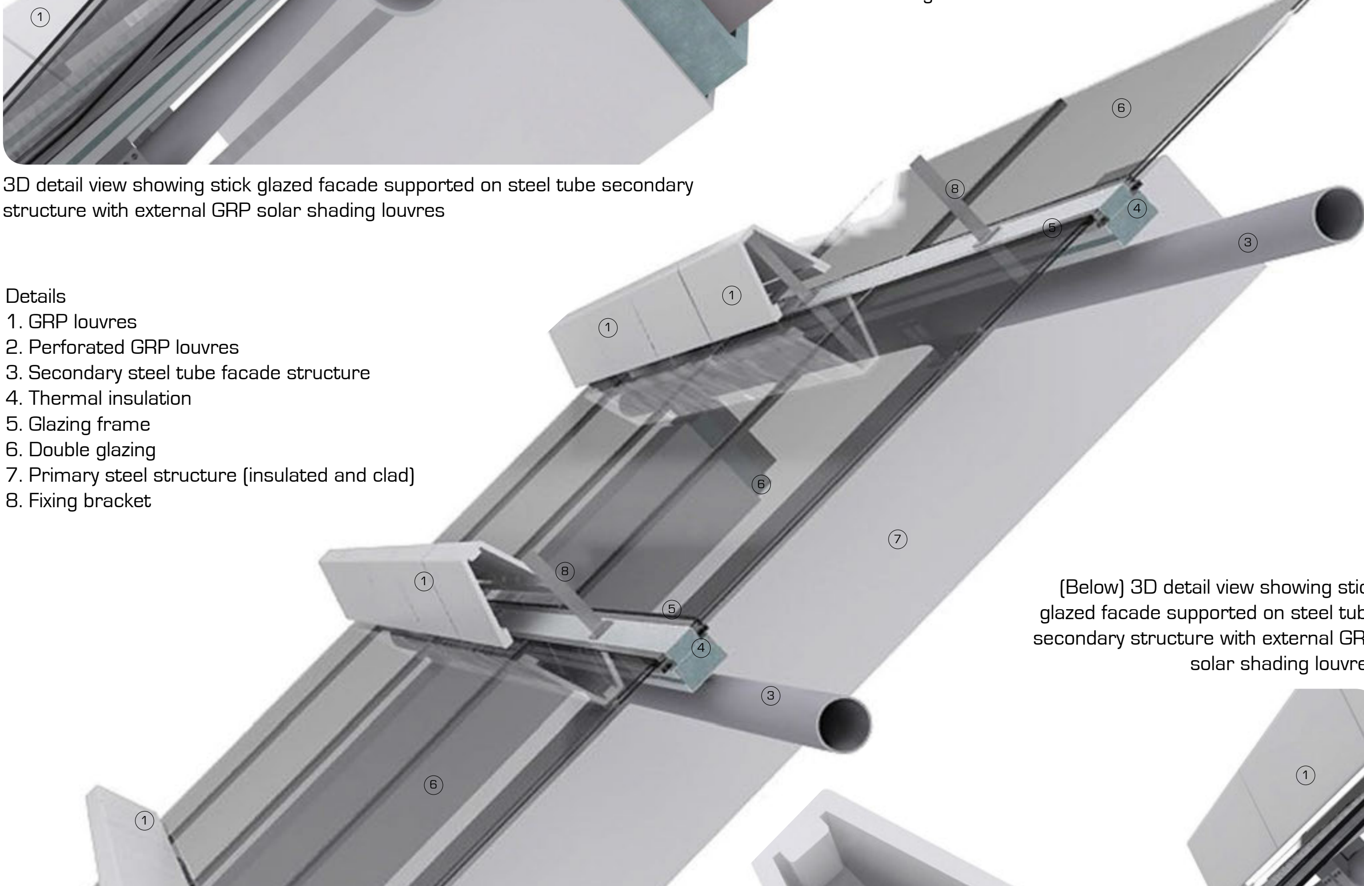
3D sectional view showing full-height stick glazed facade with external GRP solar shading louvres

18 GRP louvres on stick glazing system

3D detail view showing stick glazed facade supported on steel tube secondary structure with external GRP solar shading louvres

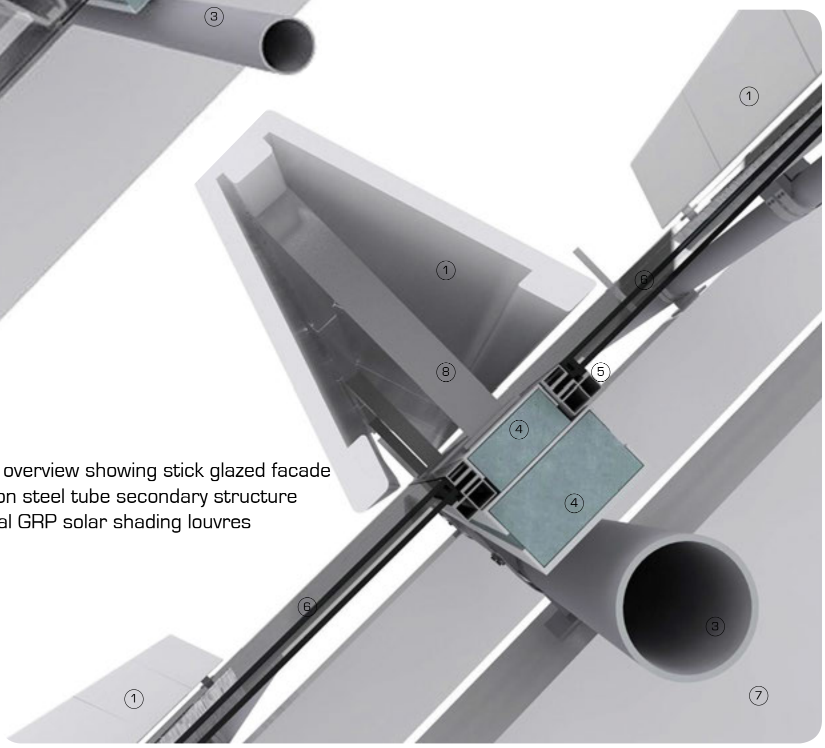
3D detail view showing stick glazed facade supported on steel tube secondary structure with external GRP solar shading louvres

Details
1. GRP louvres
2. Perforated GRP louvres
3. Secondary steel tube facade structure
4. Thermal insulation
5. Glazing frame
6. Double glazing
7. Primary steel structure (insulated and clad)
8. Fixing bracket

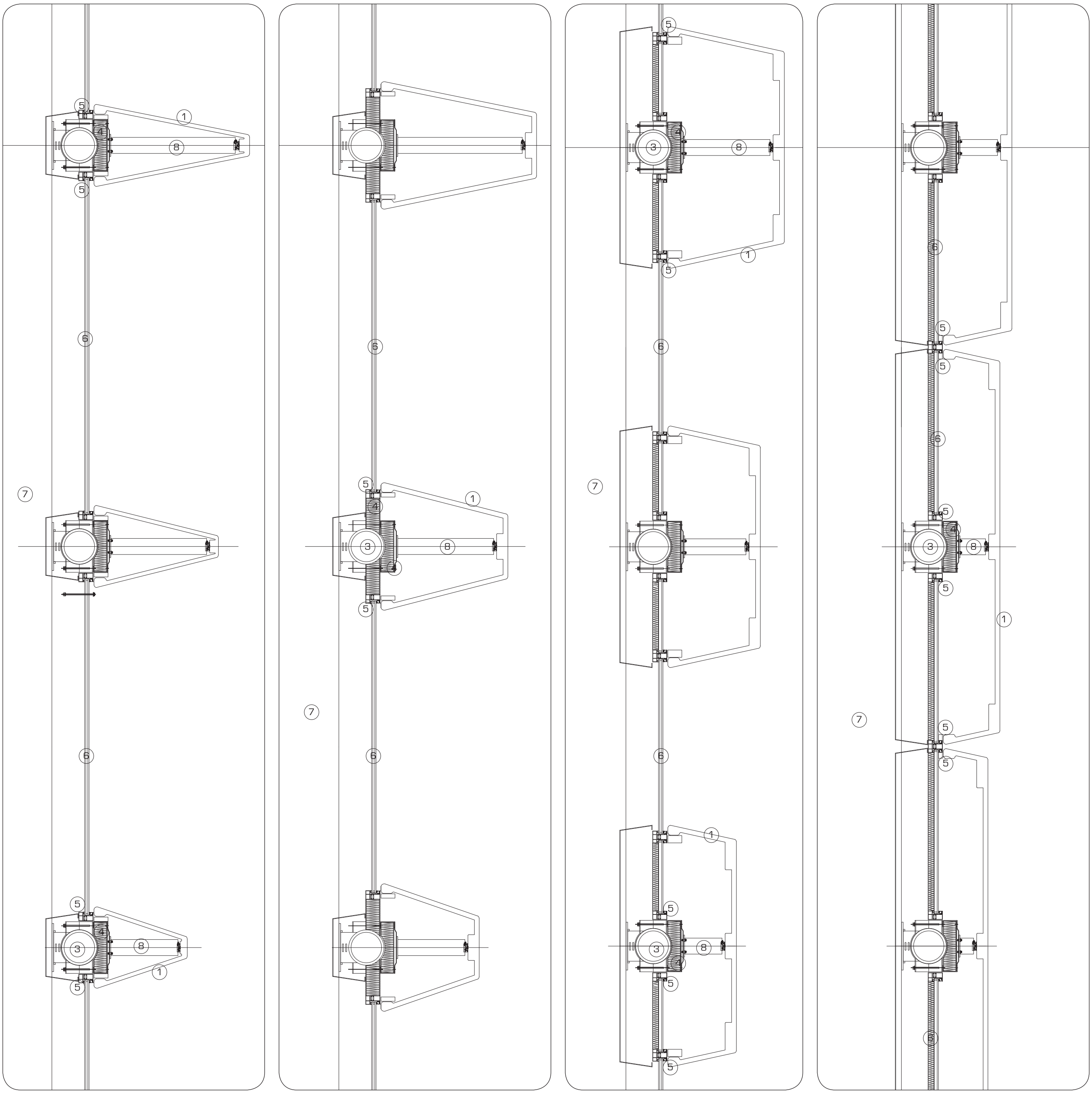


(Above) 3D overview showing stick glazed facade supported on steel tube secondary structure with external GRP solar shading louvres

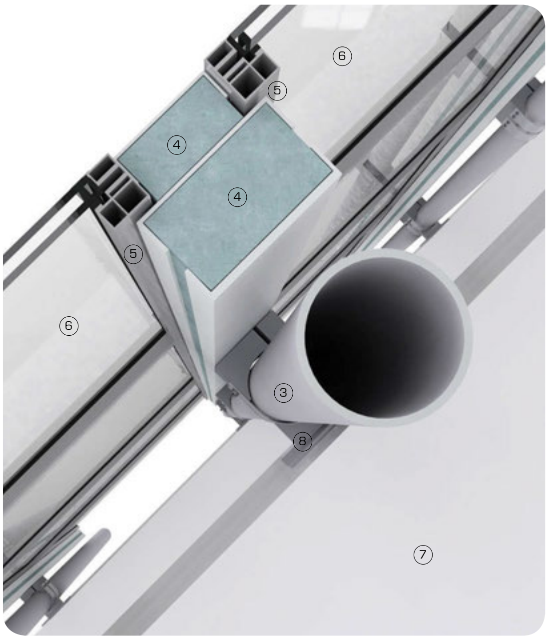
(Below) 3D detail view showing stick glazed facade supported on steel tube secondary structure with external GRP solar shading louvres



3D overviews showing stick glazed facade supported on steel tube secondary structure with external GRP solar shading louvres

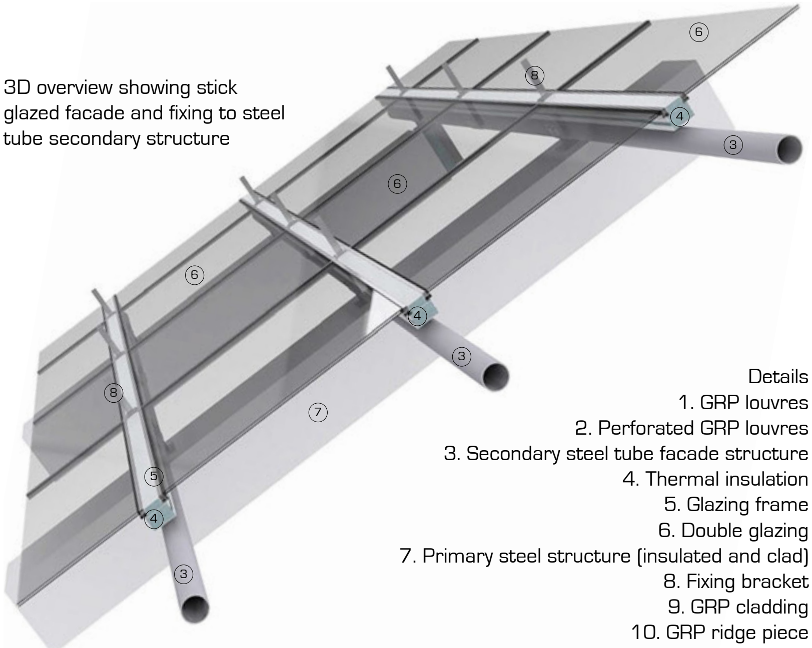


Vertical sections. Various louvre configurations along length of stick glazed facade supported on steel tube secondary structure with external GRP solar shading louvres

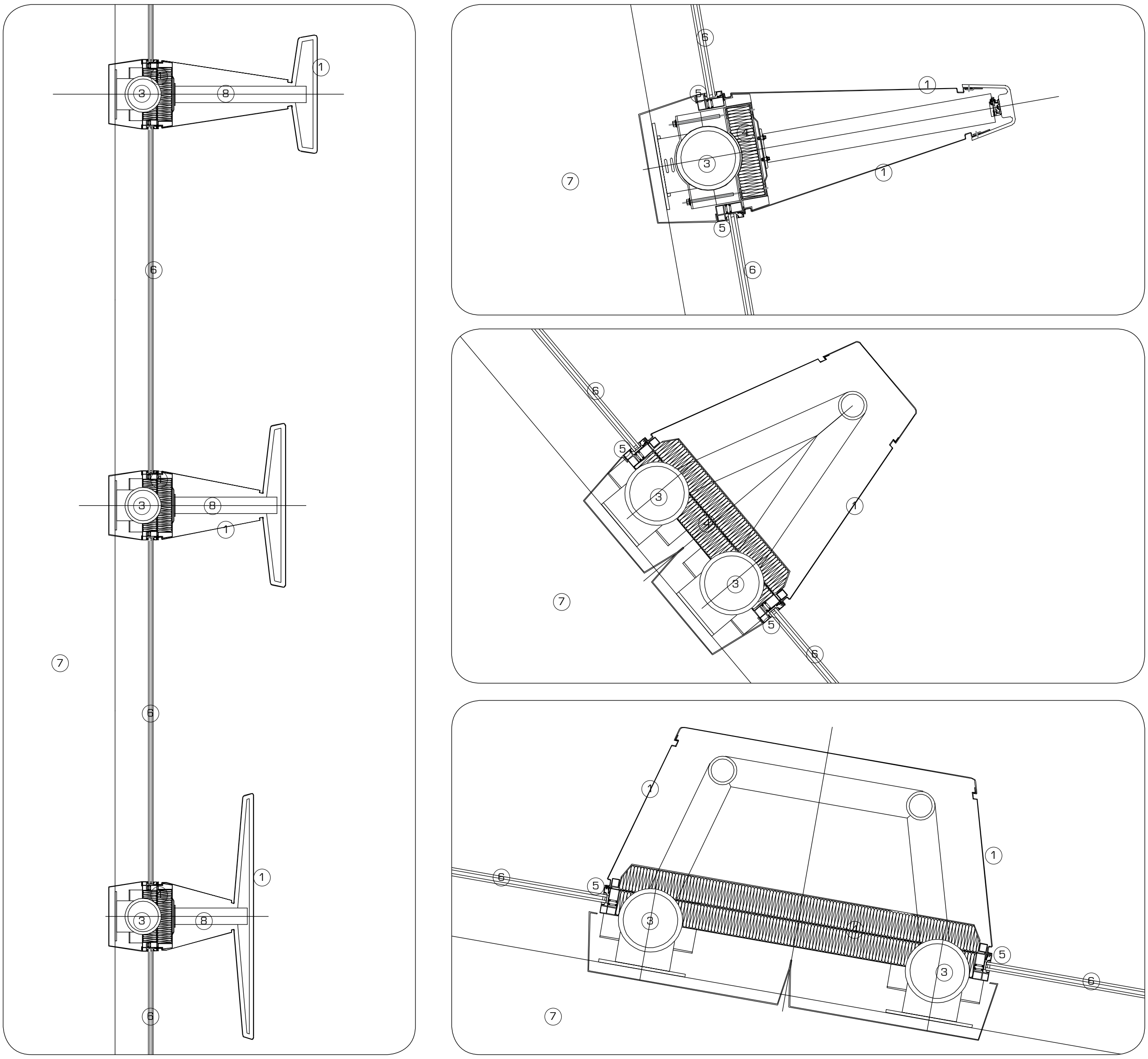


3D detail view showing stick glazed facade and fixing to steel tube secondary structure

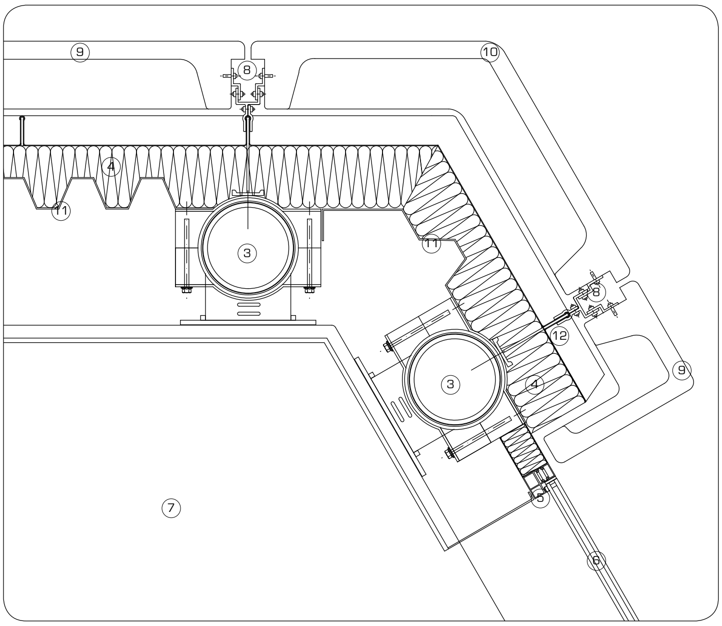
3D overview showing stick glazed facade and fixing to steel tube secondary structure



Details
1. GRP louvres
2. Perforated GRP louvres
3. Secondary steel tube facade structure
4. Thermal insulation
5. Glazing frame
6. Double glazing
7. Primary steel structure (insulated and clad)
8. Fixing bracket
9. GRP cladding
10. GRP ridge piece
11. Profiled metal deck
12. Standing seam metal deck

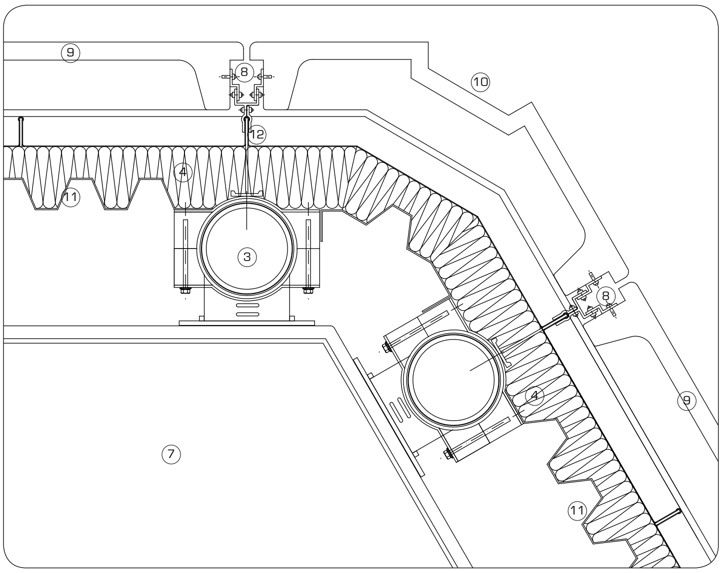


Vertical sections. Various louvre configurations along length of stick glazed facade supported on steel tube secondary structure with external GRP solar shading louvres



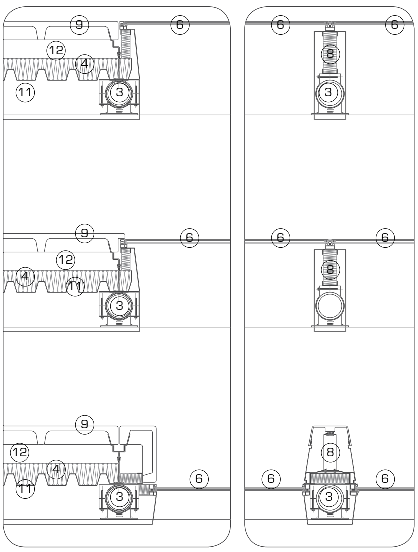
Vertical section. Interface between stick glazed facade and GRP rainscreen panels fixed to steel tube secondary structure

3D sectional view of interface between stick glazed facade and GRP rainscreen panels fixed to steel tube secondary structure

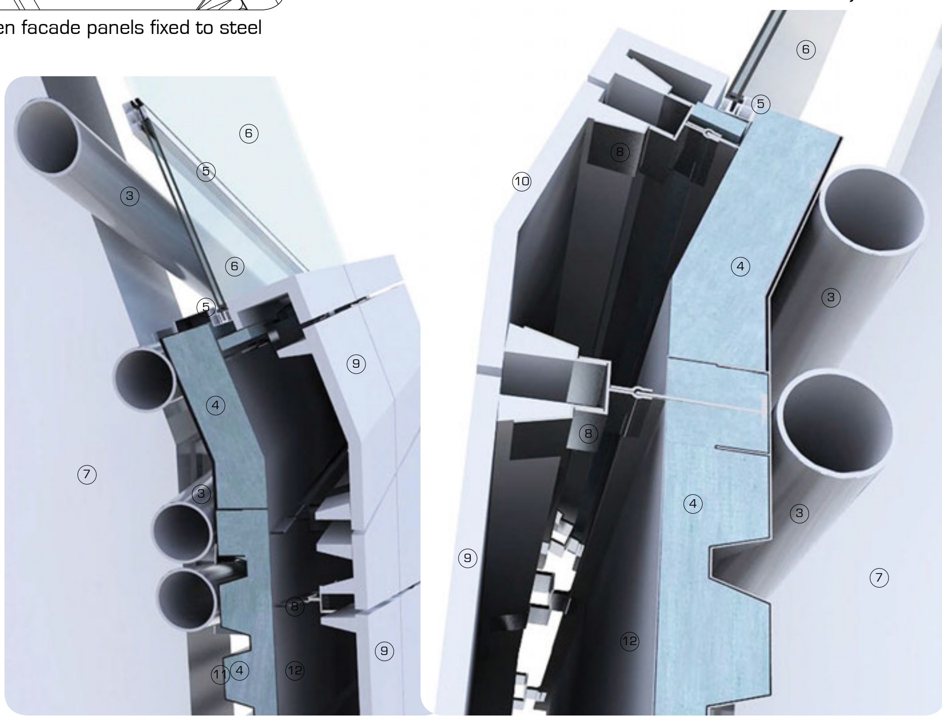


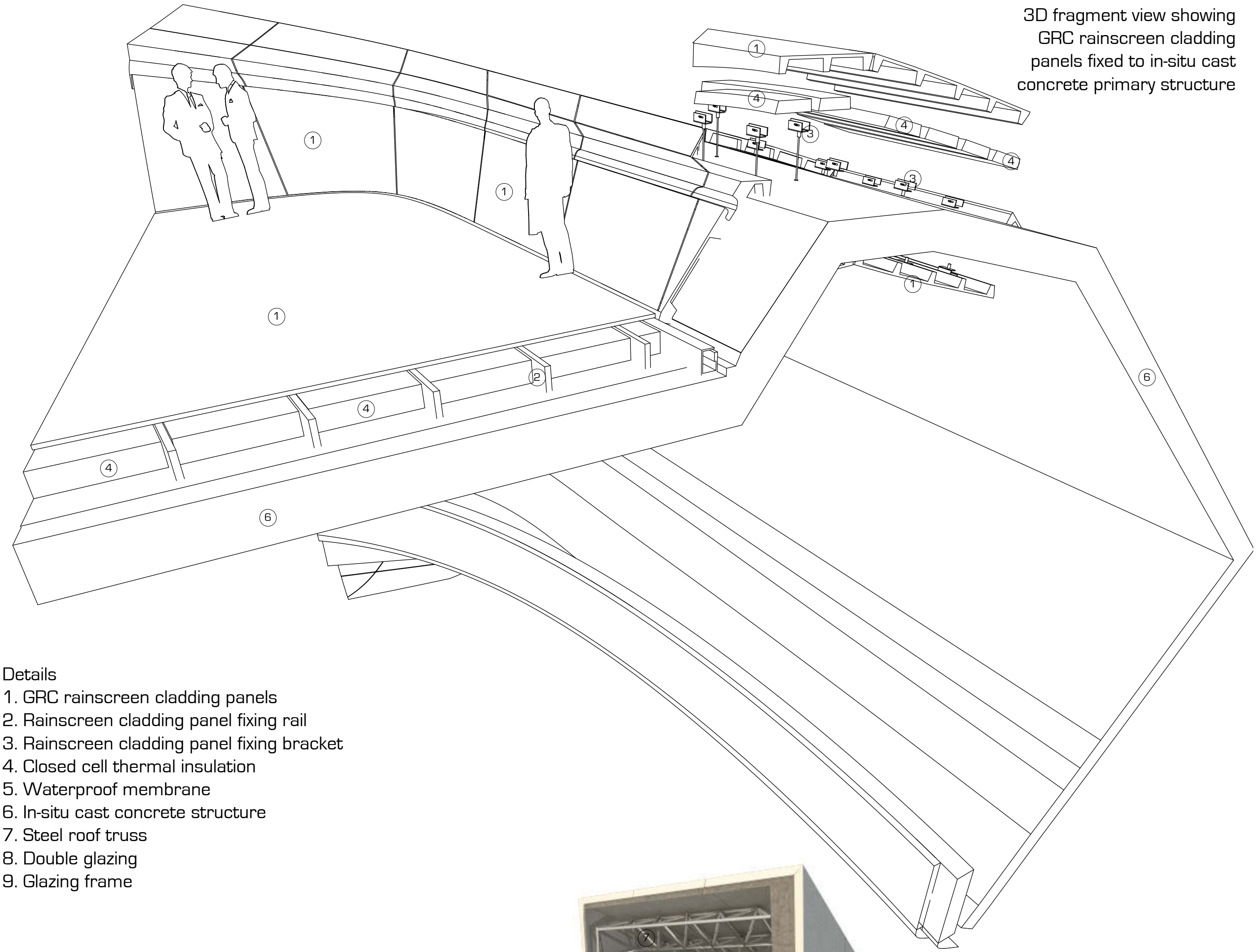
Vertical section. Edge condition of GRP rainscreen facade panels fixed to steel tube secondary structure

(Below) 3D view showing interface between stick glazed facade and GRP rainscreen panels fixed to steel tube secondary structure



Vertical sections. Various configurations of interface between stick glazed facade and GRP rainscreen panels fixed to steel tube secondary structure

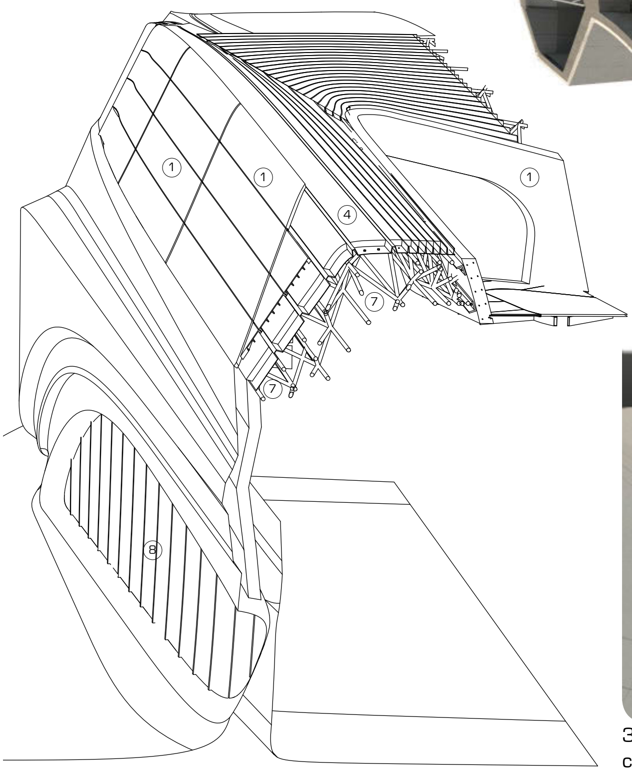


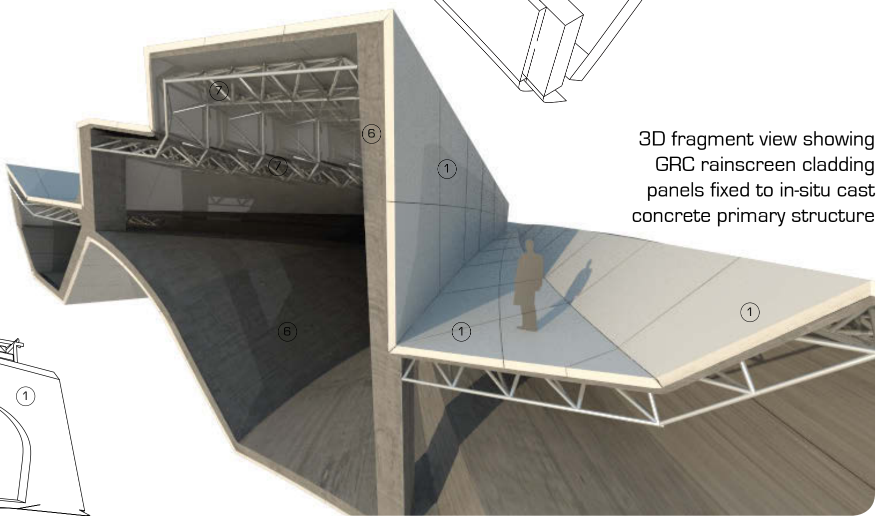


3D fragment view showing GRC rainscreen cladding panels fixed to in-situ cast concrete primary structure

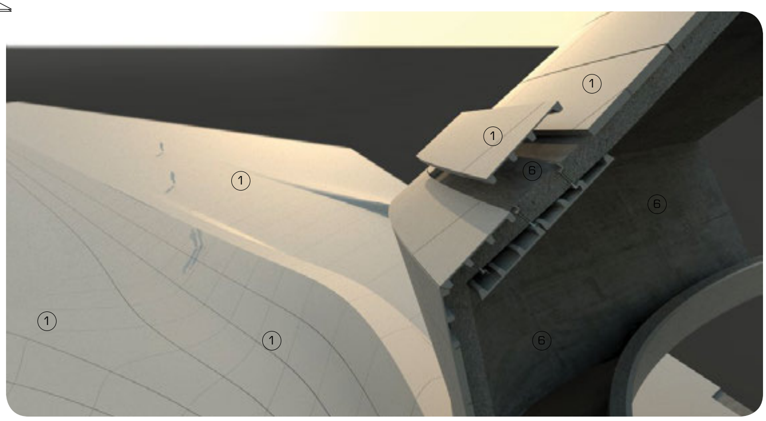
Details
1. GRC rainscreen cladding panels
2. Rainscreen cladding panel fixing rail
3. Rainscreen cladding panel fixing bracket
4. Closed cell thermal insulation
5. Waterproof membrane
6. In-situ cast concrete structure
7. Steel roof truss
8. Double glazing
9. Glazing frame

(Below) 3D sectional view showing GRC rainscreen cladding panels fixed to in-situ cast concrete primary structure and interface with full-height glazed

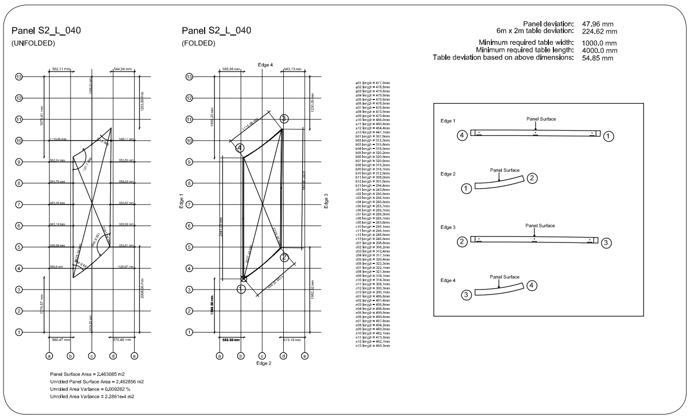


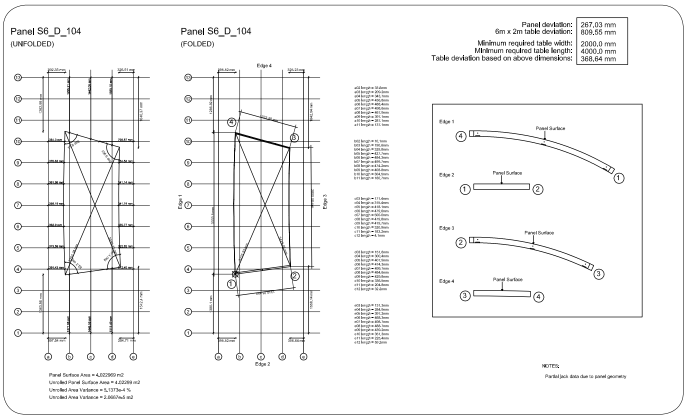


3D fragment view showing GRC rainscreen cladding panels fixed to in-situ cast concrete primary structure

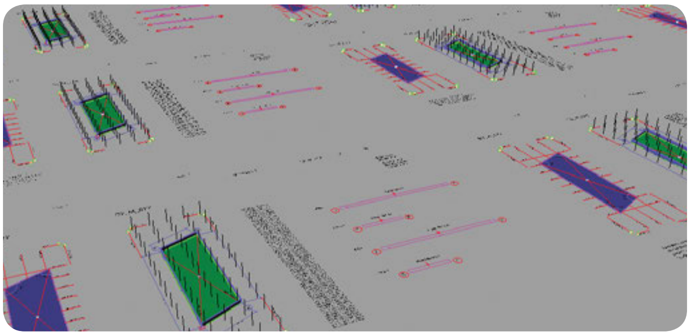


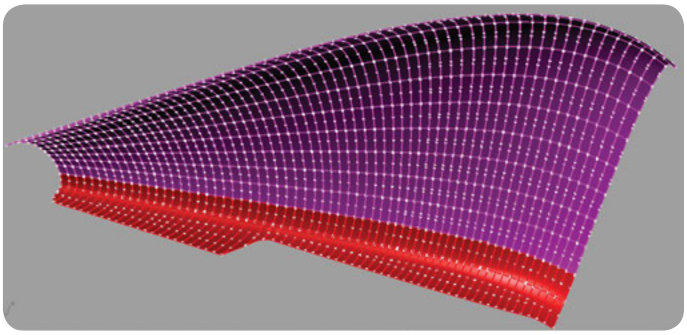
3D sectional view showing GRC rainscreen cladding panels fixed to in-situ cast concrete primary structure

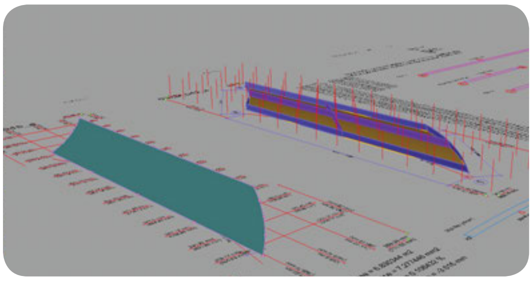


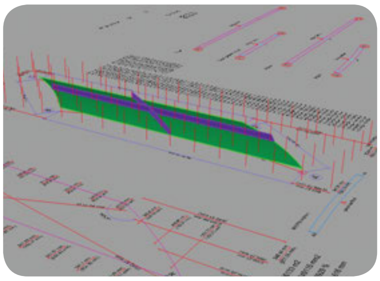


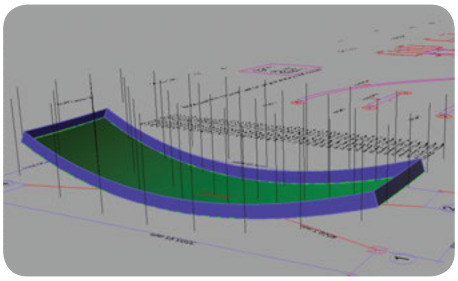
(Above and Below) Diagrams showing panelisation process of identifying, numbering and laying out individual GRC panels

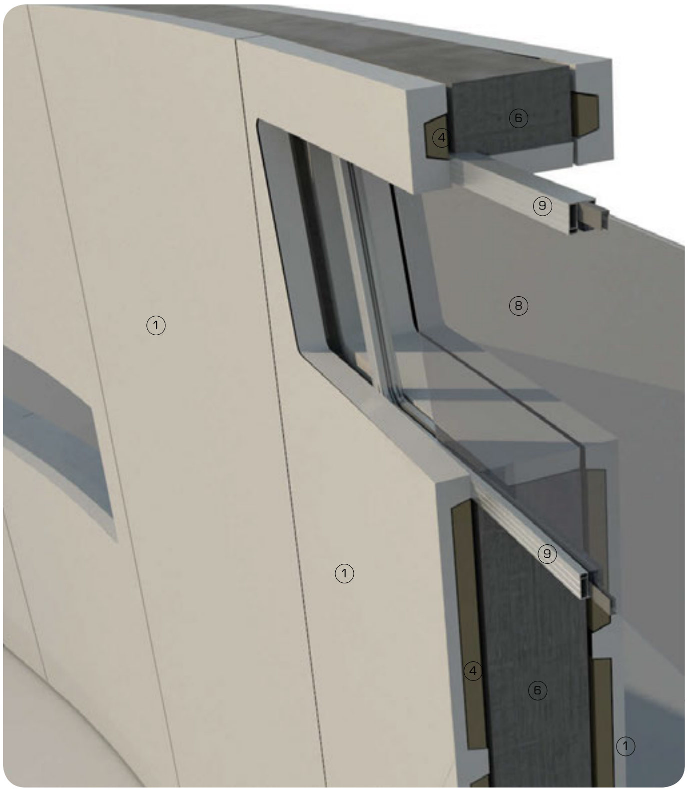


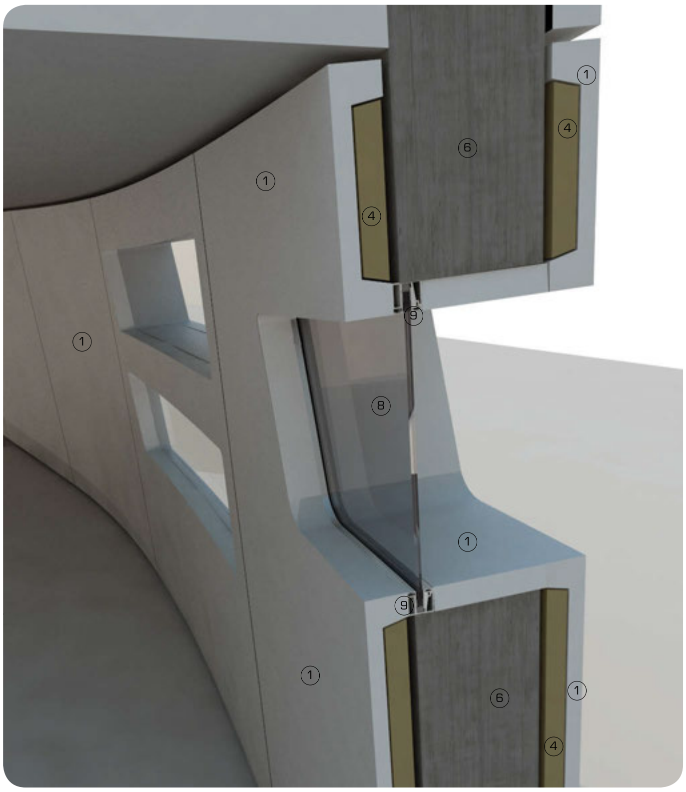




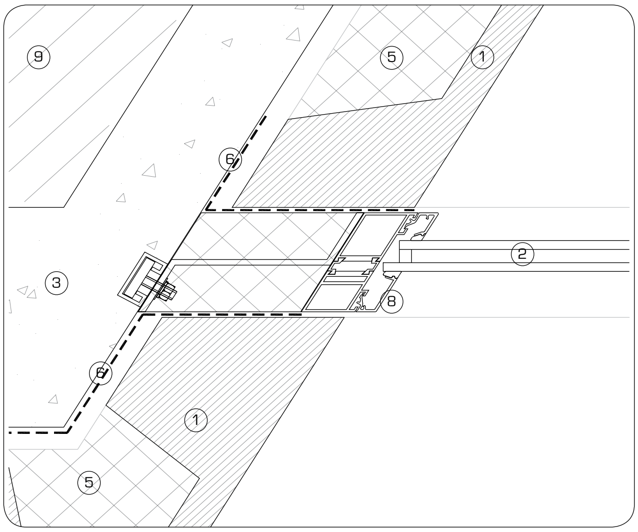




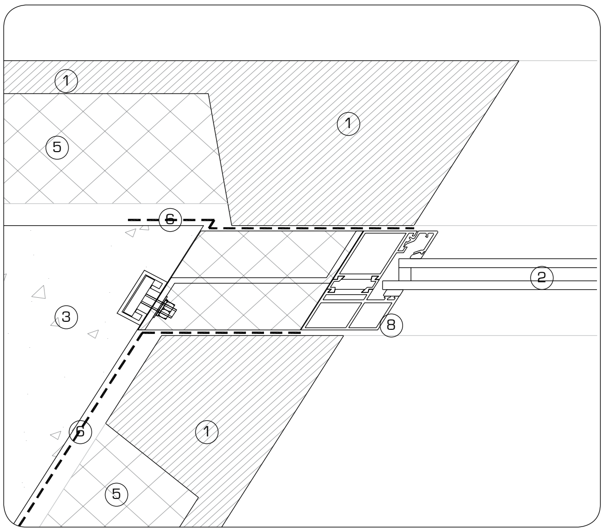




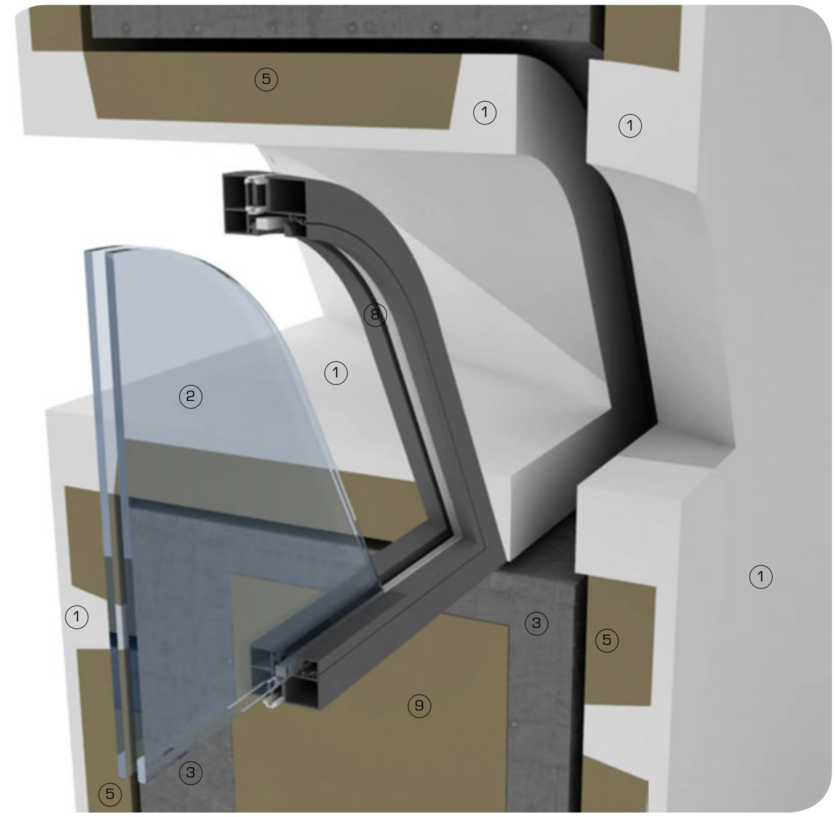
3D sectional detail view showing window set within GRC rainscreen cladding panels fixed to in-situ cast concrete primary structure



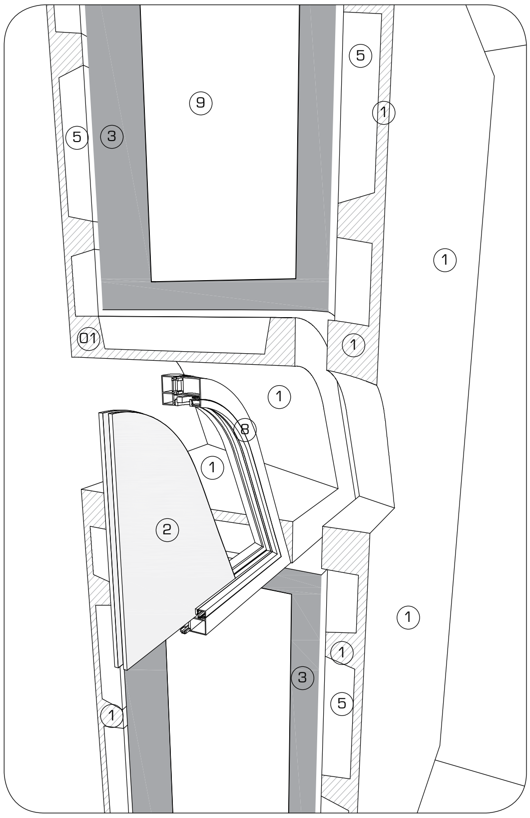
Horizontal section. Window in GRC wall



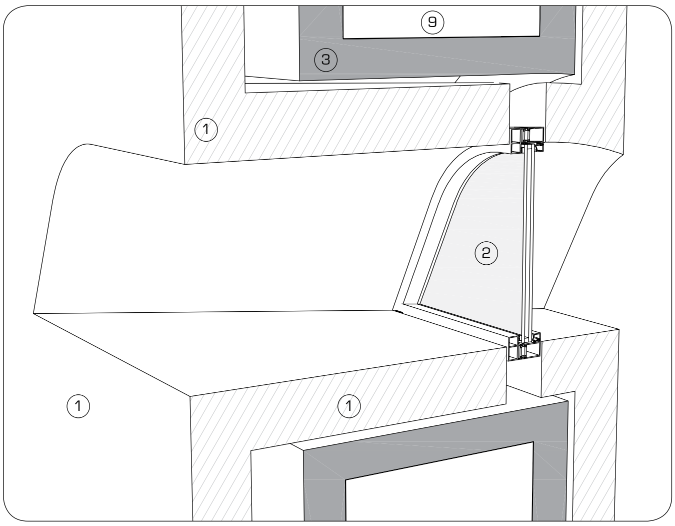
Horizontal section. Window in GRC wall

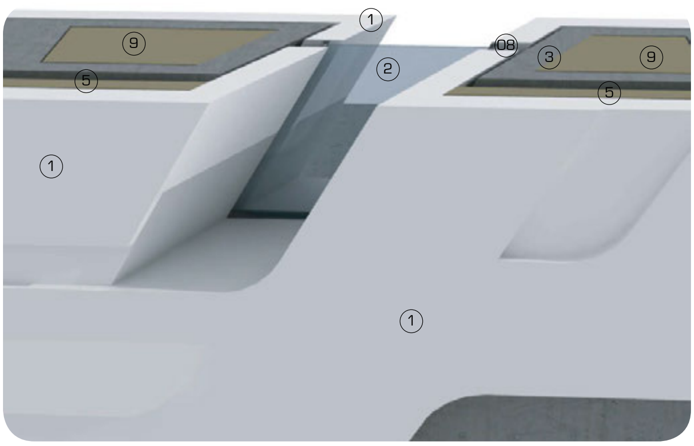


3D exploded view showing window in GRC wall

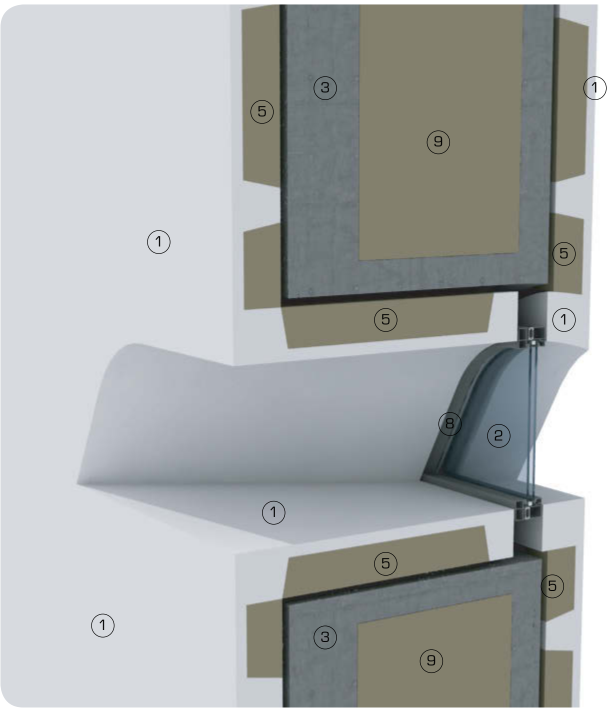


3D exploded view showing window in GRC wall

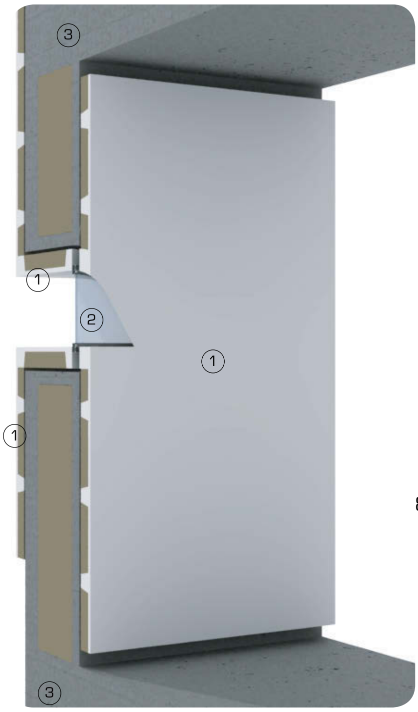




(Above) 3D view showing window frame in GRC cladding
(Right) 3D detail view showing glazing and GRC faced wall connection

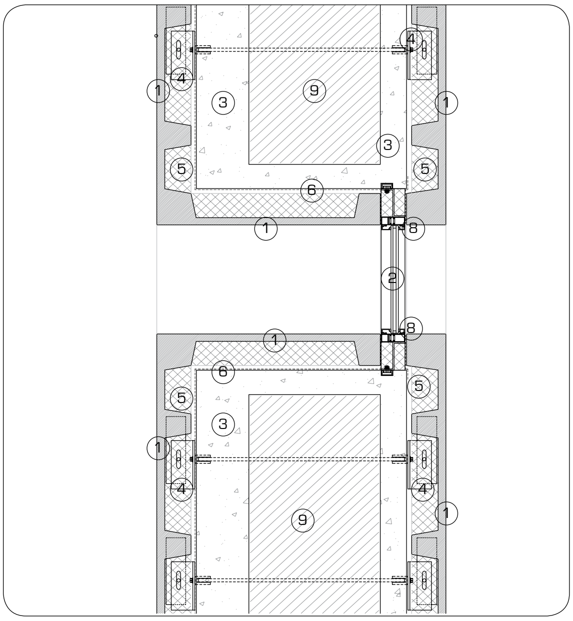


3D view showing window frame in GRC cladding

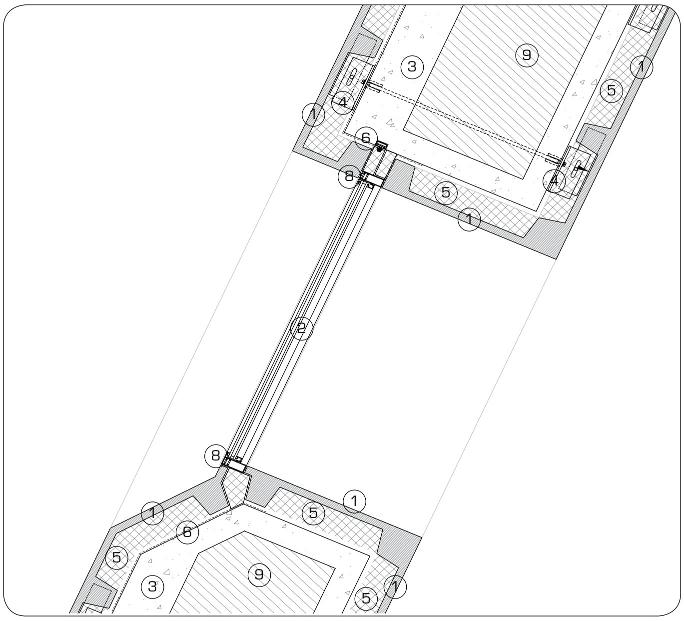


3D view showing window frame in GRC cladding

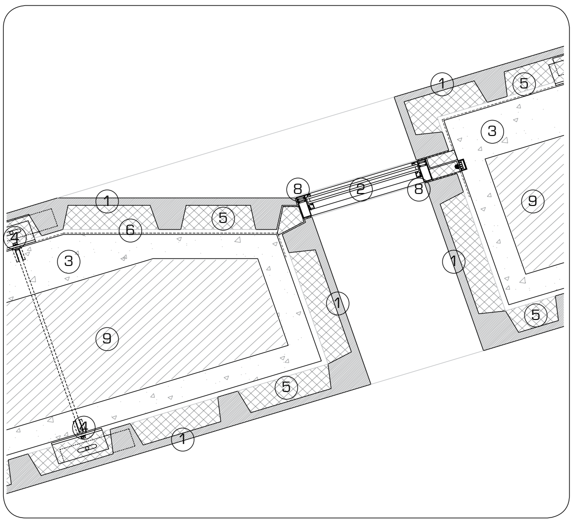
Details
1. GRC panel
2. Double glazed unit
3. Concrete backing wall
4. Deadload fixing to GRC panel
5. Closed cell thermal insulation bonded to GRC panel
6. Insulated separating layer between GRC & concrete wall
7. Continuous waterproof membrane
8. Thermally broken window profile
9. Thermal insulation
10. Secondary steelwork to contractor design



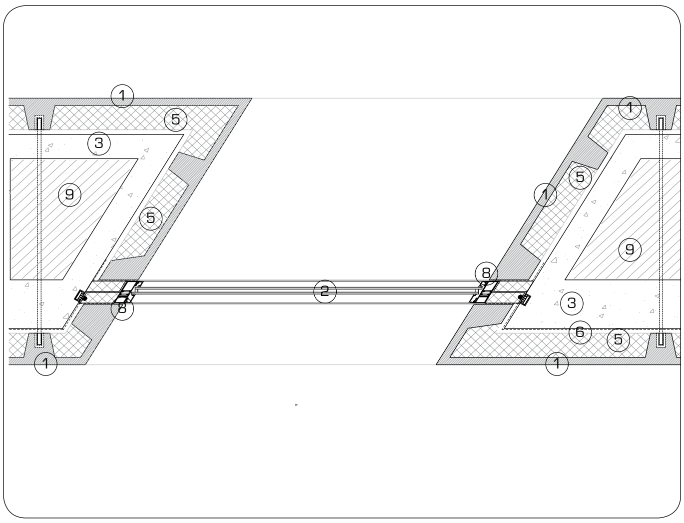
Vertical section. GRC cladding and glazing



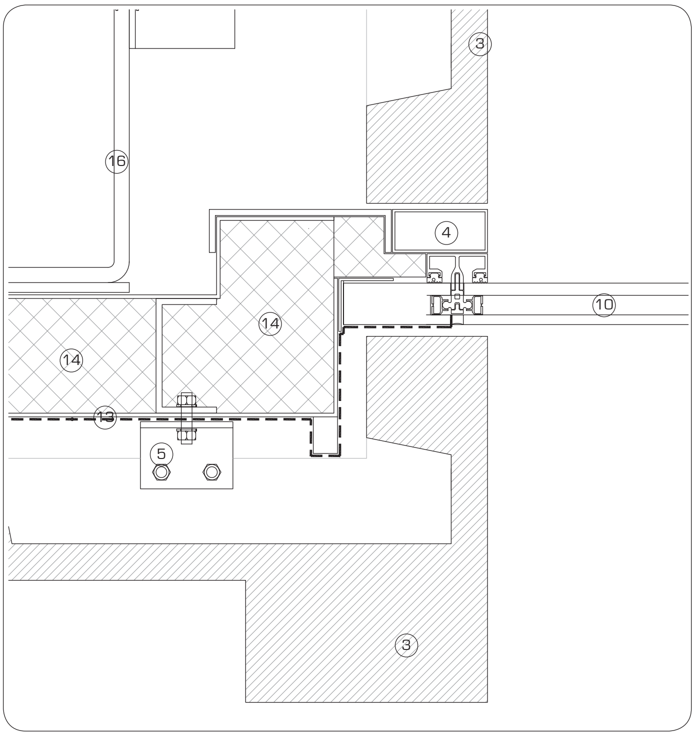
Vertical section. GRC cladding and glazing



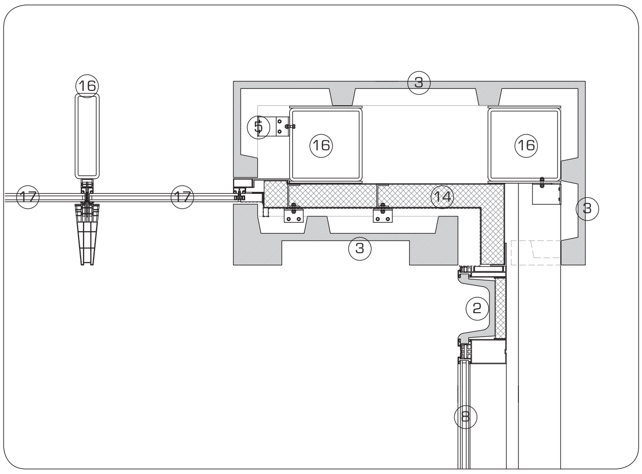
Horizontal section. GRC cladding and glazing



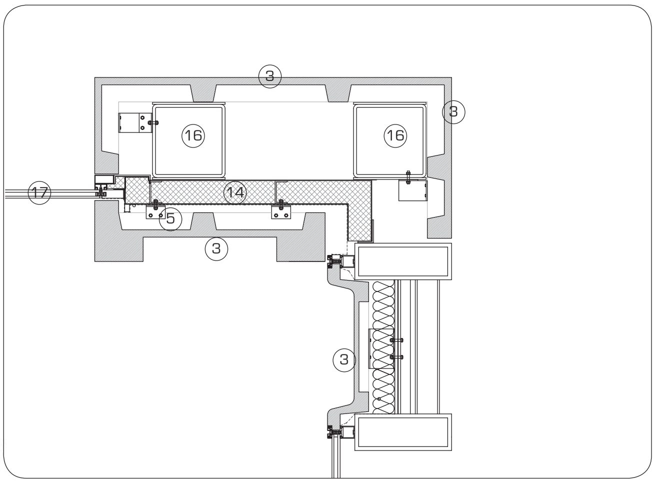
Horizontal section. GRC cladding and glazing



Horizontal section. GRC cladding and glazing

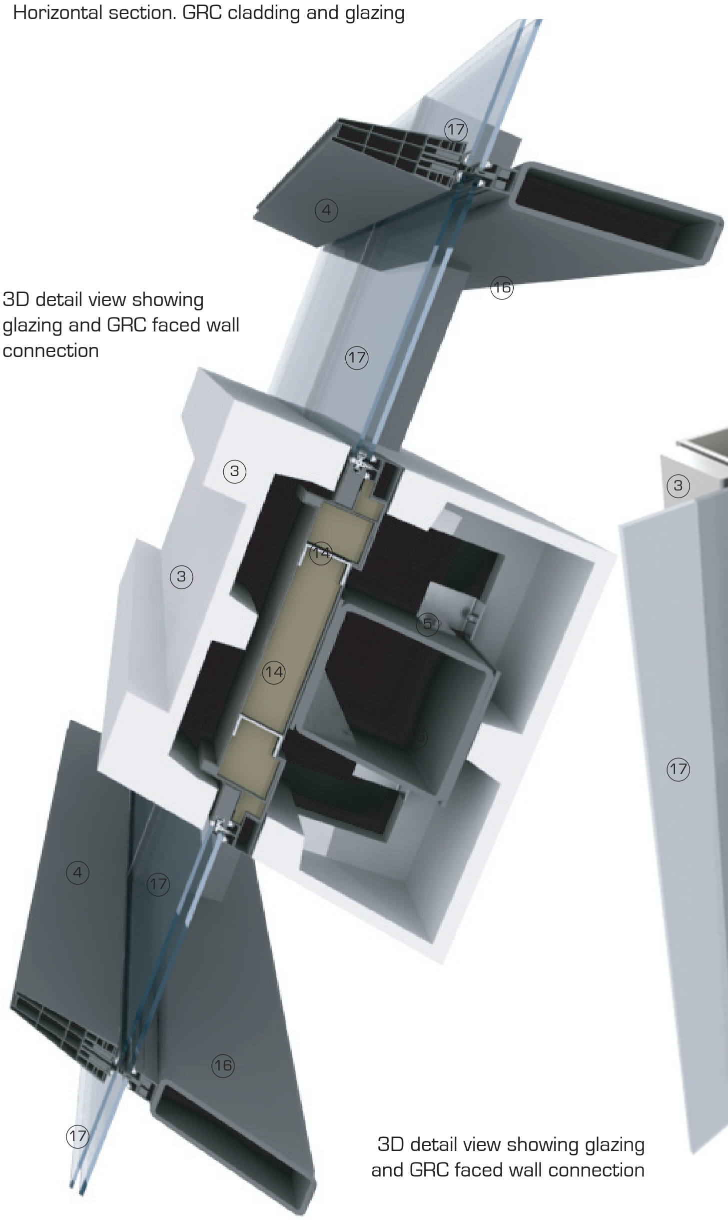


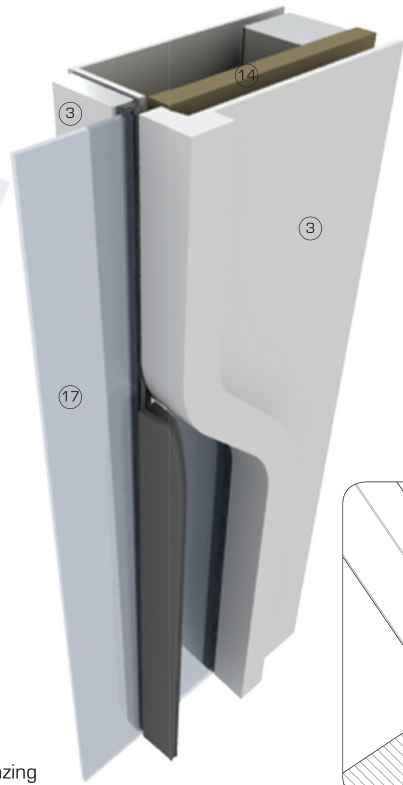
Horizontal section. GRC cladding and glazing



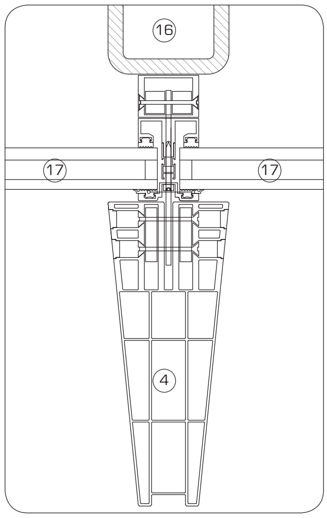
Horizontal section. GRC cladding and glazing

3D detail view showing
glazing and GRC faced wall
connection

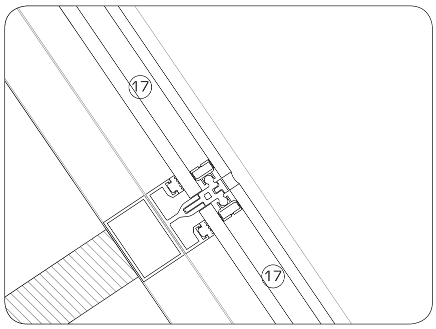




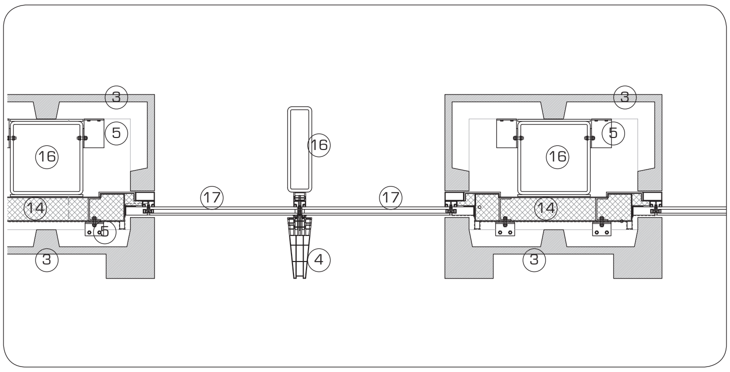
3D detail view showing glazing
and GRC faced wall connection



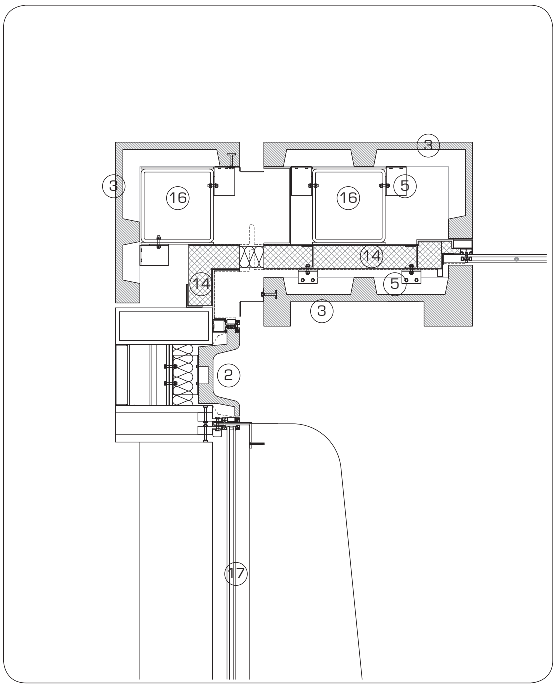
Horizontal section. Glazing



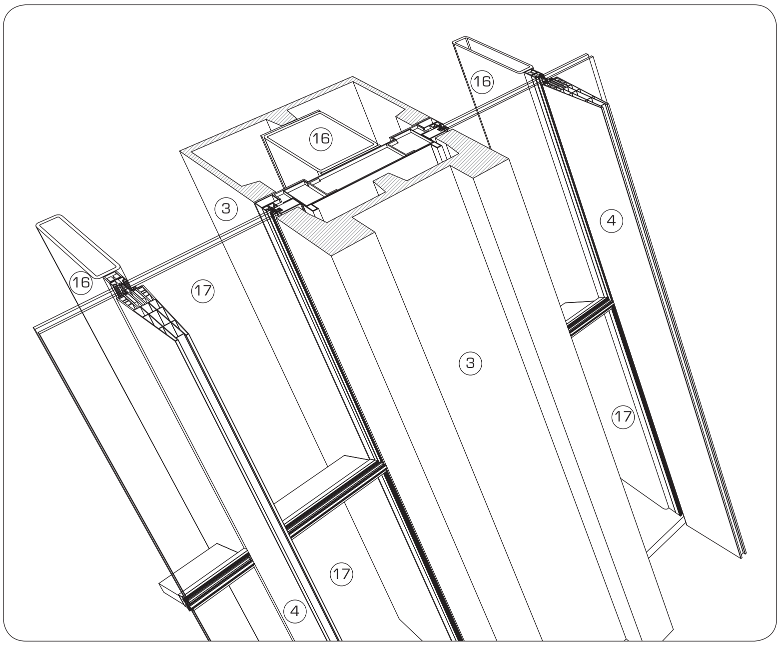
Vertical section. Glazing



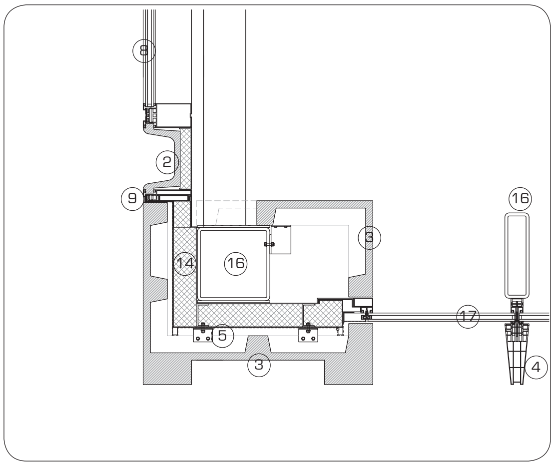
Horizontal section. GRC cladding and glazing



Horizontal section. GRC cladding and glazing



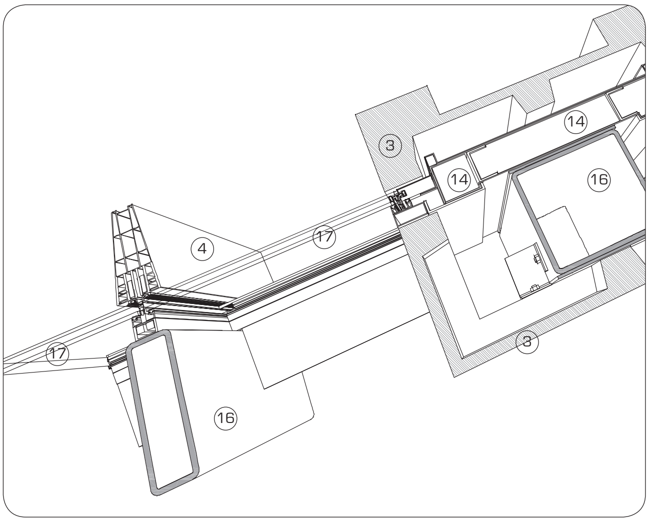
3D detail view showing glazing and GRC faced wall connection



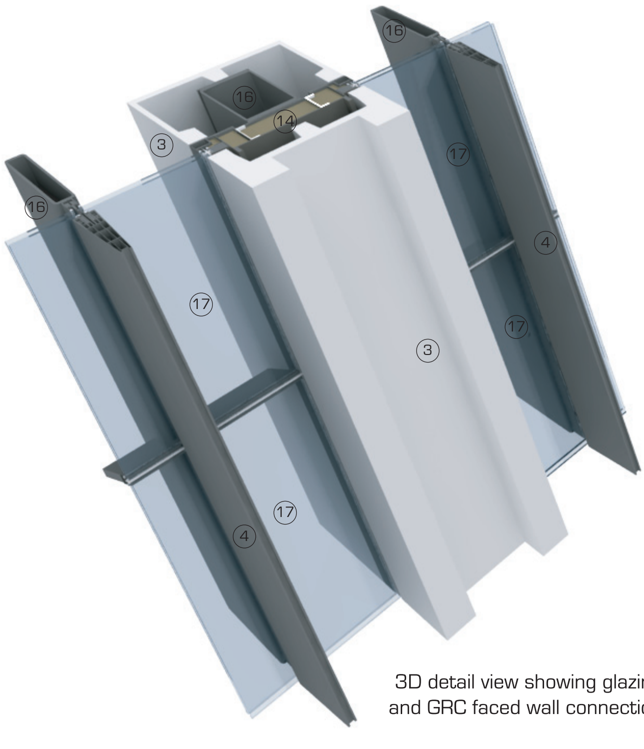
Horizontal section. GRC cladding and glazing

Details

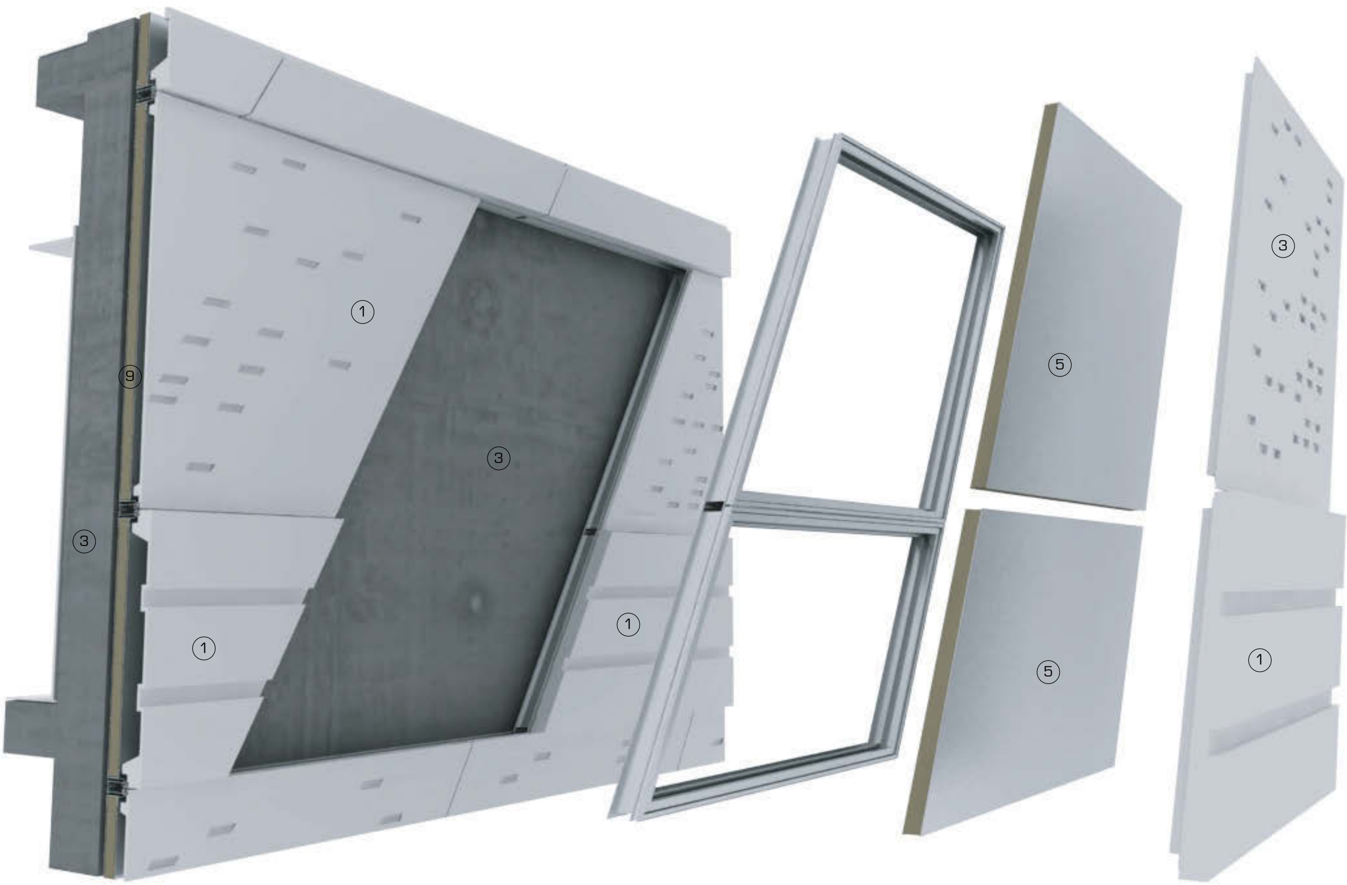
1. GRC shadow gap panel
2. Aluminium faced insulated panel
3. GRC panel
4. Extruded aluminium section
5. Fixing bracket for GRC panel
6. GRC shading louvre
7. Extruded aluminium support bracket for GRC shading louvre
8. Double glazed unit
9. Unitised glazing frame
10. Toggle fixed glazing system
11. Metal panel
12. Rubber based seal
13. Continuous waterproof membrane
14. Thermal insulation
15. Metal flashing
16. Secondary steelwork to contractor design
17. Stick glazing



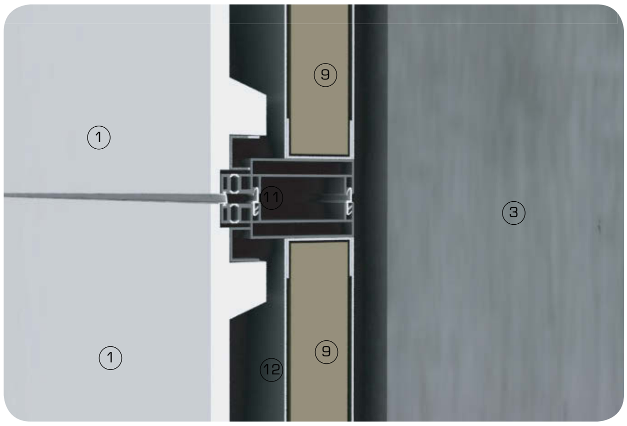
3D detail of glazing and GRC faced wall connection



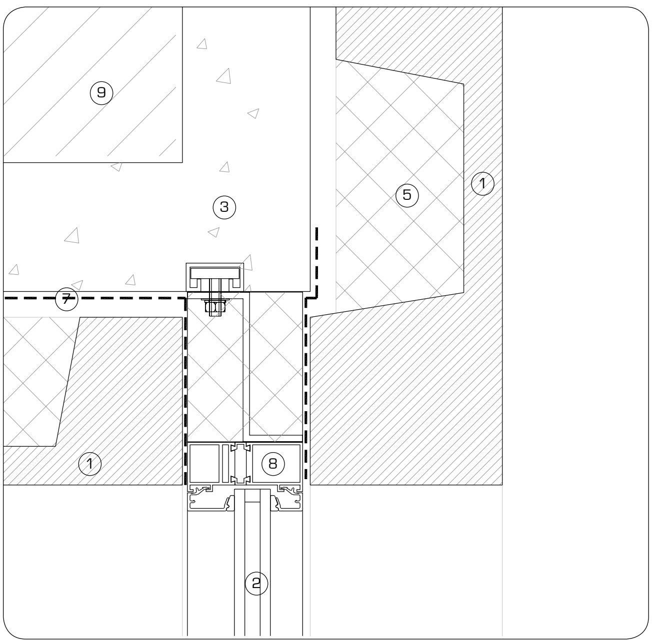
3D detail view showing glazing and GRC faced wall connection



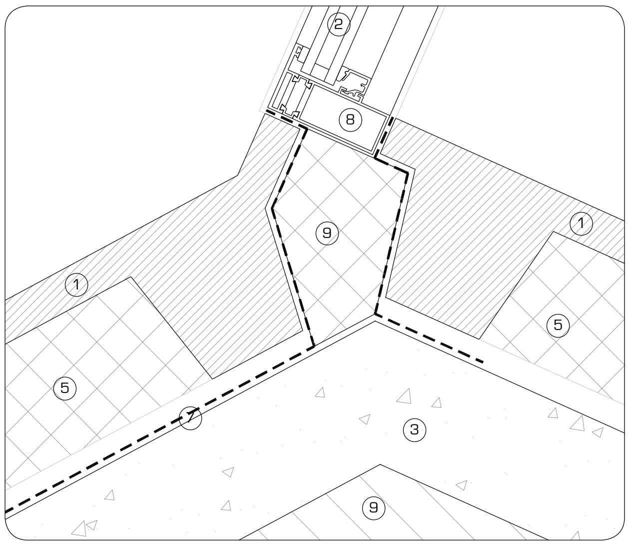
Details
1. GRC panel
2. Double glazed unit
3. Concrete backing wall
4. Deadload fixing to GRC panel
5. Closed cell thermal insulation bonded to GRC panel
6. Insulated separating layer between GRC & concrete wall
7. Continuous waterproof membrane
8. Thermally broken window profile
9. Thermal insulation
10. Secondary steelwork to contractor design
11. Frame for GRC panel
12. Metal panel



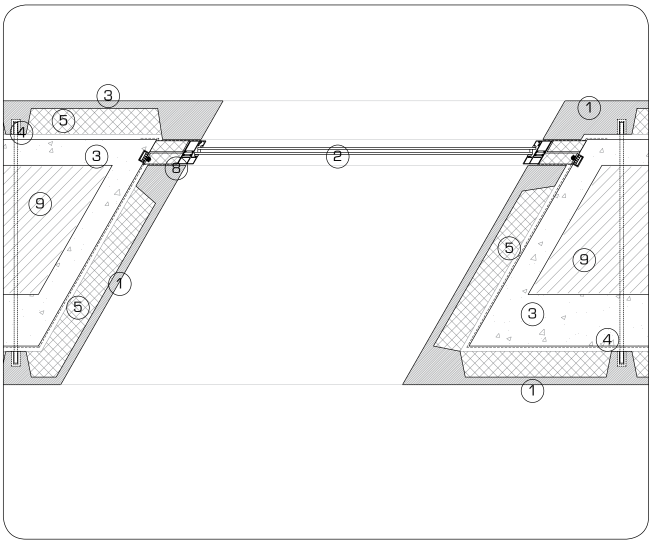
3D detail view showing external GRC cladding



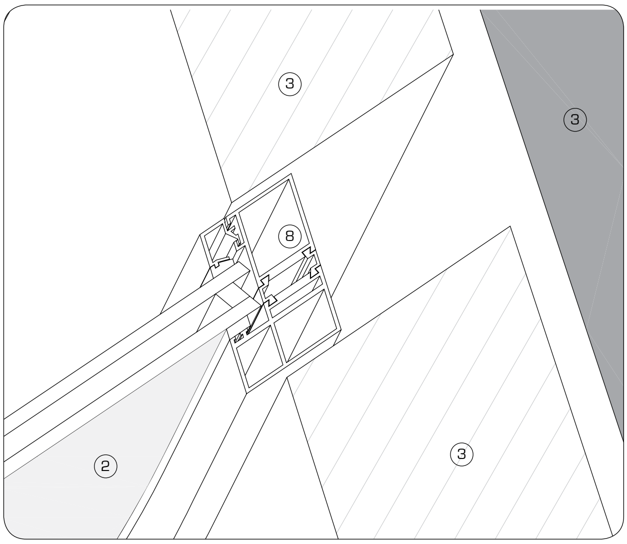
Vertical section. GRC cladding and glazing



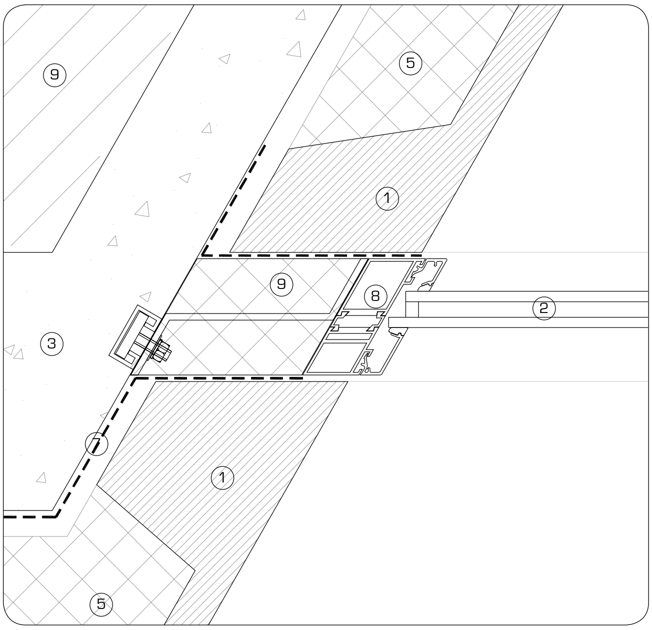
Vertical section. GRC cladding and glazing



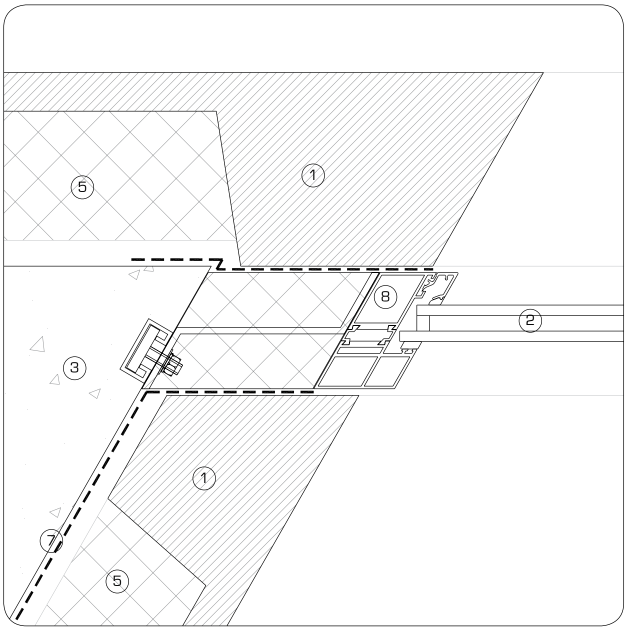
Horizontal section. GRC cladding and glazing



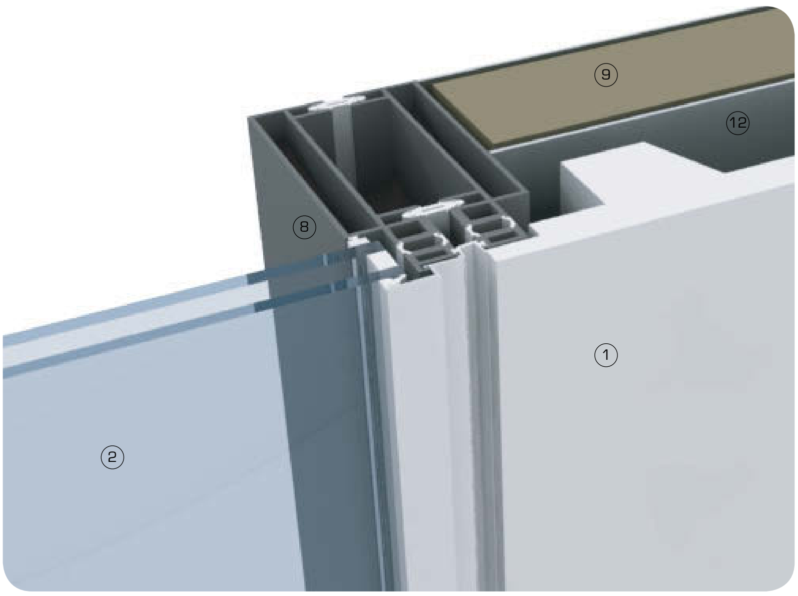
3D view showing window frame in GRC cladding



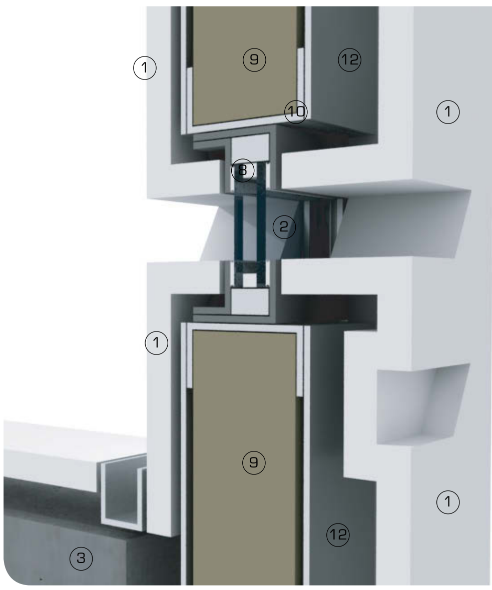
Horizontal section. GRC cladding and glazing



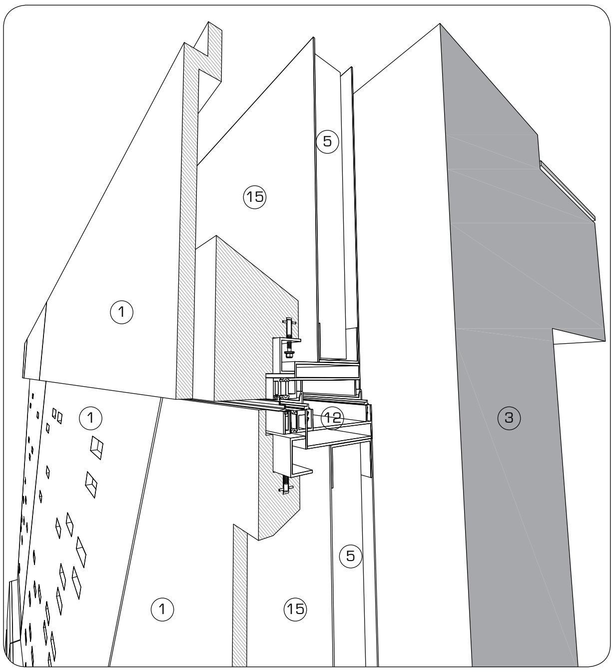
Horizontal section. GRC cladding and glazing



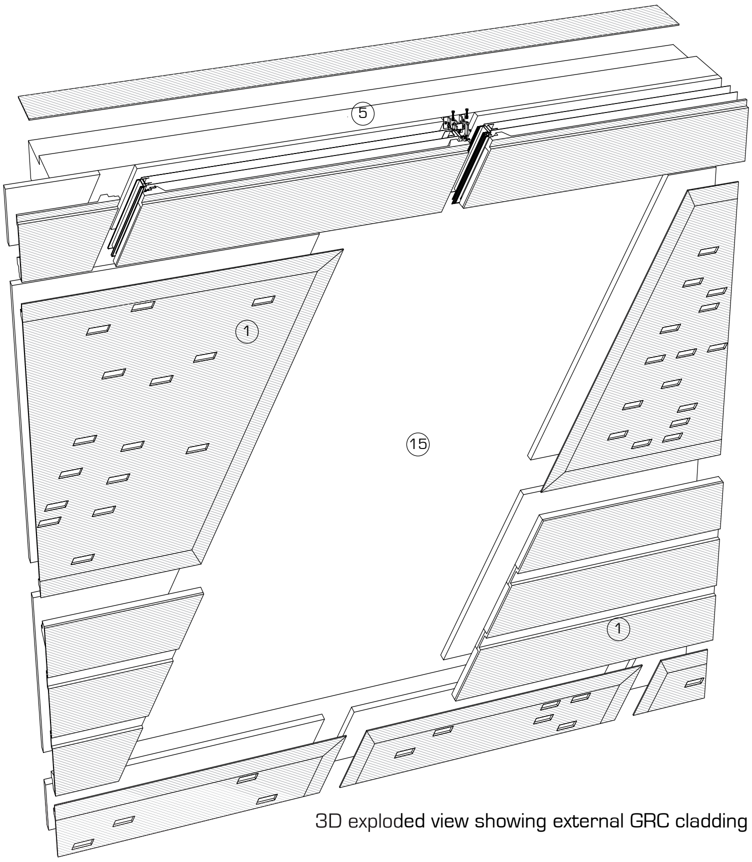
3D detail view showing external GRC cladding and glazing



3D detail view showing external GRC cladding and glazing

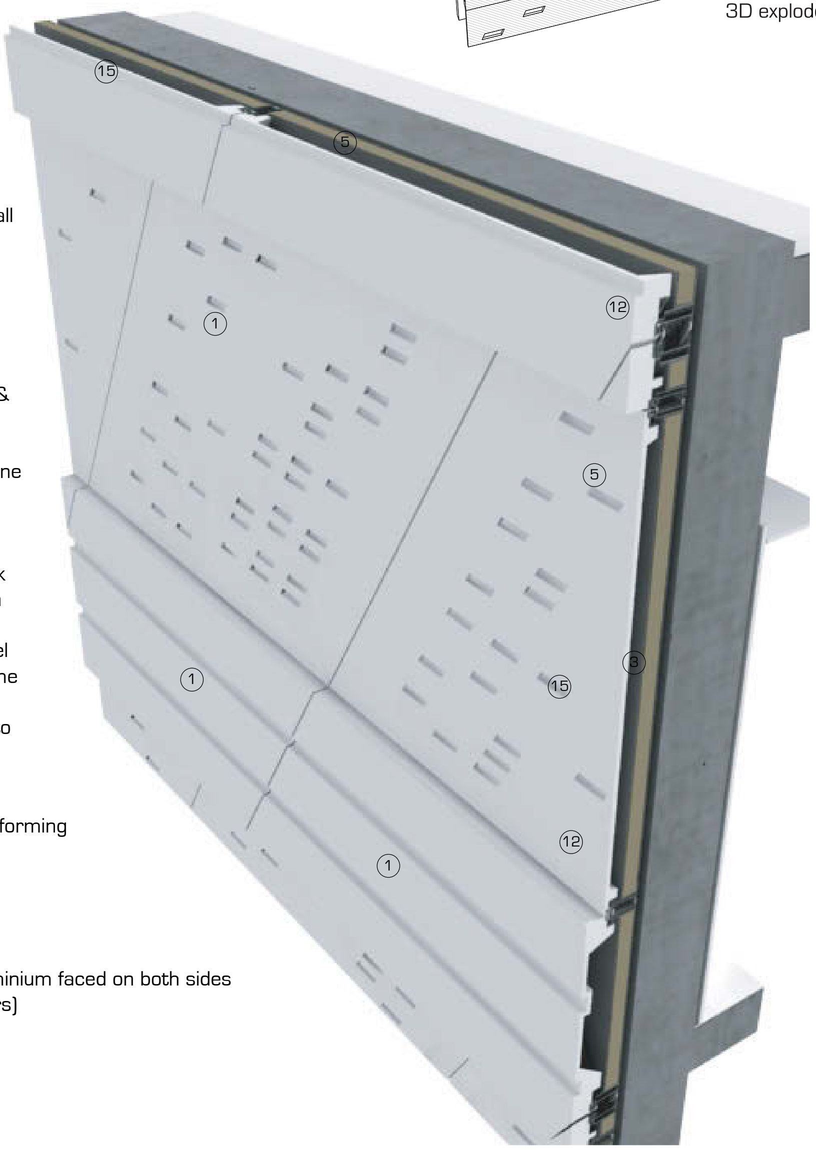


3D detail view showing external GRC cladding

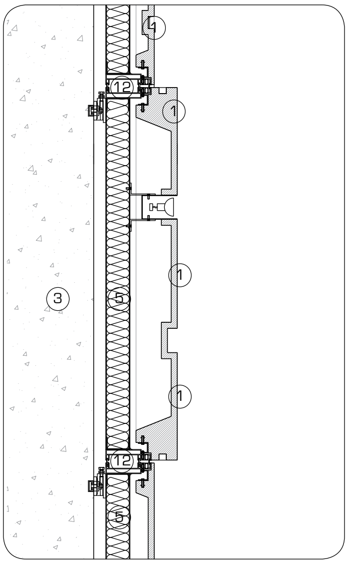


3D exploded view showing external GRC cladding

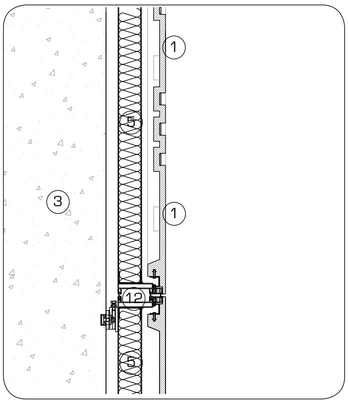
3D view showing external GRC cladding



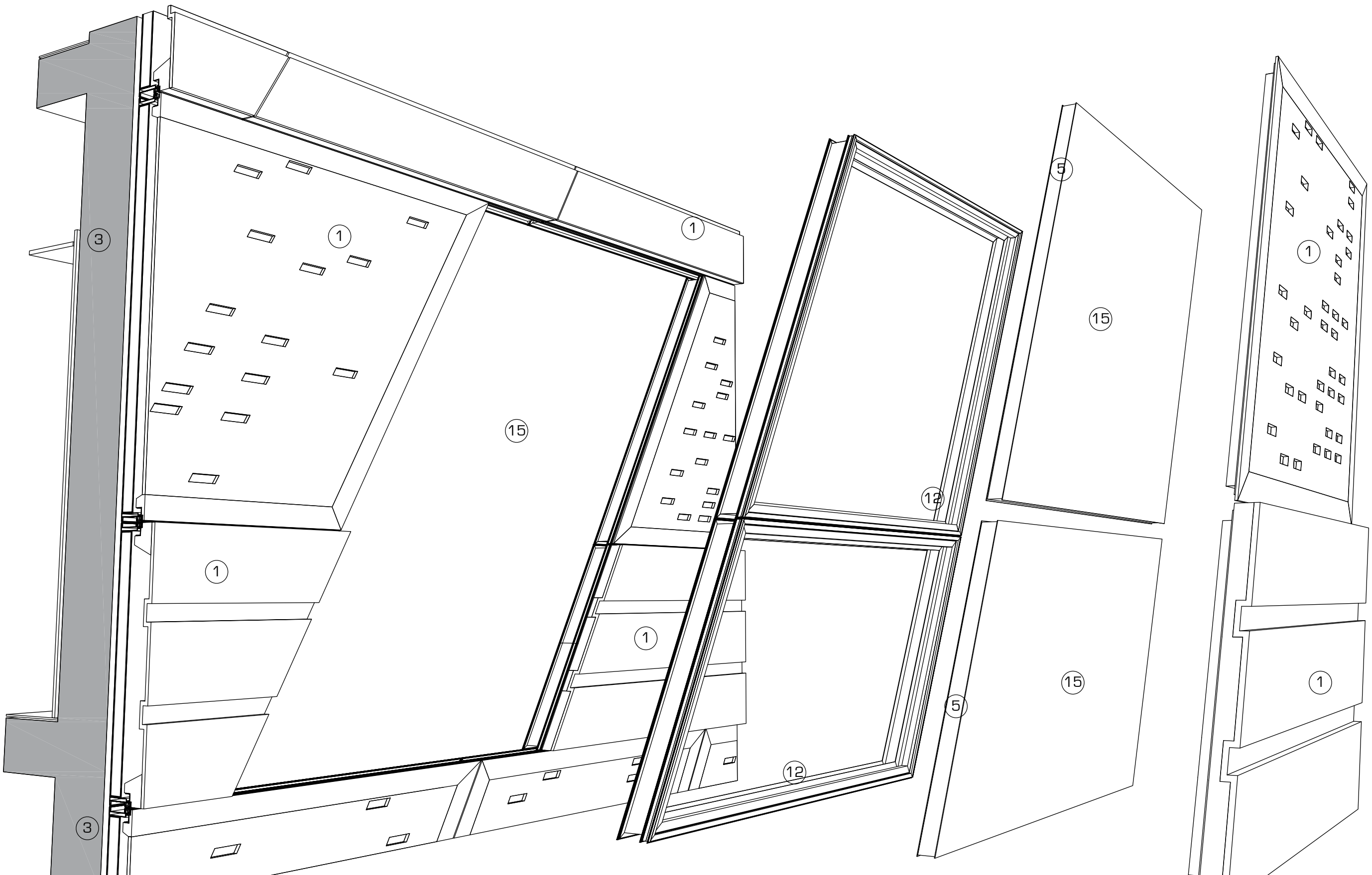
Details
1. GRC panel
2. Double glazed unit
3. Concrete backing wall
4. Deadload fixing to GRC panel
5. Closed cell thermal insulation bonded to GRC panel
6. Insulated separating layer between GRC & concrete wall
7. Continuous waterproof membrane
8. Thermally broken window profile
9. Thermal insulation
10. Secondary steelwork to contractor design
11. Fixing bracket
12. Frame for GRC panel
13. Unitised glazing frame
14. Bracket supporting unitised panel fixed to top of slab
15. Metal panel
16. Thermal break
17. Extruded aluminium forming unitised panel
18. Rubber based seal
19. Outer seal
20. Inner seal
21. Air seal
22. Insulated panel, aluminium faced on both sides
23. Light fitting (by others)



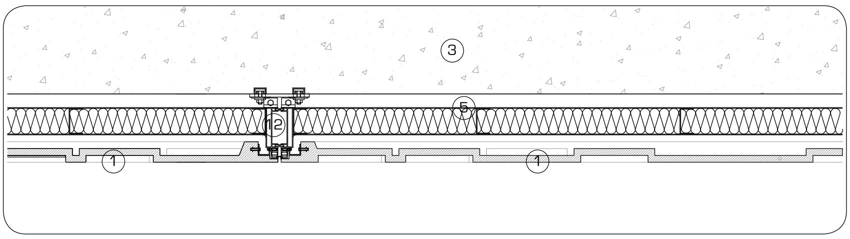
Vertical section. GRC cladding



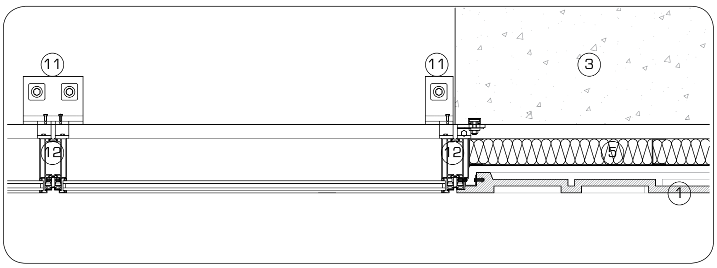
Vertical section. GRC cladding



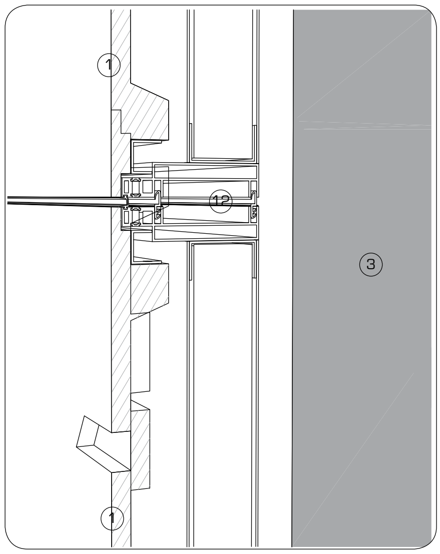
3D exploded view showing external GRC cladding and glazing



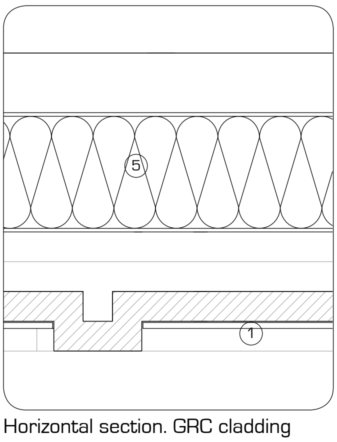
Horizontal section. GRC cladding



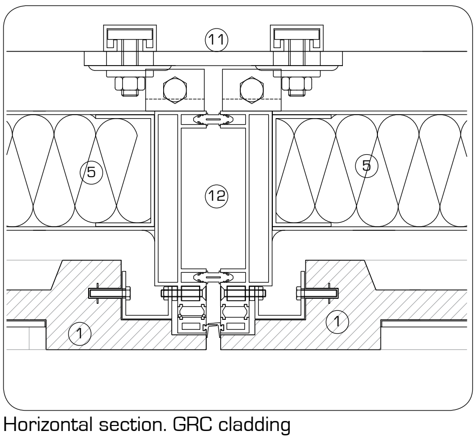
Horizontal section. GRC cladding and glazing



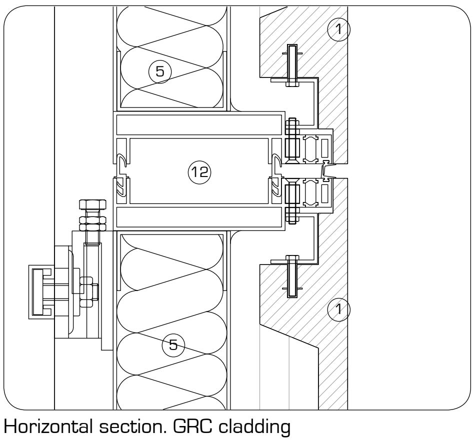
Vertical section. GRC cladding



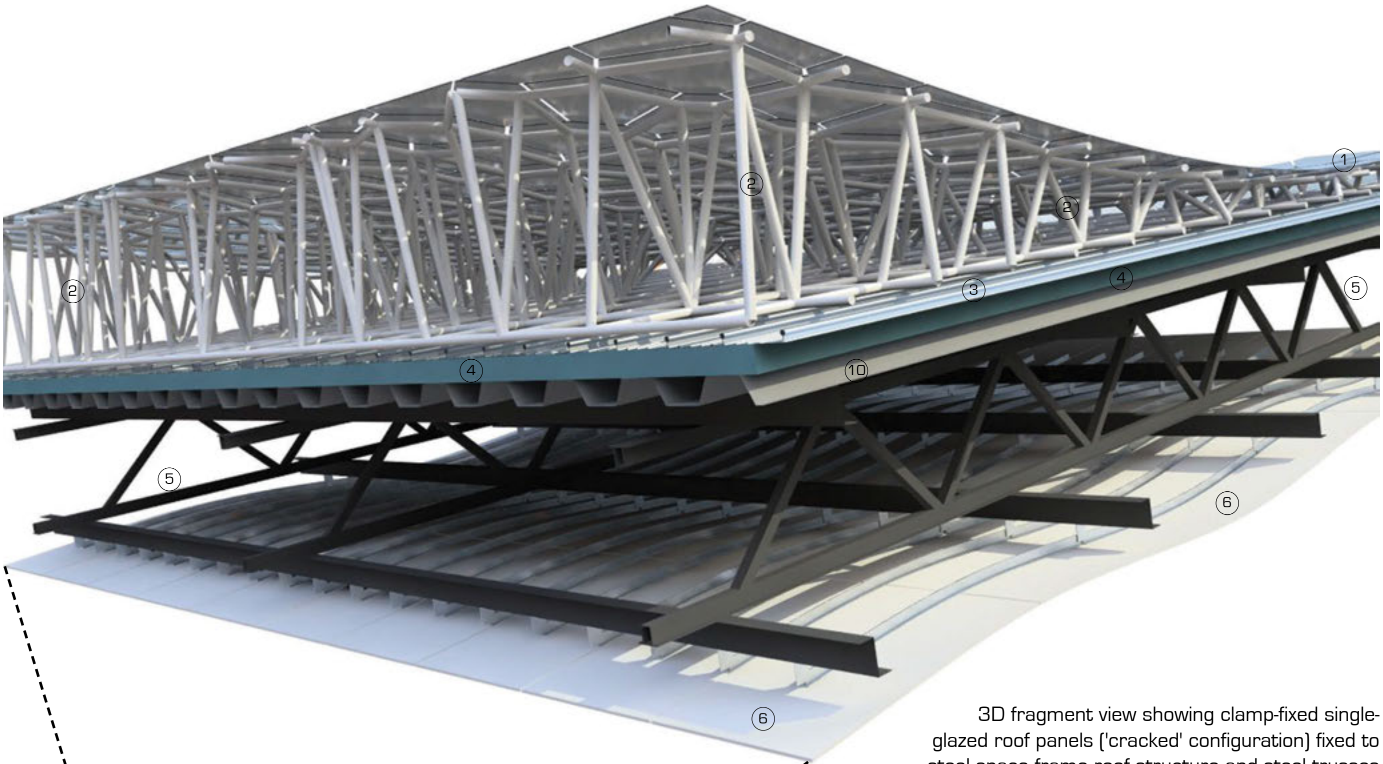
Horizontal section. GRC cladding



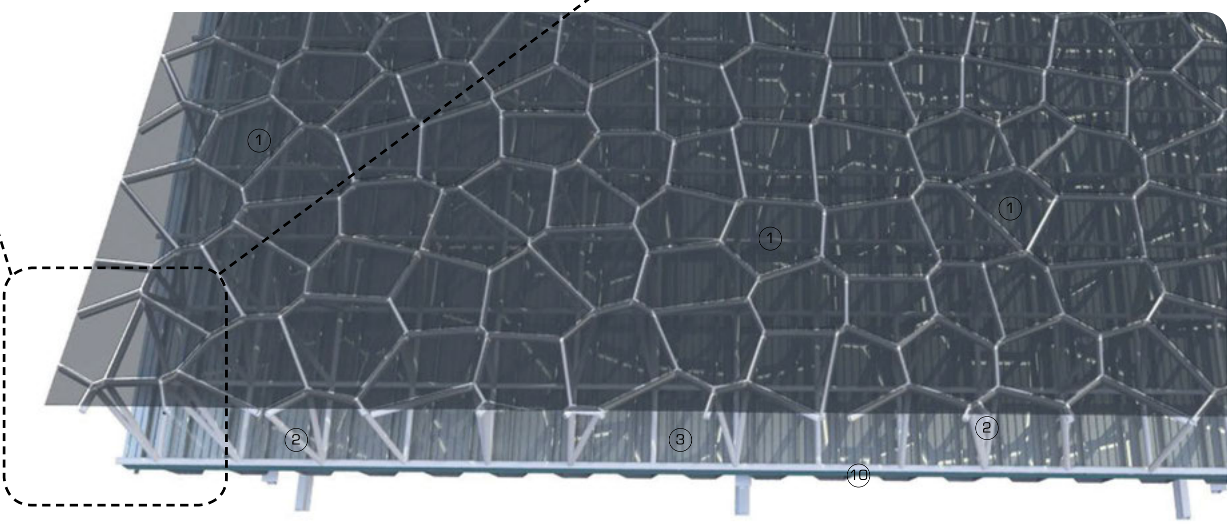
Horizontal section. GRC cladding

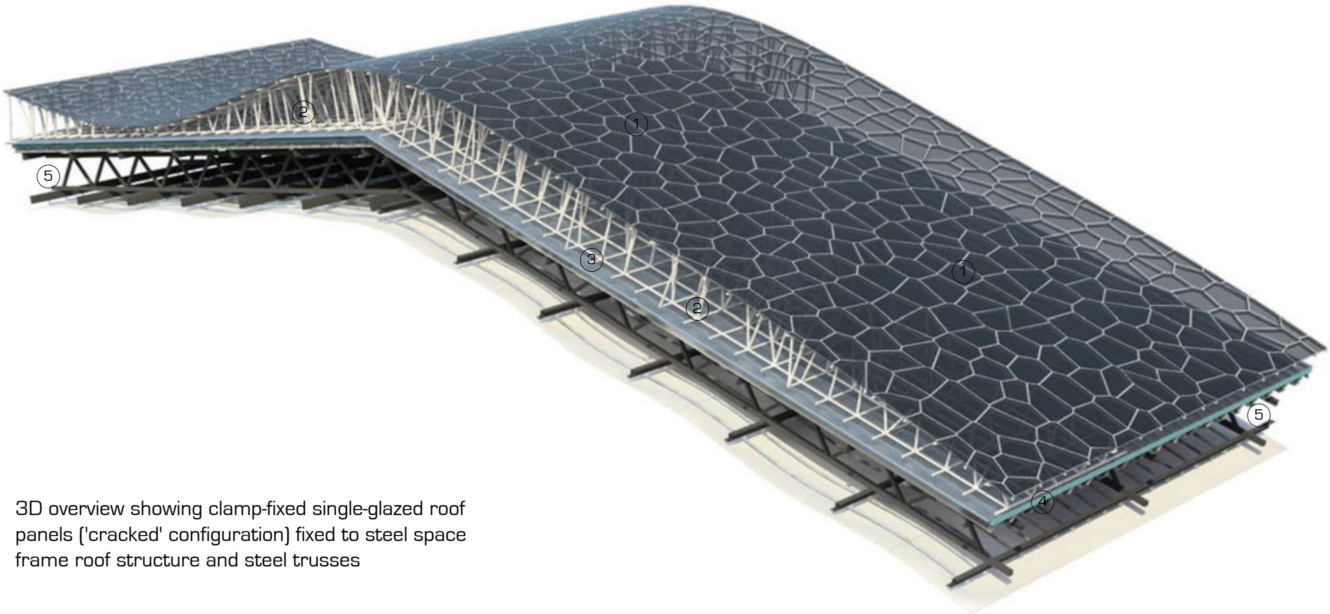


Horizontal section. GRC cladding

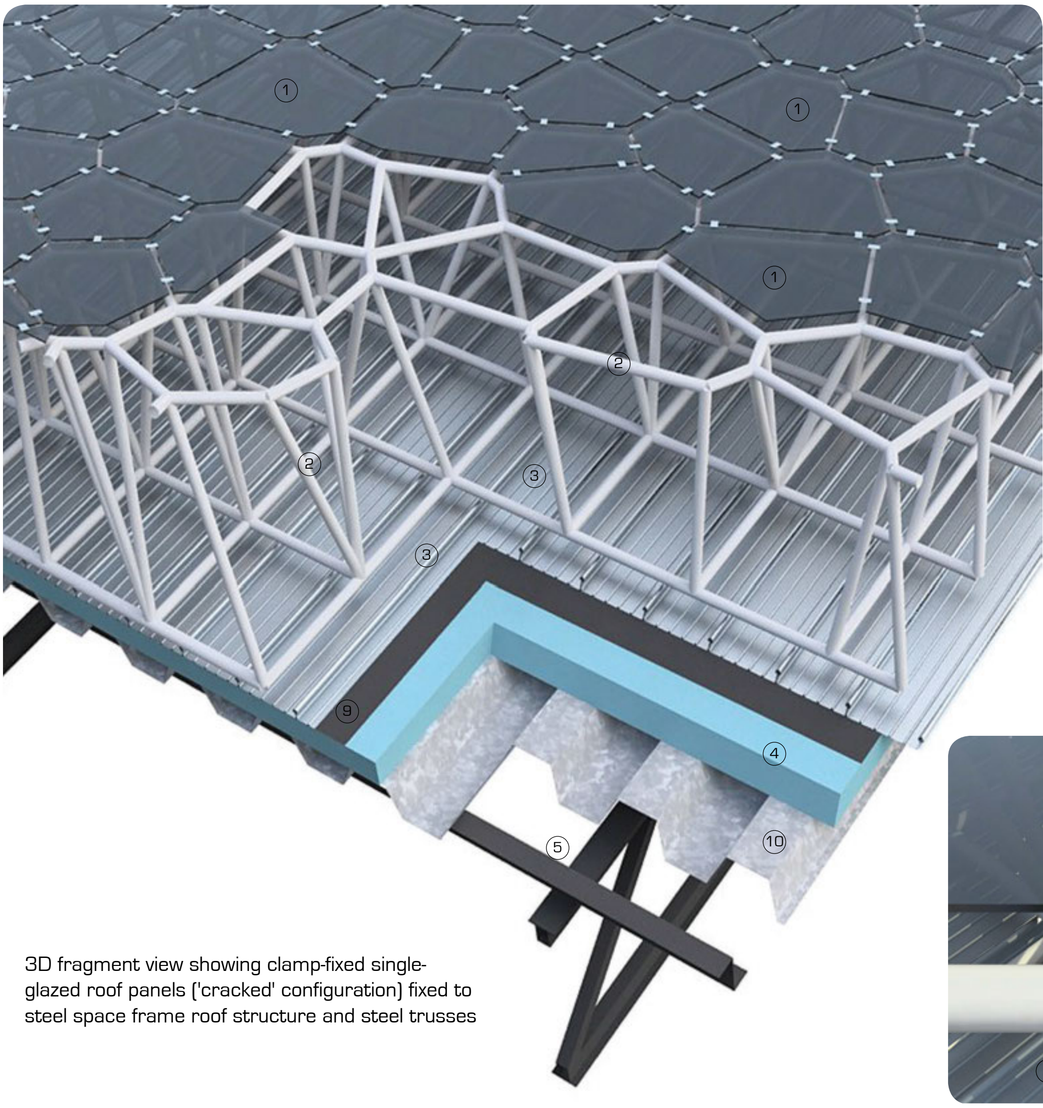


3D fragment view showing clamp-fixed single-glazed roof panels ('cracked' configuration) fixed to steel space frame roof structure and steel trusses





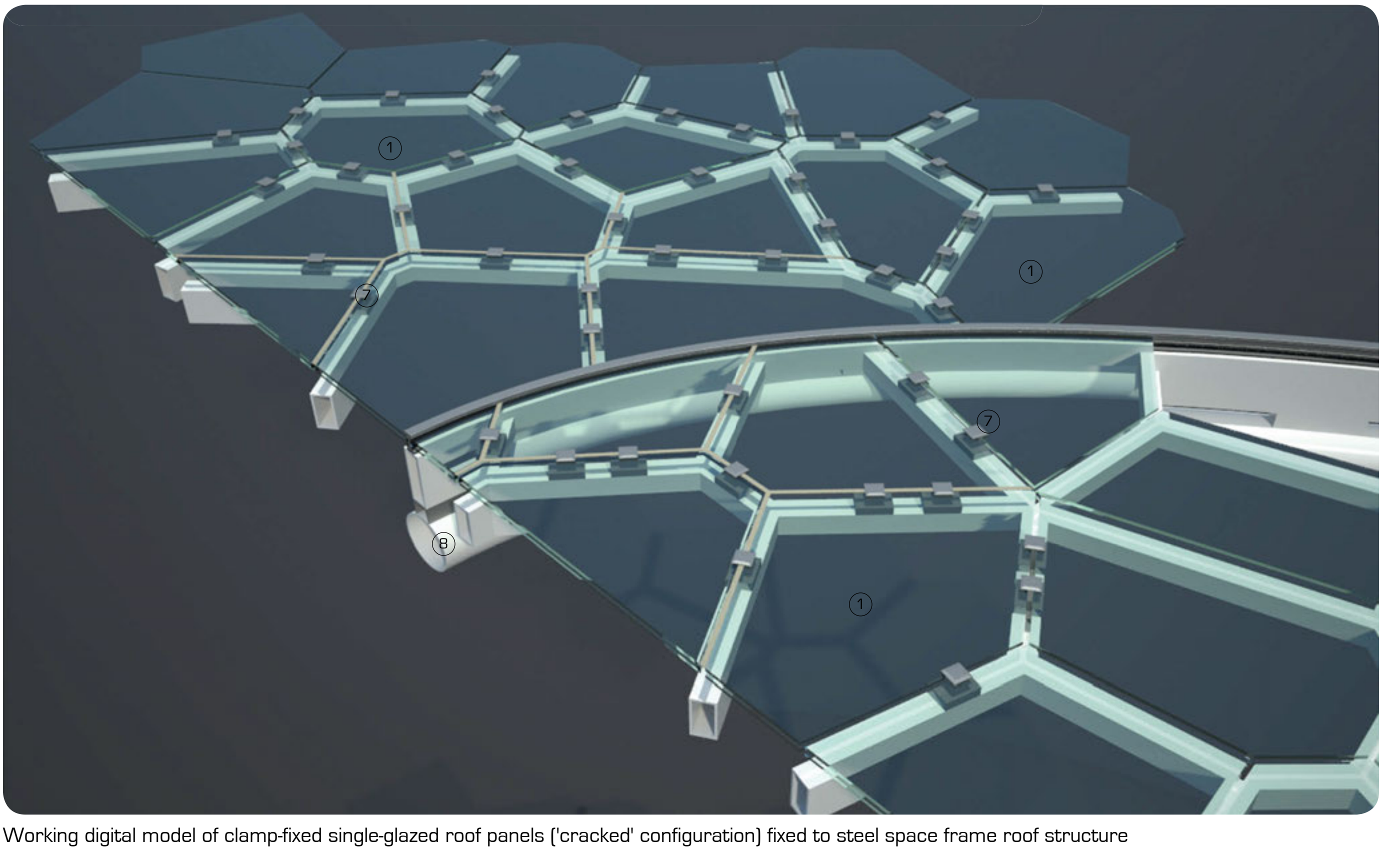
3D overview showing clamp-fixed single-glazed roof panels ('cracked' configuration) fixed to steel space frame roof structure and steel trusses



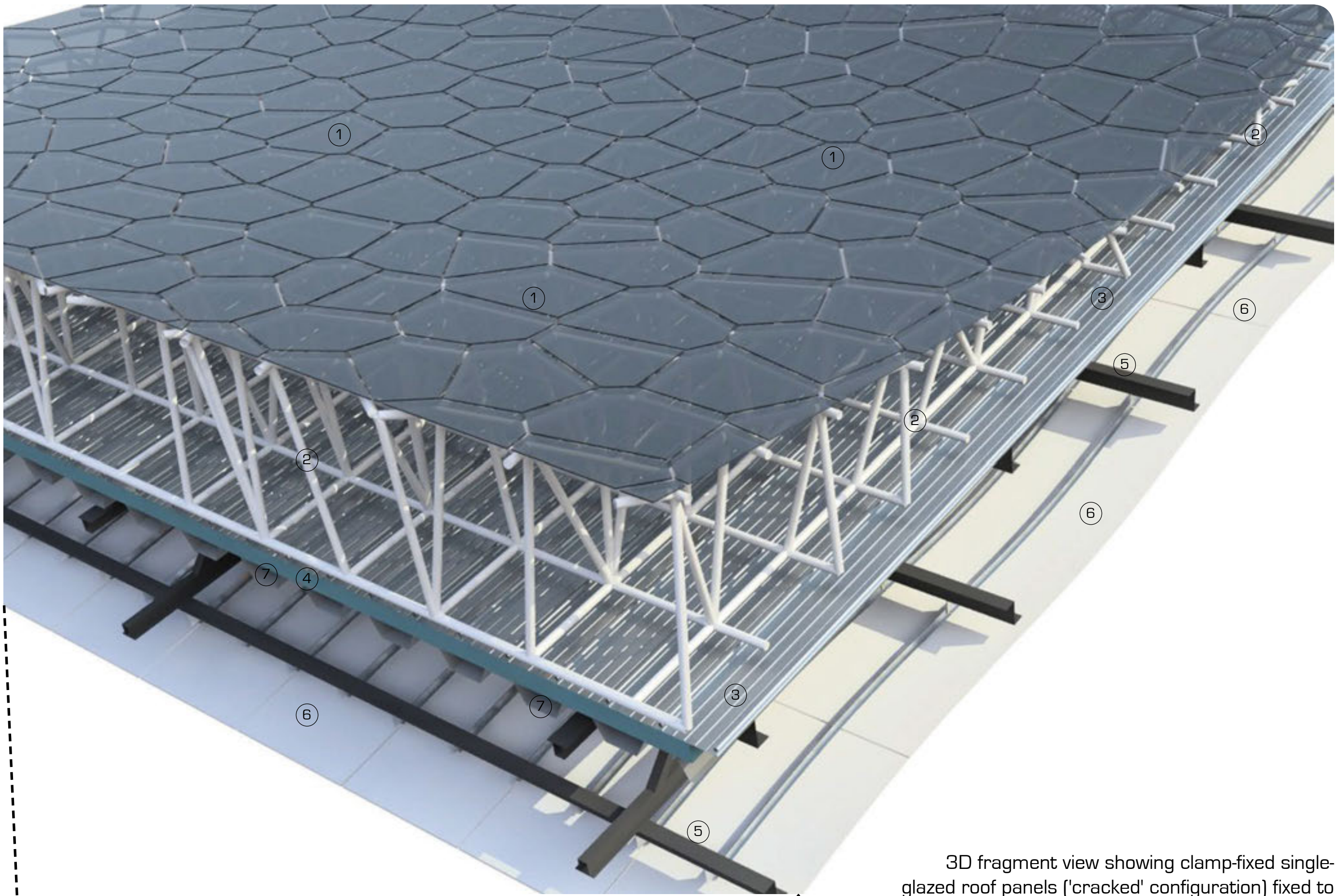
Details
1. Glazed cladding panels
2. Steel space frame roof support
3. Standing seam metal deck
4. Thermal insulation
5. Steel roof truss structure
6. Internal finish
7. Glazing clamp
8. Steel tube cladding support
9. Waterproof membrane
10. Profiled metal deck

(Below) 3D detail view showing clamp-fixing on single-glazed roof panels ('cracked' configuration) fixed to steel space frame roof structure

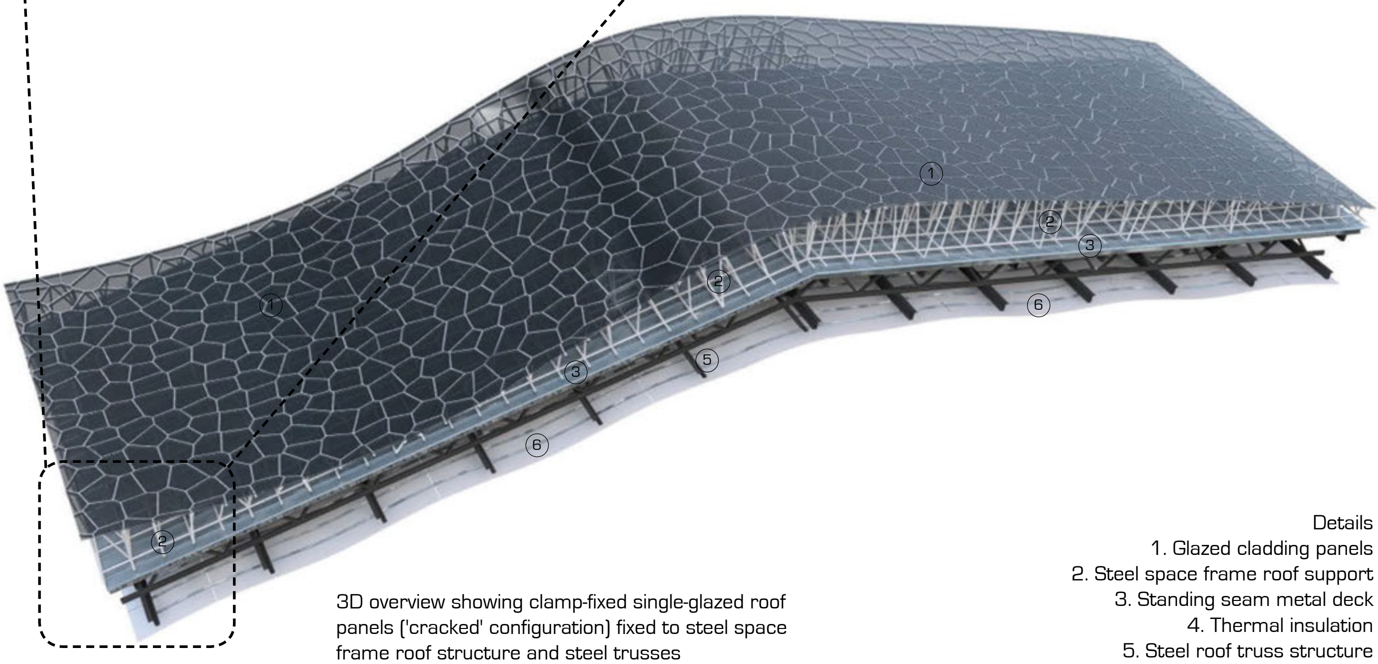
3D fragment view showing clamp-fixed single-glazed roof panels ('cracked' configuration) fixed to steel space frame roof structure and steel trusses



Working digital model of clamp-fixed single-glazed roof panels ('cracked' configuration) fixed to steel space frame roof structure



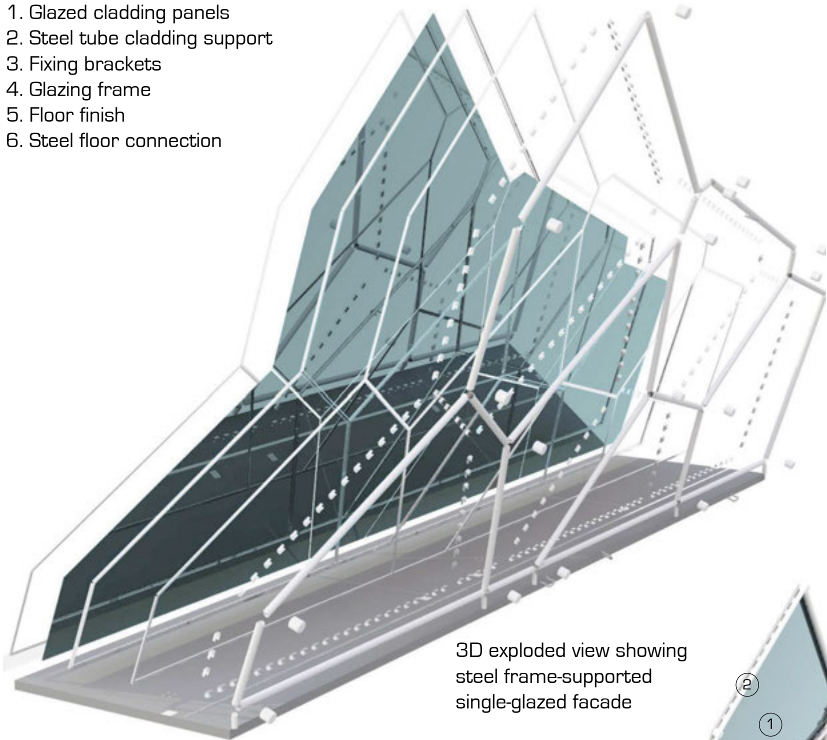
3D fragment view showing clamp-fixed single-glazed roof panels ('cracked' configuration) fixed to steel space frame roof structure and steel trusses



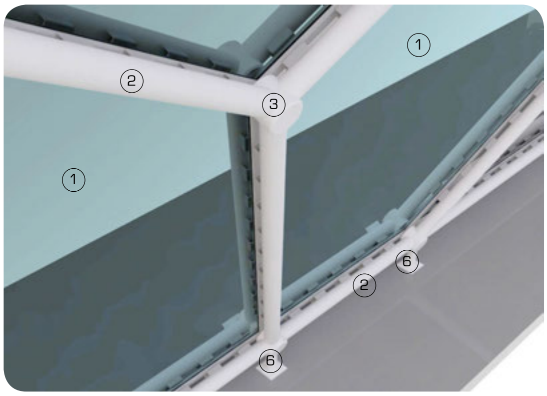
3D overview showing clamp-fixed single-glazed roof panels ('cracked' configuration) fixed to steel space frame roof structure and steel trusses

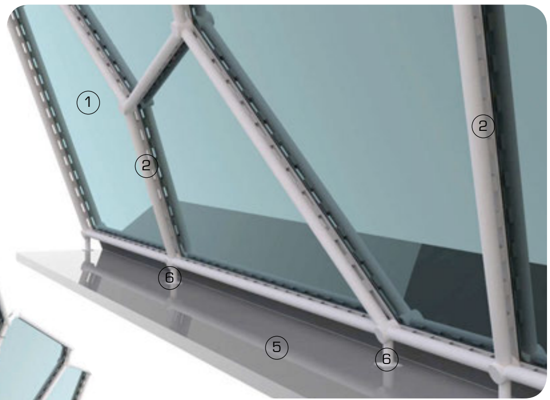
Details
1. Glazed cladding panels
2. Steel space frame roof support
3. Standing seam metal deck
4. Thermal insulation
5. Steel roof truss structure
6. Internal finish
7. Profiled metal deck

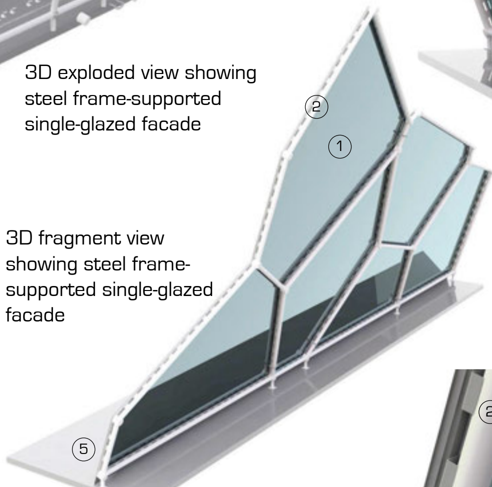
Details
1. Glazed cladding panels
2. Steel tube cladding support
3. Fixing brackets
4. Glazing frame
5. Floor finish
6. Steel floor connection



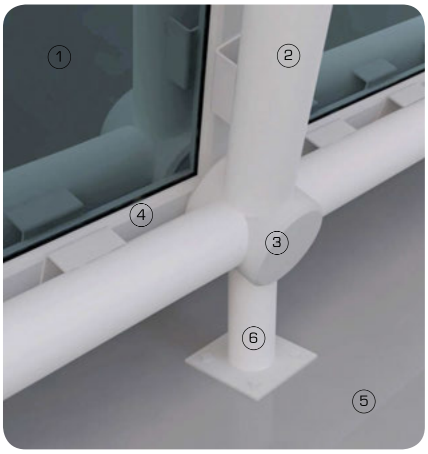
3D exploded view showing steel frame-supported single-glazed facade



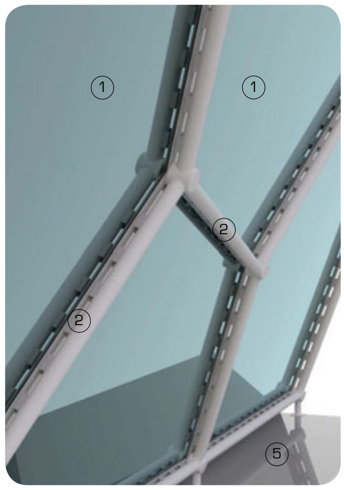


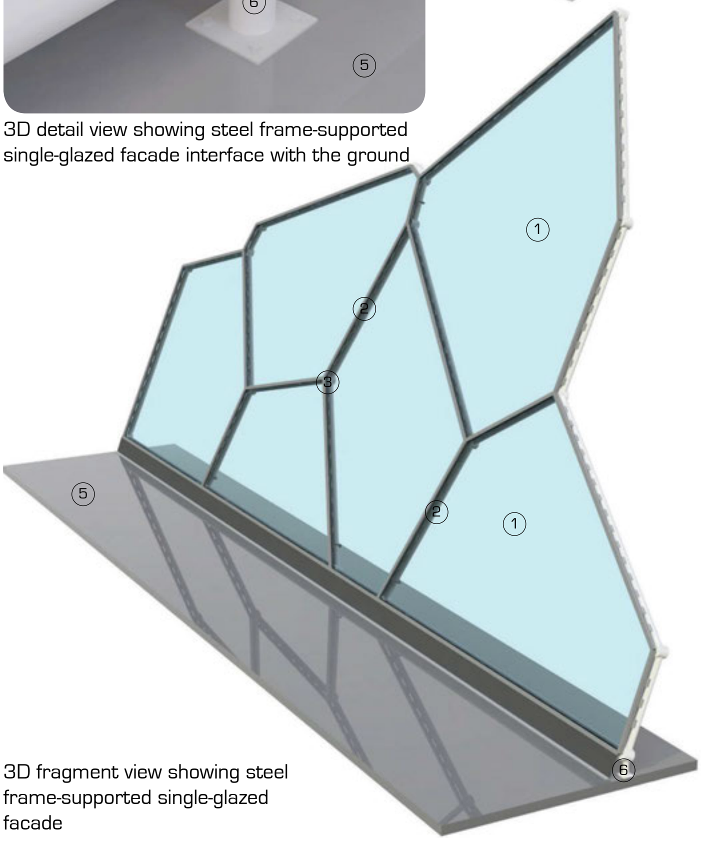


3D fragment view showing steel frame-supported single-glazed facade

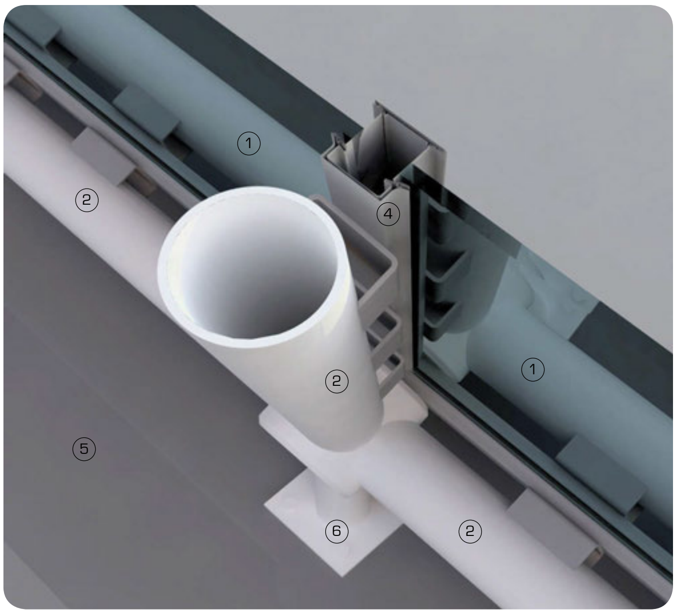


3D detail view showing steel frame-supported single-glazed facade interface with the ground

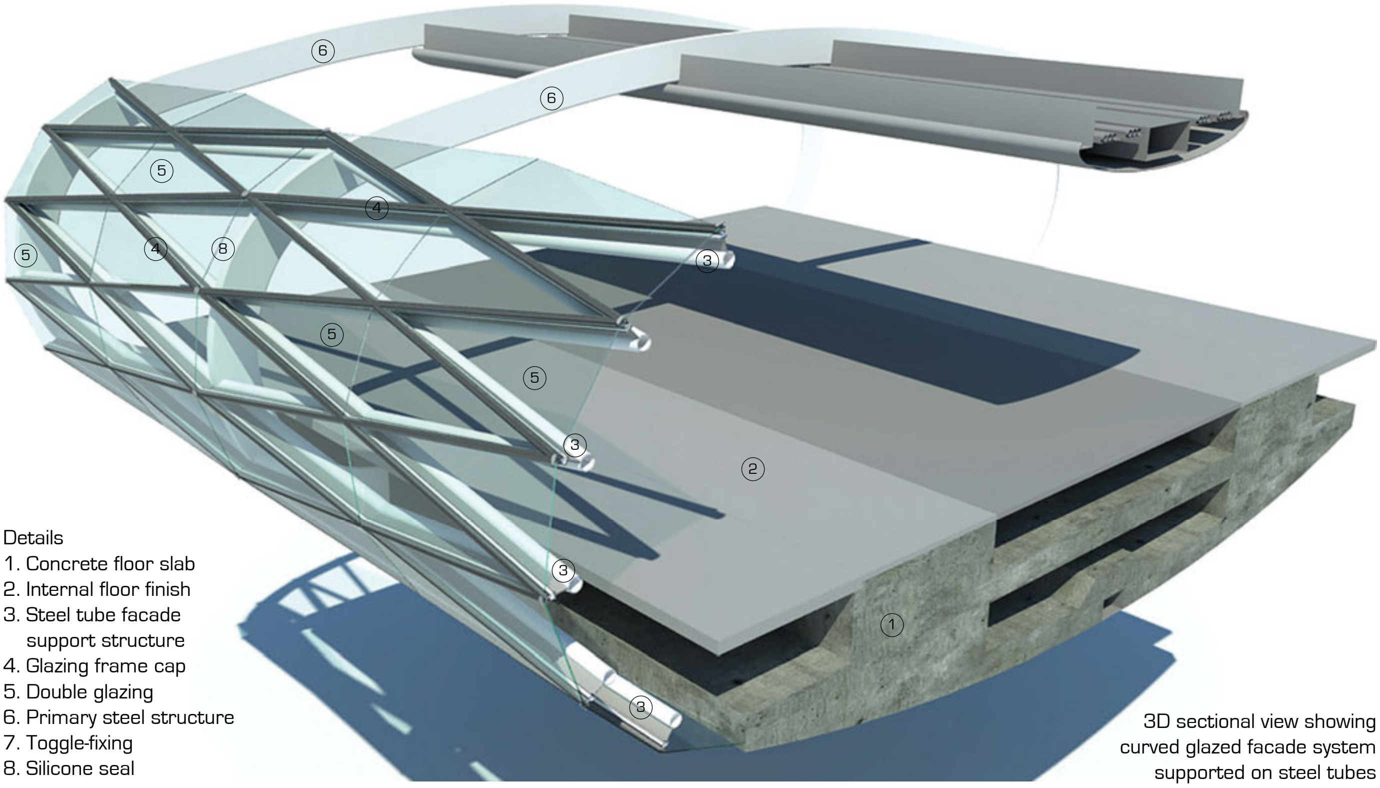




3D fragment view showing steel frame-supported single-glazed facade

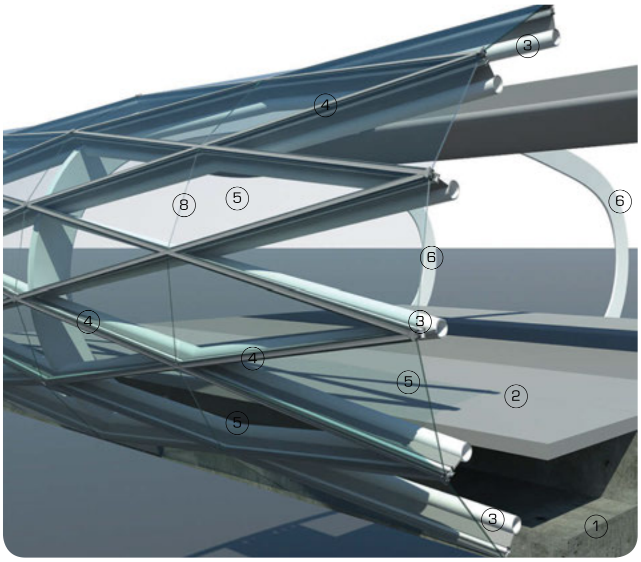


3D detail views showing steel frame-supported single-glazed facade

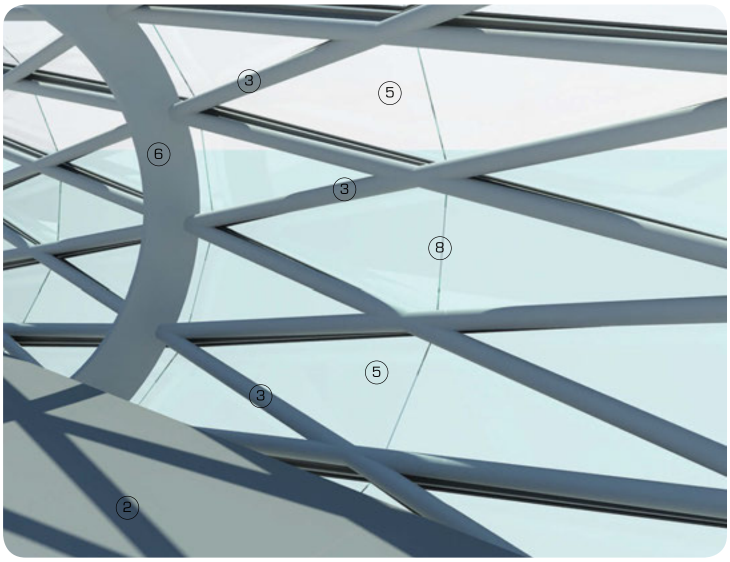


Details
1. Concrete floor slab
2. Internal floor finish
3. Steel tube facade support structure
4. Glazing frame cap
5. Double glazing
6. Primary steel structure
7. Toggle-fixing
8. Silicone seal

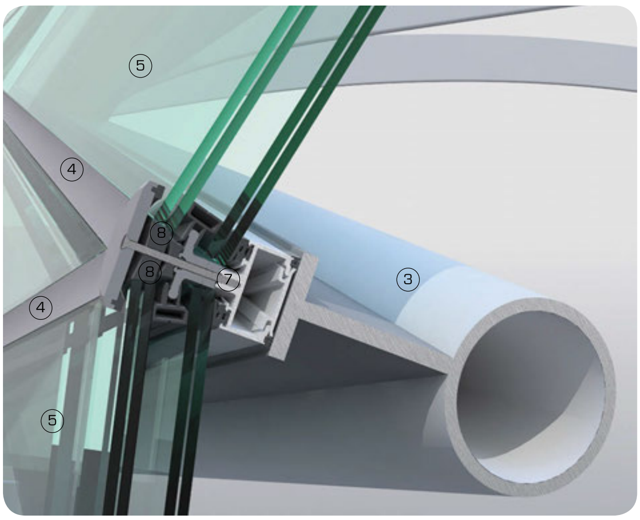
3D sectional view showing curved glazed facade system supported on steel tubes

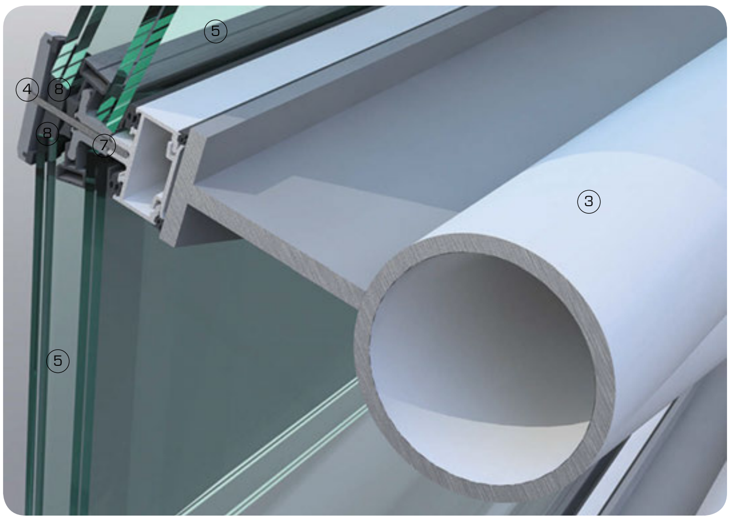


3D sectional view showing curved glazed facade system supported on steel tubes



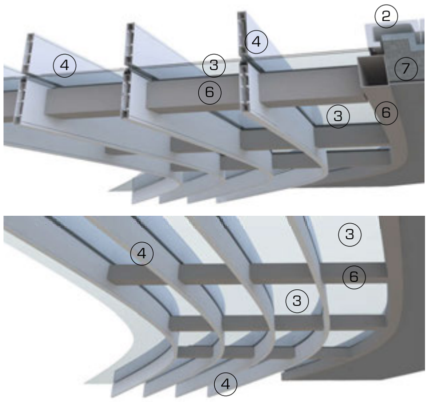
3D internal view showing curved glazed facade system supported on steel tubes



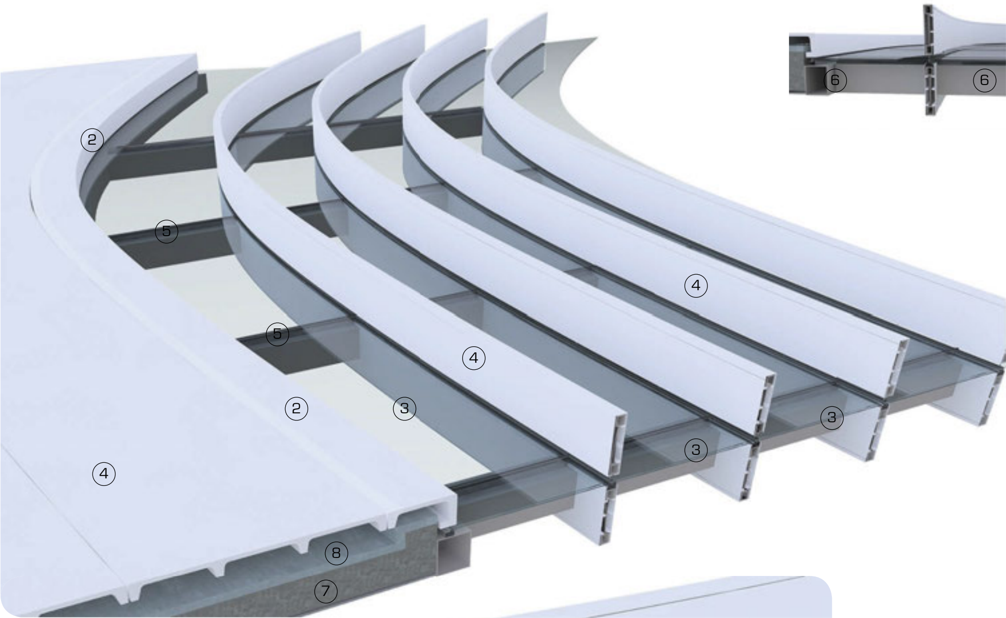


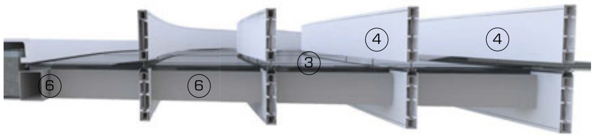
3D detail views showing toggle-fixed curved glazed facade system supported on steel tubes

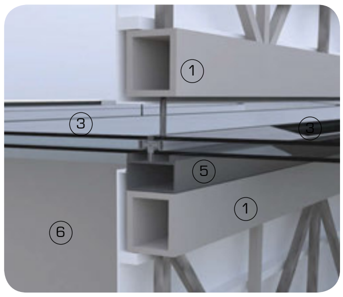
3D sectional view showing toggle-fixed glazed rooflight with GRP-clad structural trusses to form blade-like solar shading louvres and interface with opaque GRP rainscreen roof cladding



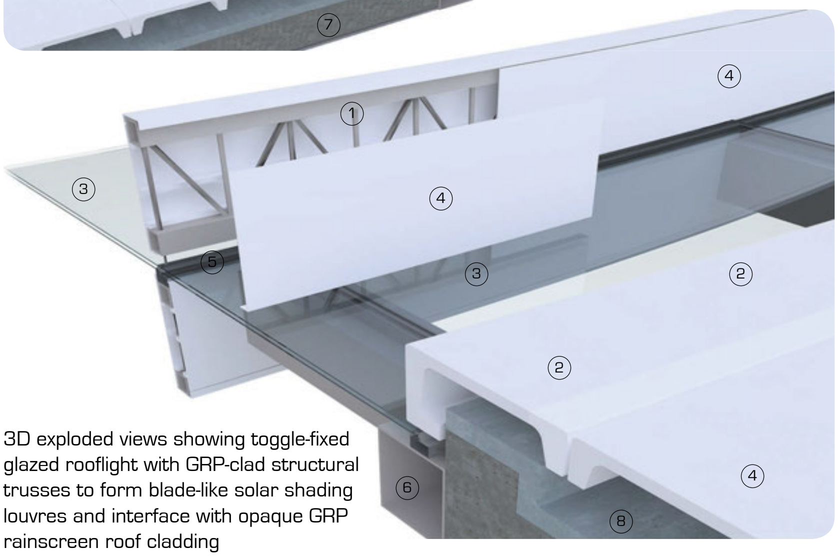
3D sectional views showing underside of toggle-fixed glazed rooflight with GRP-clad structural trusses to form blade-like solar shading louvres

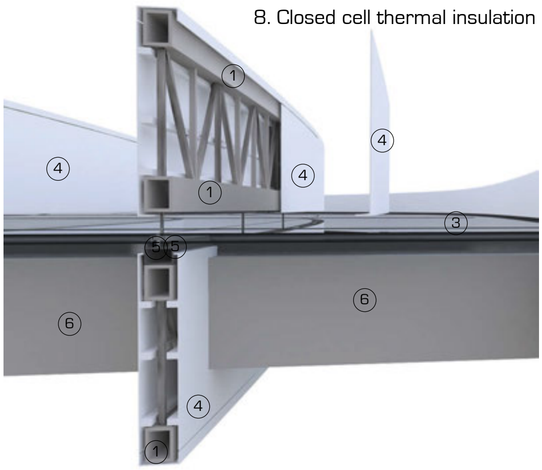




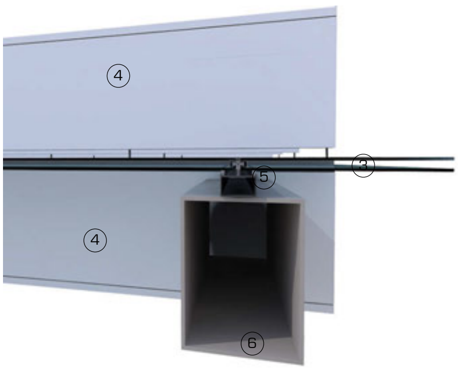


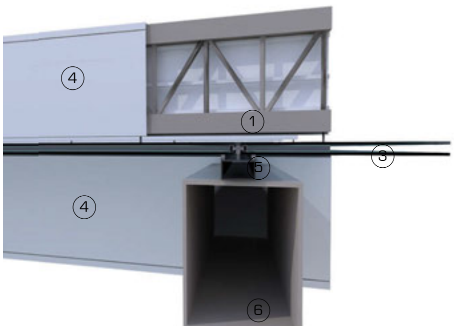
Details
1. Primary steel truss structure
2. GRC edge piece
3. Toggle-fixed glazed rooflight
4. GRC cladding
5. Glazing frame
6. Steel structural member
7. Concrete roof deck
8. Closed cell thermal insulation

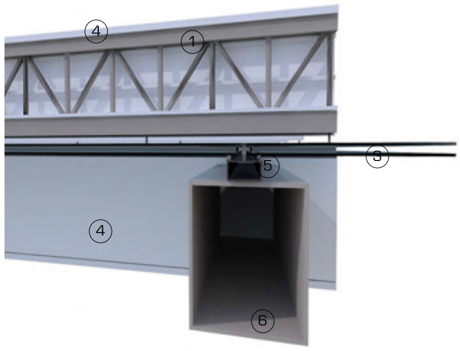


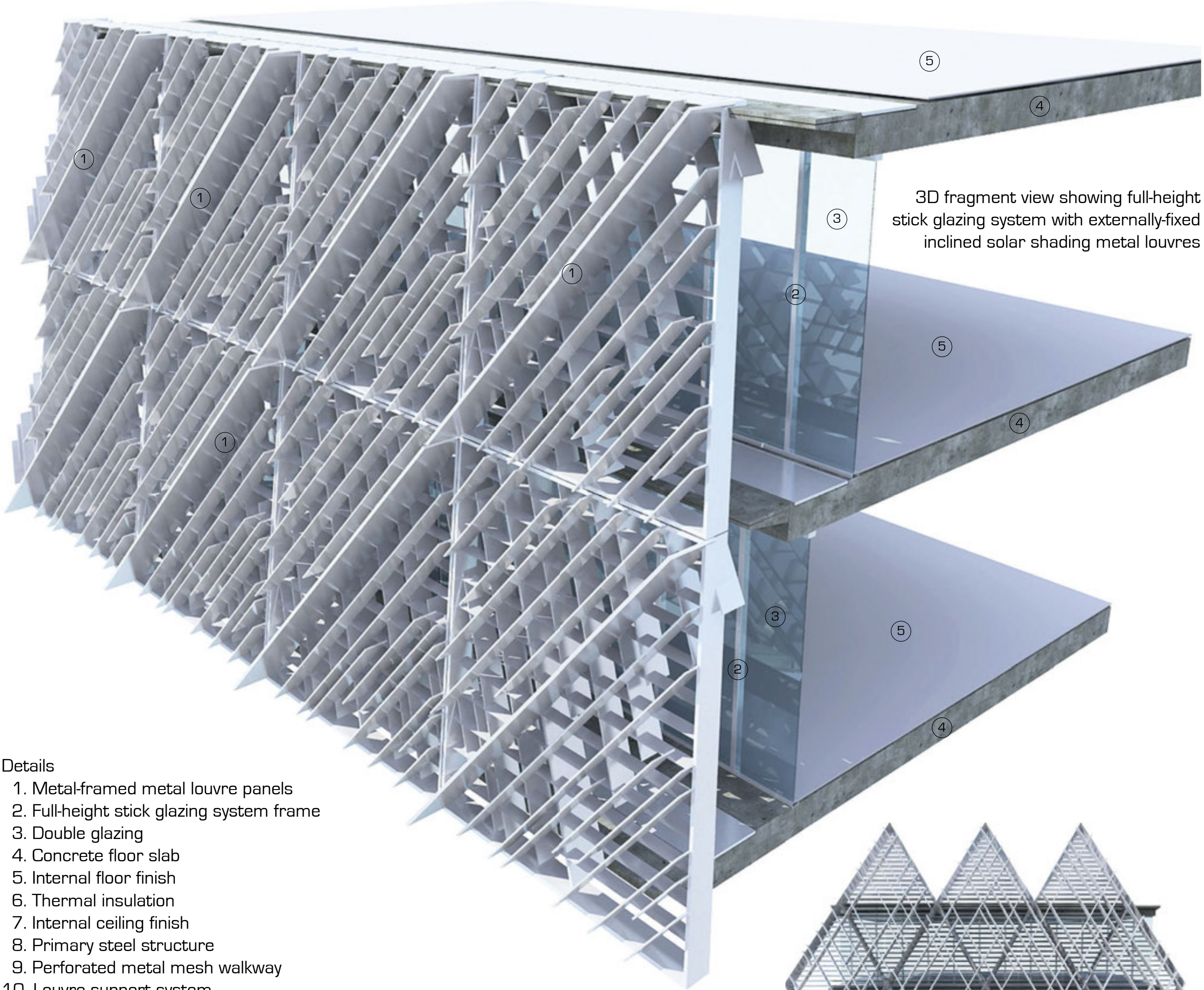


3D exploded views showing toggle-fixed glazed rooflight with GRP-clad structural trusses to form blade-like solar shading louvres and interface with opaque GRP rainscreen roof cladding



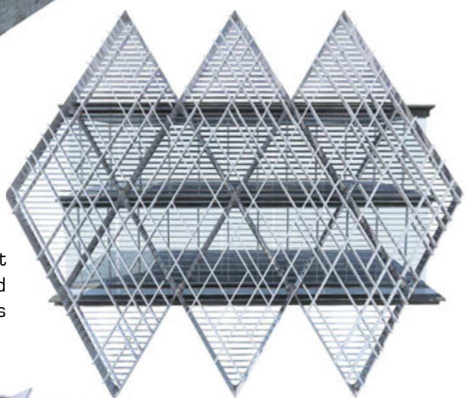




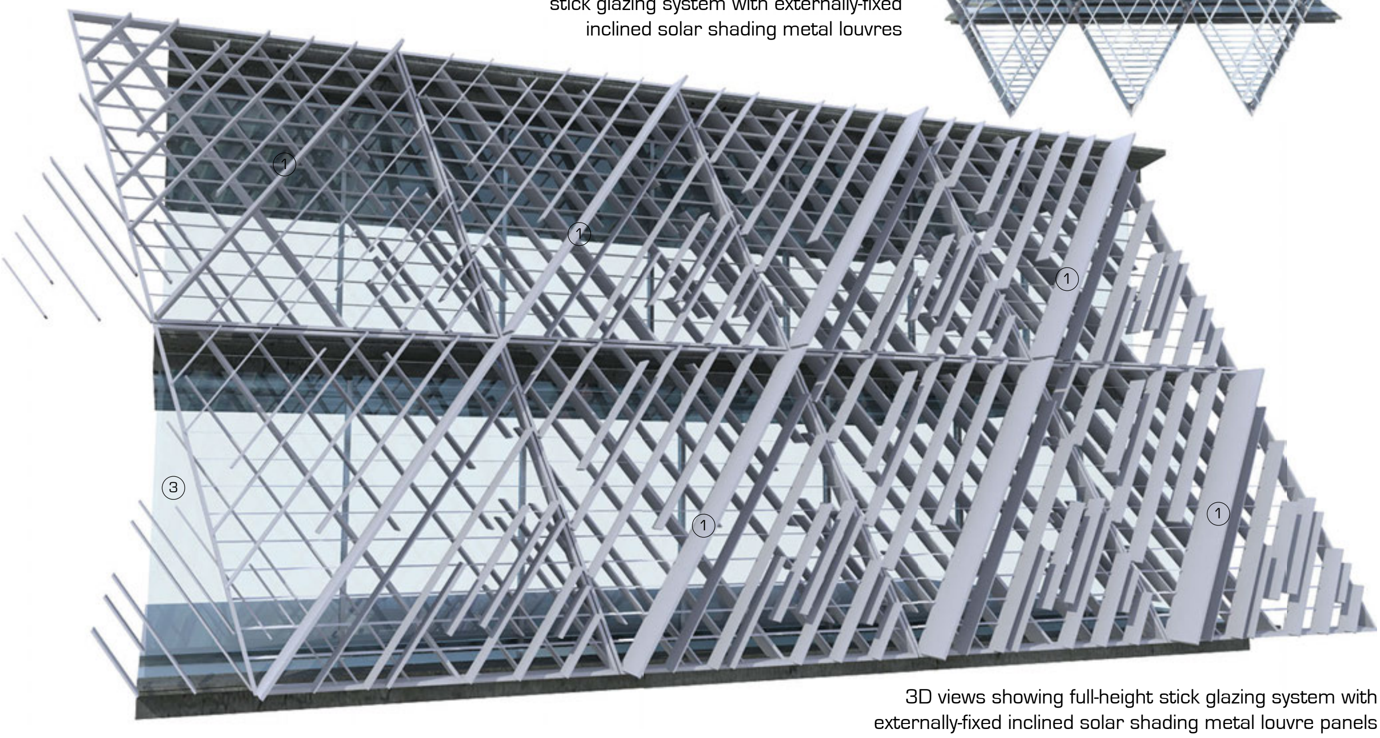


3D fragment view showing full-height stick glazing system with externally-fixed inclined solar shading metal louvres

Details
1. Metal-framed metal louvre panels
2. Full-height stick glazing system frame
3. Double glazing
4. Concrete floor slab
5. Internal floor finish
6. Thermal insulation
7. Internal ceiling finish
8. Primary steel structure
9. Perforated metal mesh walkway
10. Louvre support system
11. Metal flashing



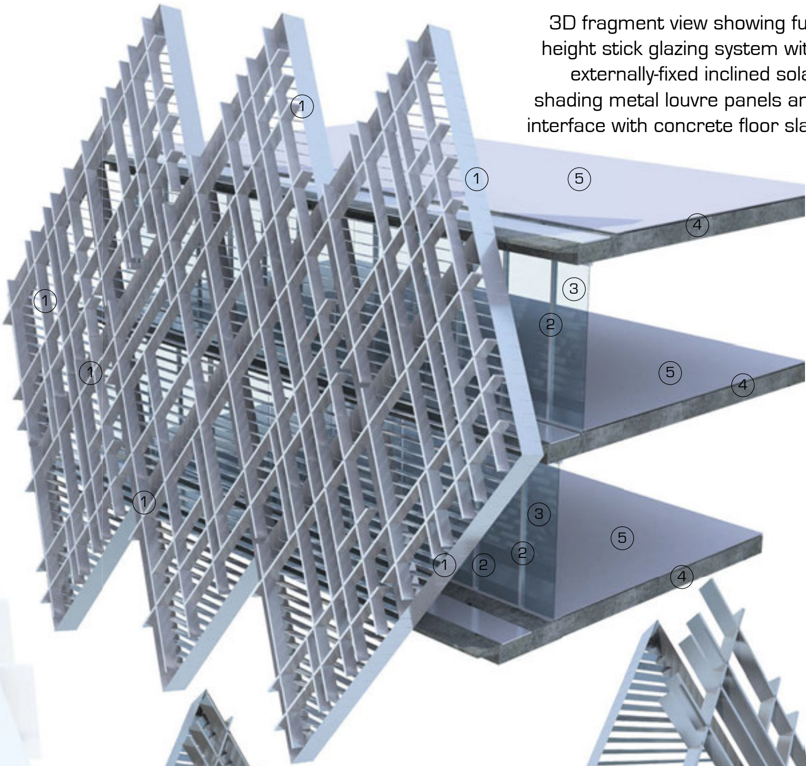
3D fragment view showing full-height stick glazing system with externally-fixed inclined solar shading metal louvres

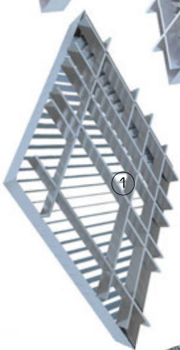


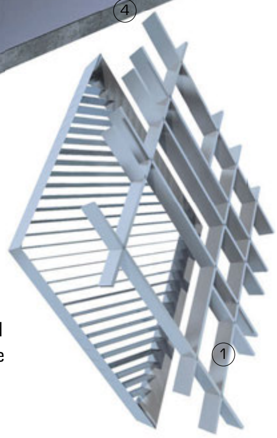
3D views showing full-height stick glazing system with externally-fixed inclined solar shading metal louvre panels

3D sectional view showing space between full-height stick glazing system and externally-fixed inclined solar shading metal louvre panels

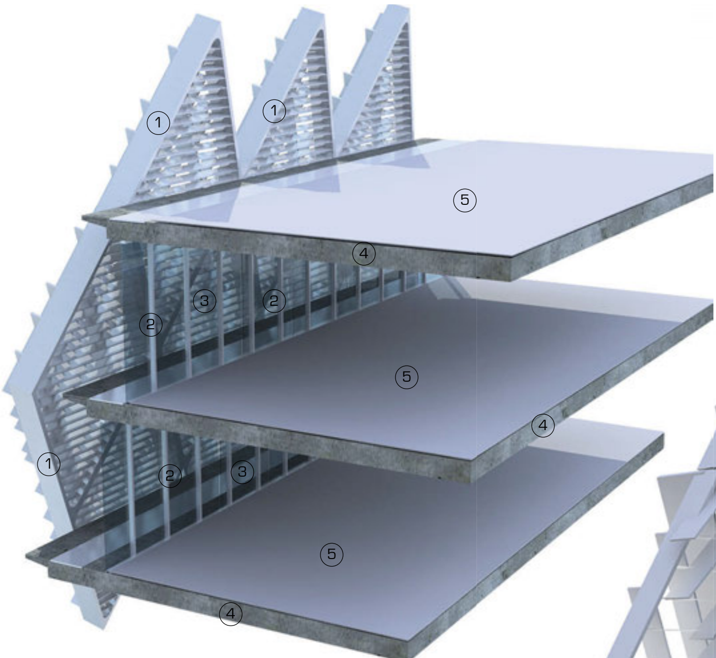
3D fragment view showing full-height stick glazing system with externally-fixed inclined solar shading metal louvre panels and interface with concrete floor slab



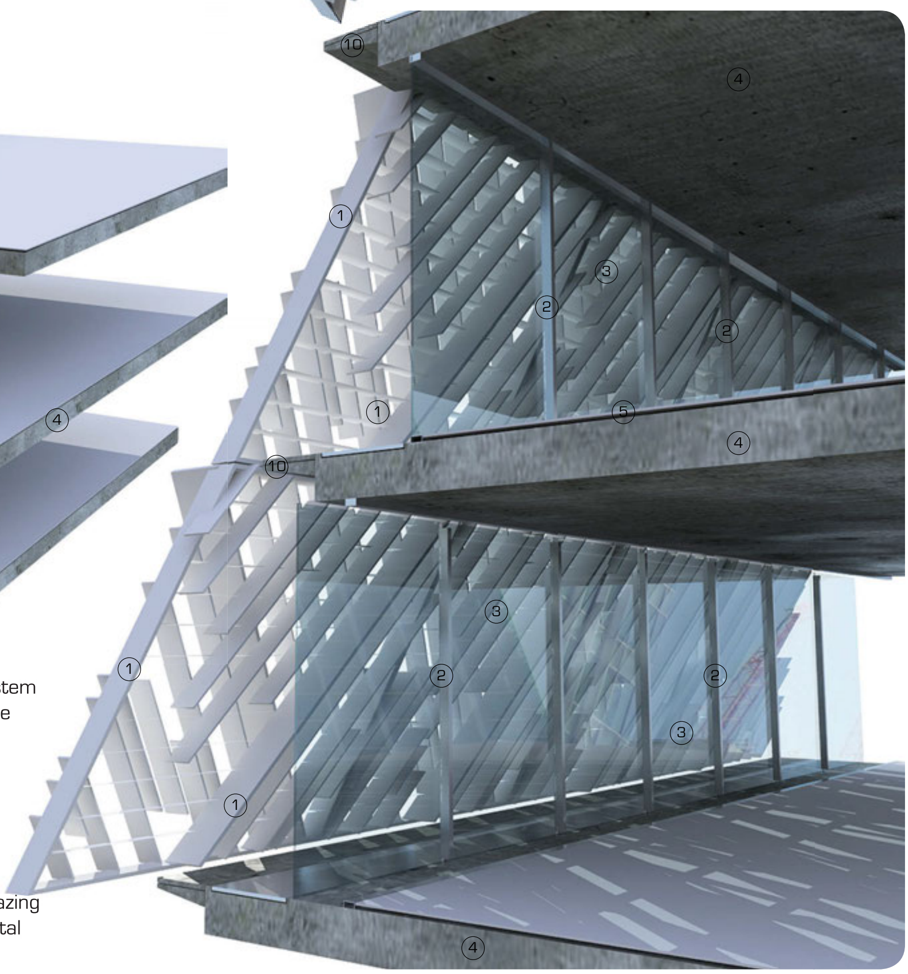




3D views showing inclined solar shading metal louvre panels

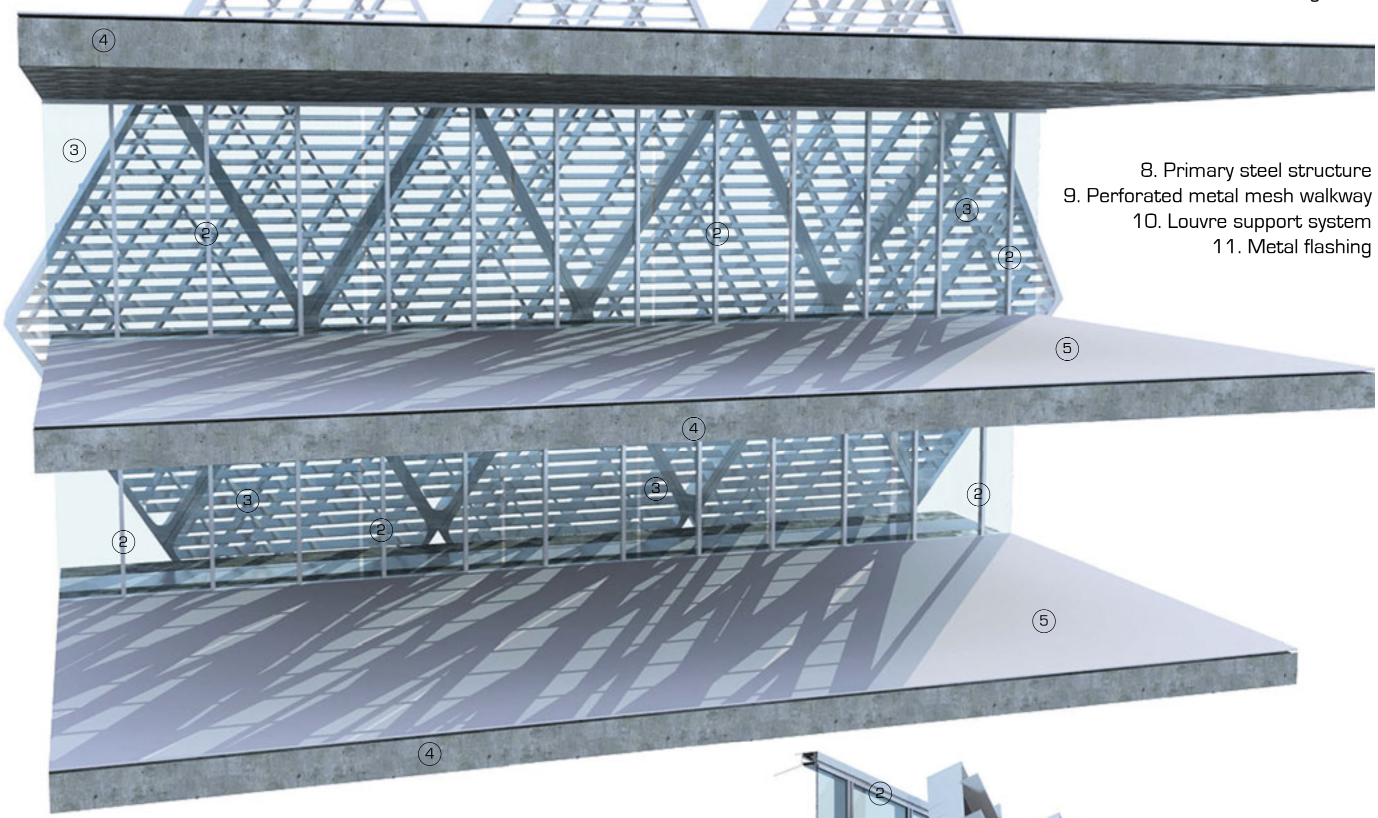


3D fragment view showing full-height stick glazing system with externally-fixed inclined solar shading metal louvre panels and interface with concrete floor slab



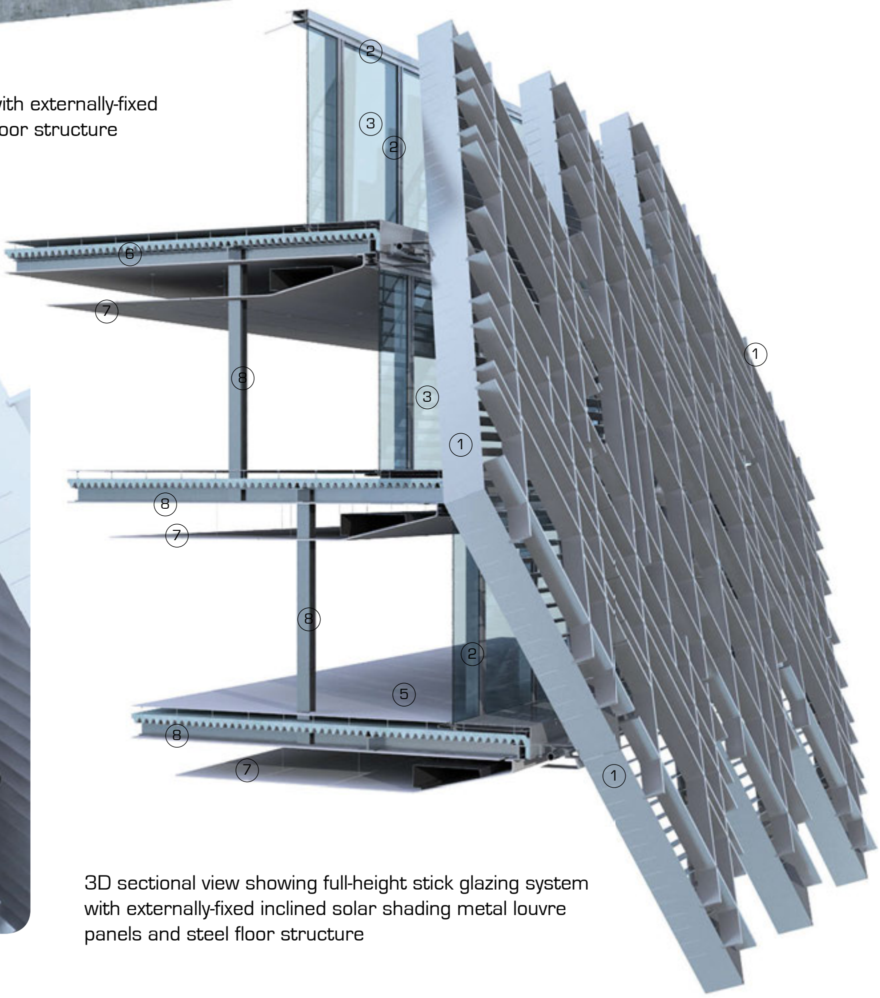
3D internal fragment view showing full-height stick glazing system with externally-fixed inclined solar shading metal louvre panels and interface with concrete floor slab

Details
1. Metal-framed metal louvre panels
2. Full-height stick glazing system frame
3. Double glazing
4. Concrete floor slab
5. Internal floor finish
6. Thermal insulation on profiled metal deck
7. Internal ceiling finish
8. Primary steel structure
9. Perforated metal mesh walkway
10. Louvre support system
11. Metal flashing



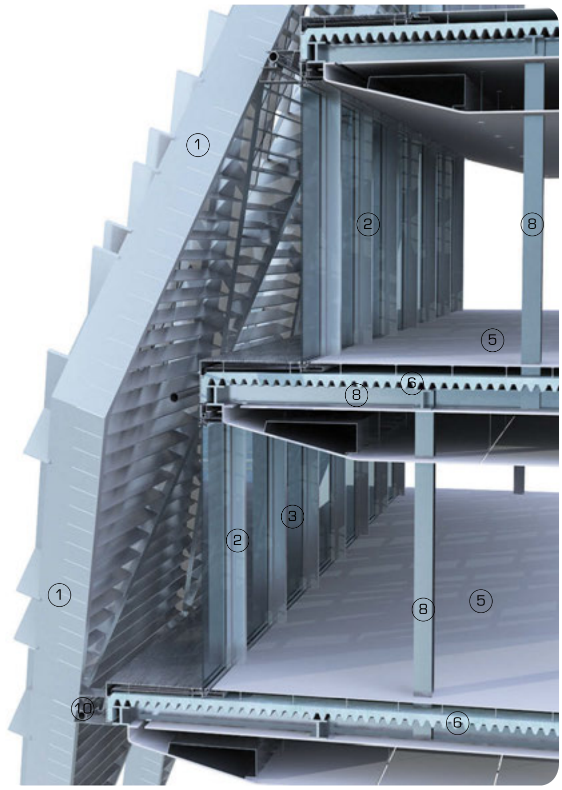
3D internal view showing full-height stick glazing system with externally-fixed inclined solar shading metal louvre panels and concrete floor structure

3D internal sectional view showing full-height stick glazing system with externally-fixed inclined solar shading metal louvre panels and steel floor structure



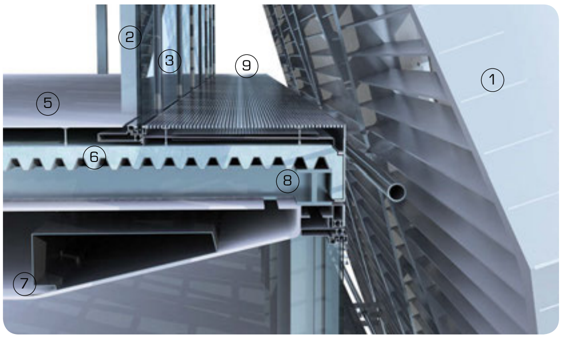
3D sectional view showing full-height stick glazing system with externally-fixed inclined solar shading metal louvre panels and steel floor structure

3D underside view showing full-height stick glazing system with externally-fixed inclined solar shading metal louvre panels and steel floor structure

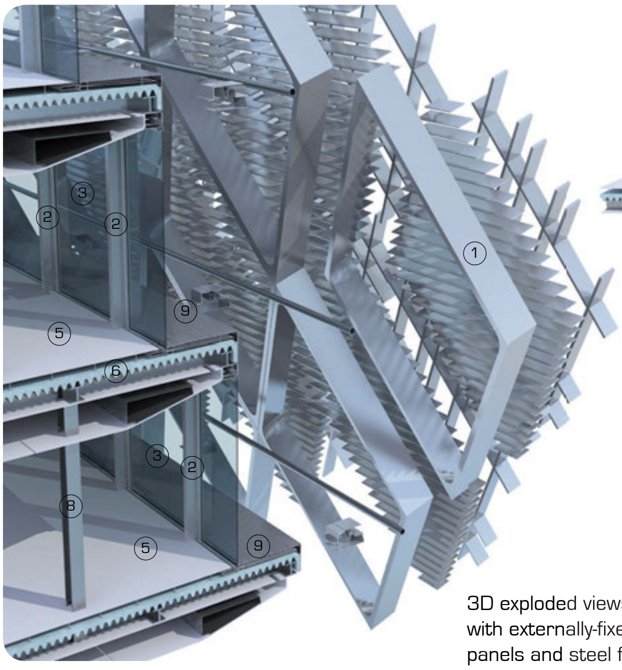


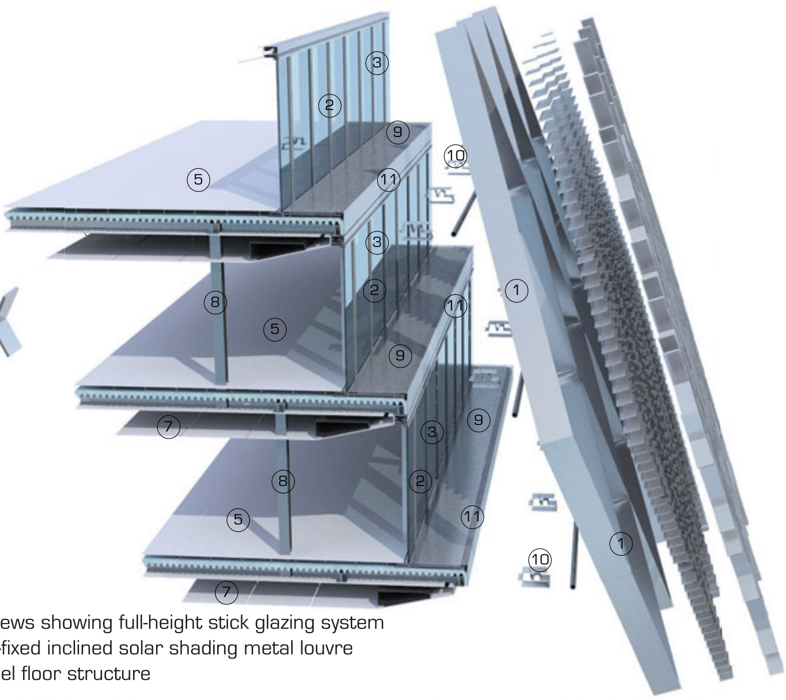
3D internal view showing full-height stick glazing system with externally-fixed inclined solar shading metal louvre panels and steel floor structure

3D view showing full-height stick glazing system with externally-fixed inclined solar shading metal louvre panels and steel floor structure

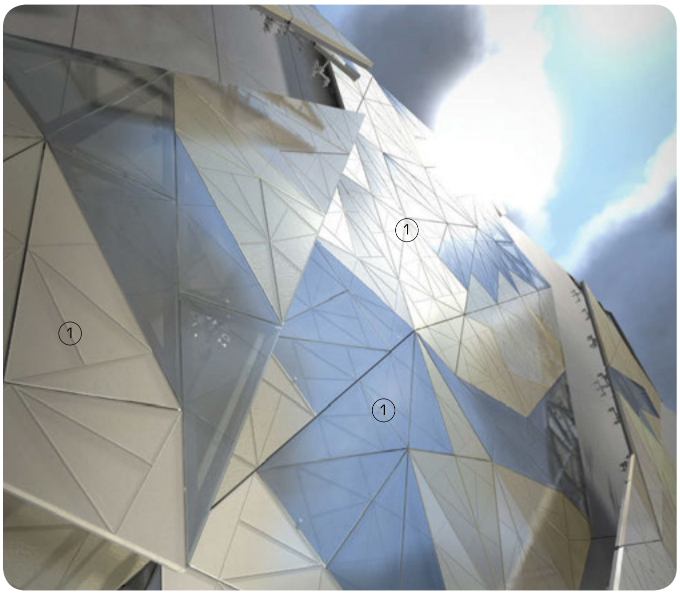


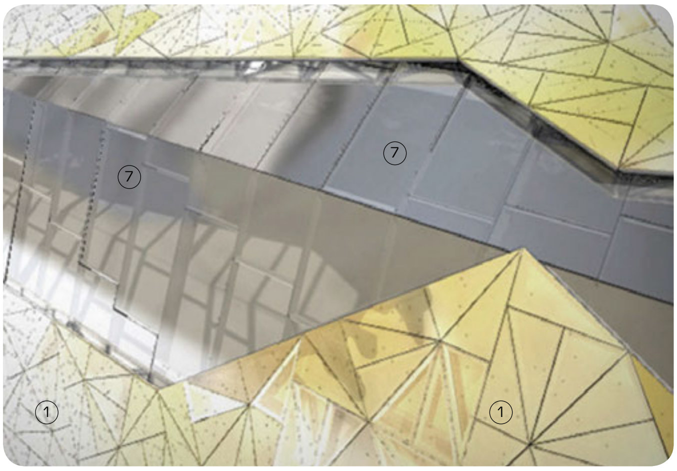
3D detail view shhowing full-height stick glazing system with externally-fixed inclined solar shading metal louvre panels and steel floor structure

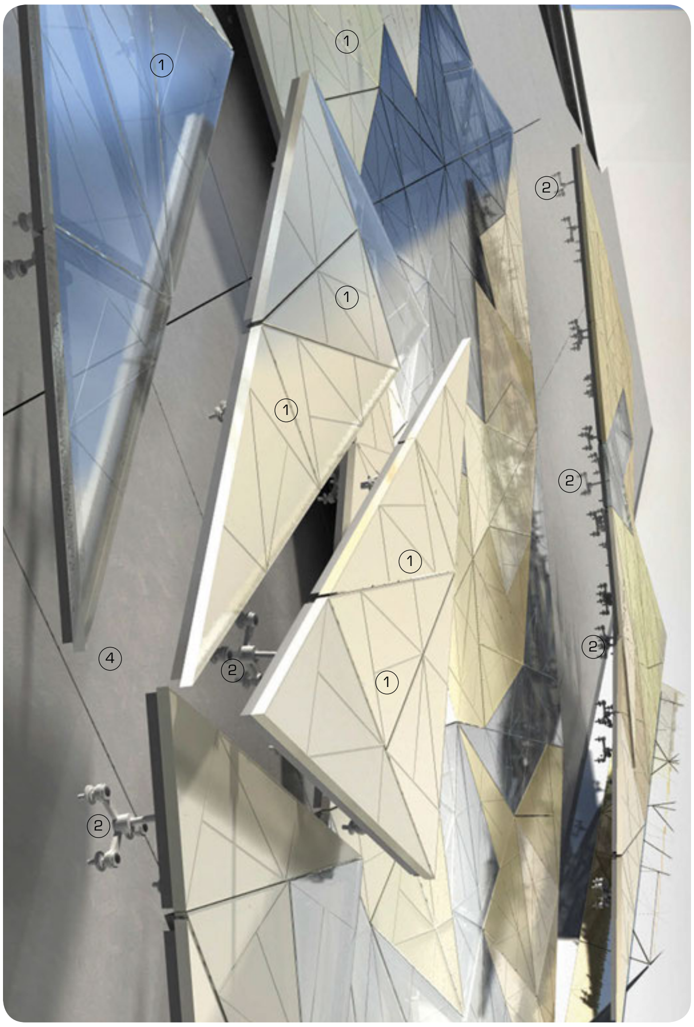




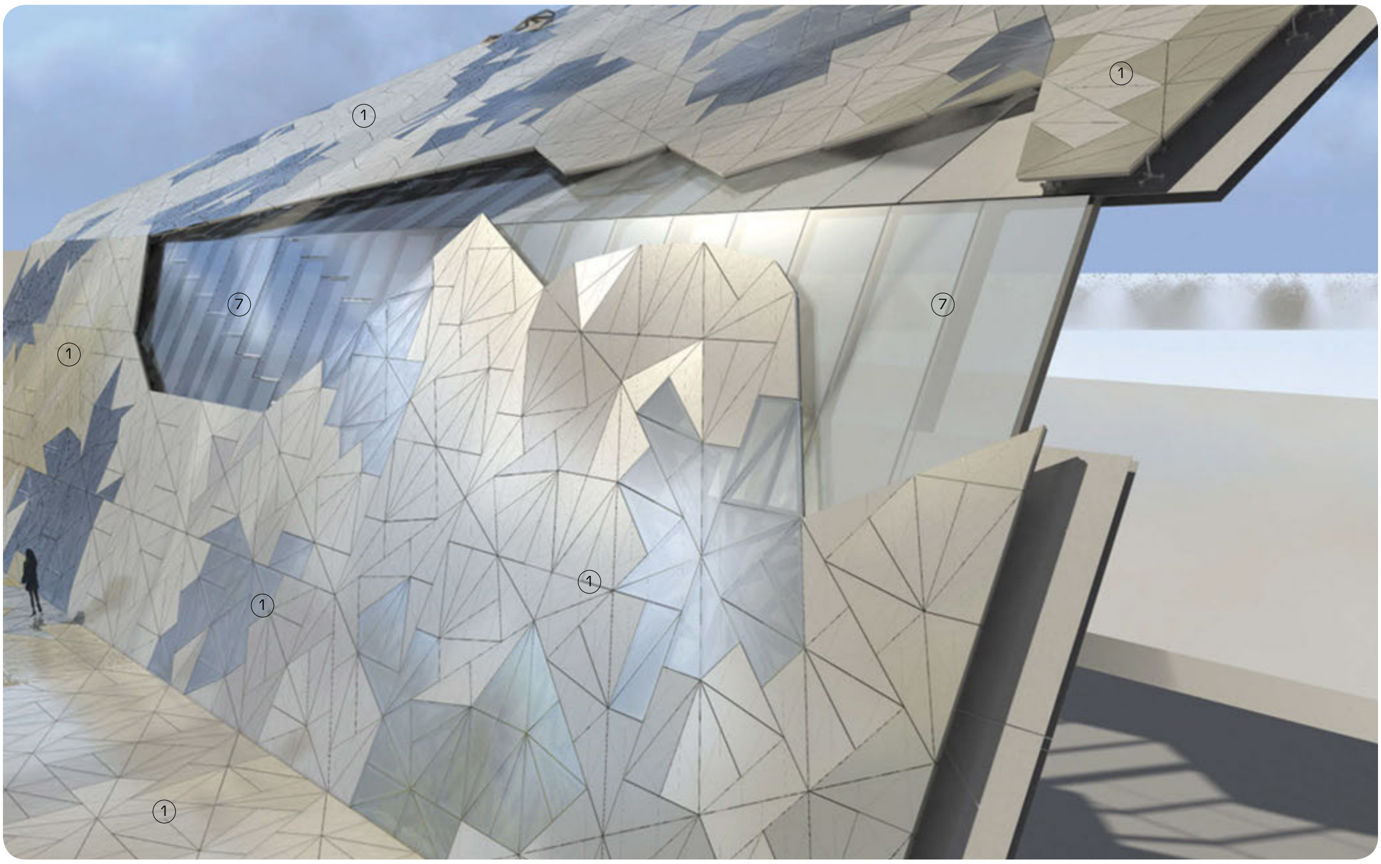
3D exploded views showing full-height stick glazing system with externally-fixed inclined solar shading metal louvre panels and steel floor structure



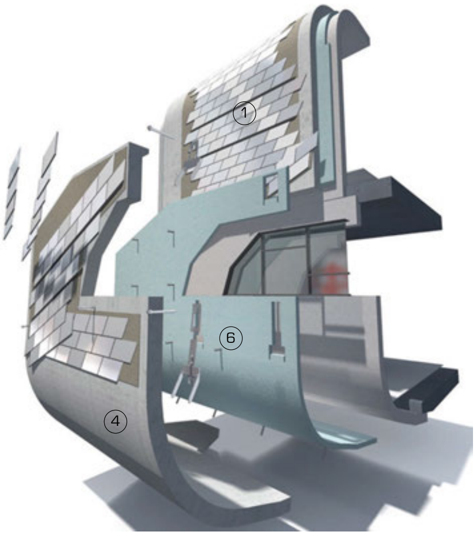




3D views showing tiled rainscreen cladding panels fixed to in-situ cast concrete primary structure with inset full-height unitised glazing

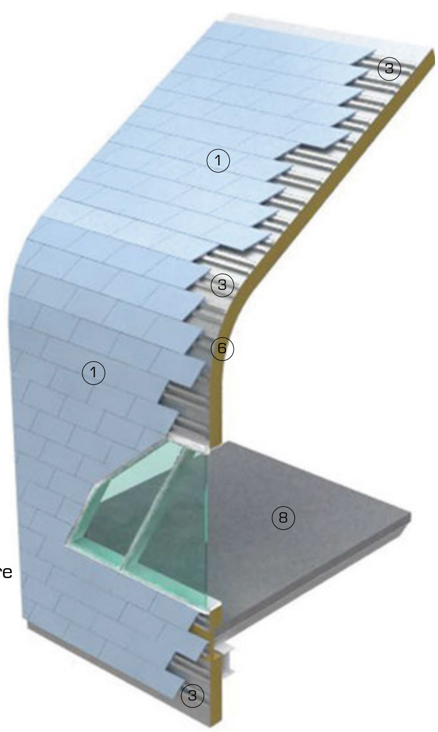


3D view showing tiled rainscreen cladding panels fixed to in-situ cast concrete primary structure

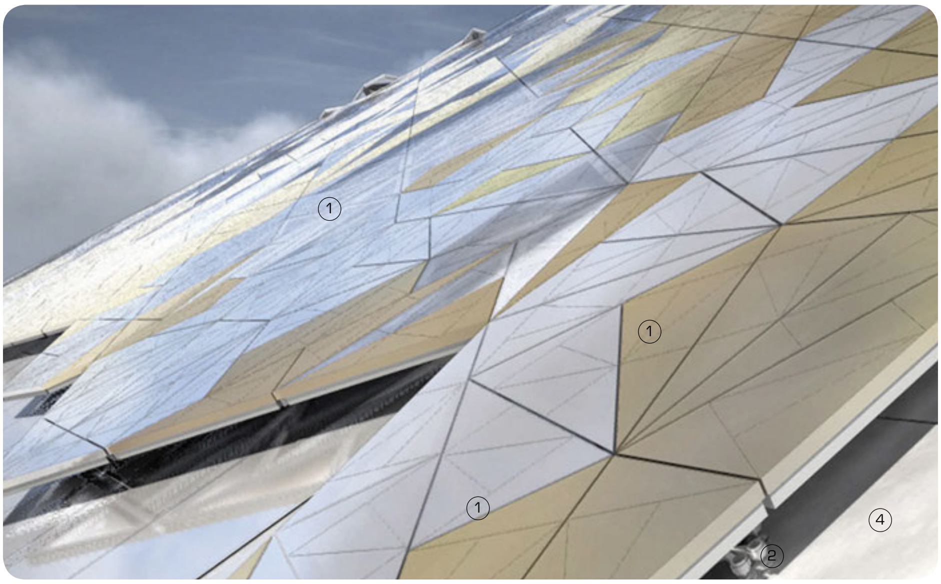


3D exploded view showing tiled rainscreen cladding panels fixed to in-situ cast concrete primary structure

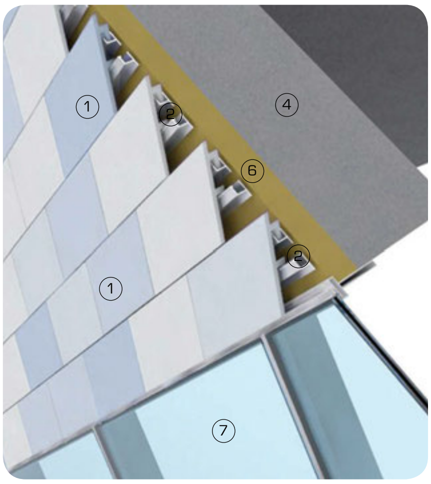
3D internal views showing tiled rainscreen cladding panels fixed to in-situ cast concrete primary structure with inset full-height unitised glazing

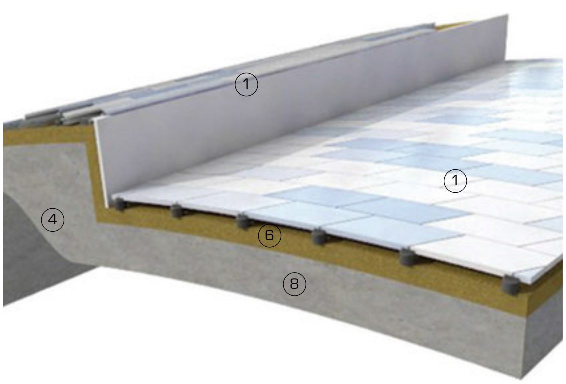


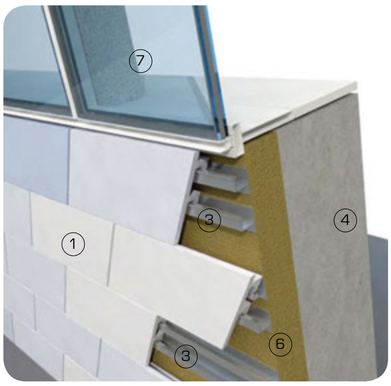
Details
1. Tiled rainscreen cladding panels
2. Rainscreen panel fixing bracket
3. Rainscreen panel fixing rail
4. In-situ cast concrete structural backing wall
5. Primary steel column
6. Thermal insulation
7. Unitised double glazing
8. Concrete floor slab

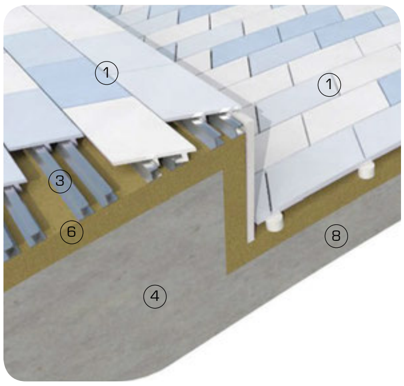


3D view showing tiled rainscreen cladding panels fixed to in-situ cast concrete primary structure with inset full-height unitised glazing

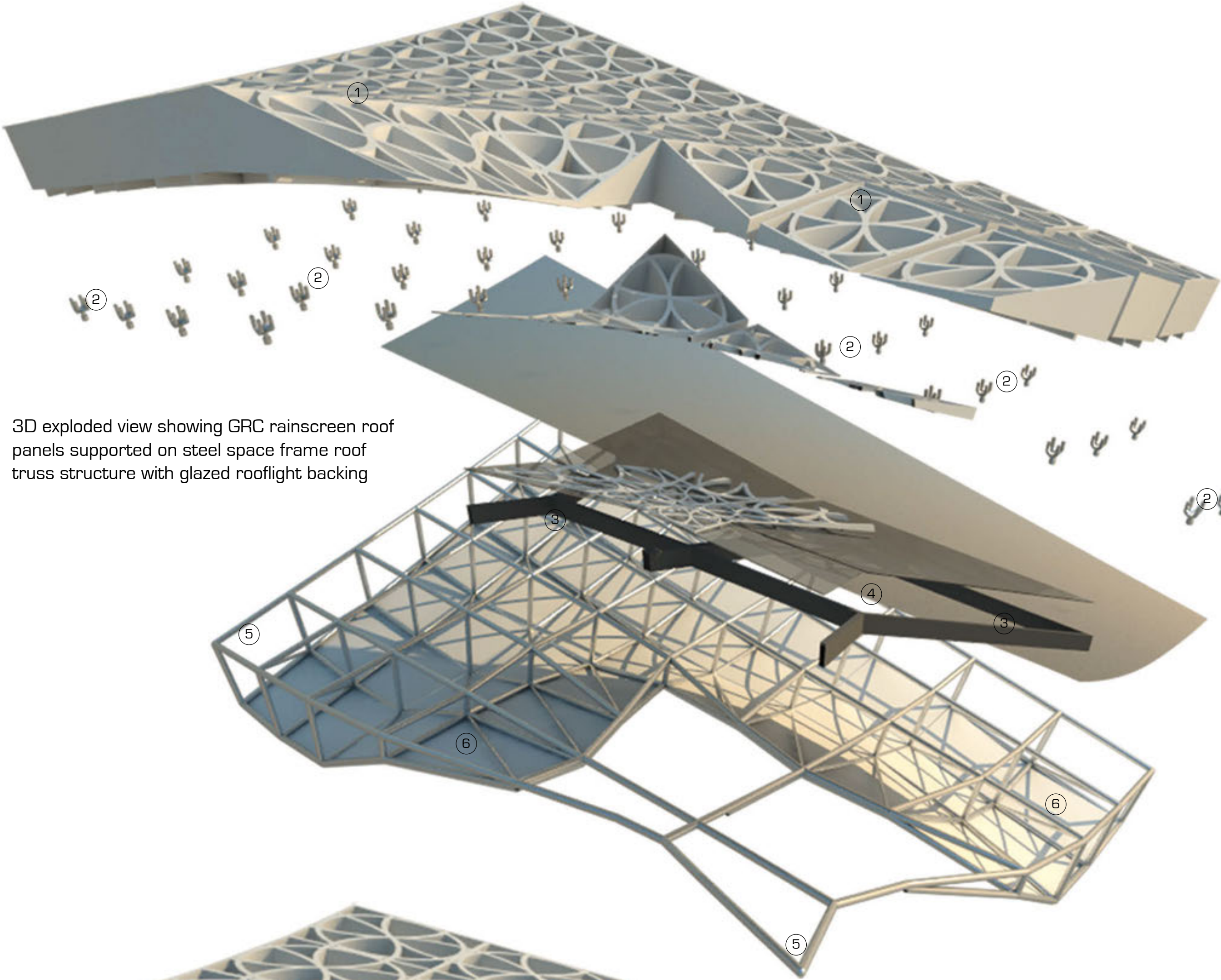




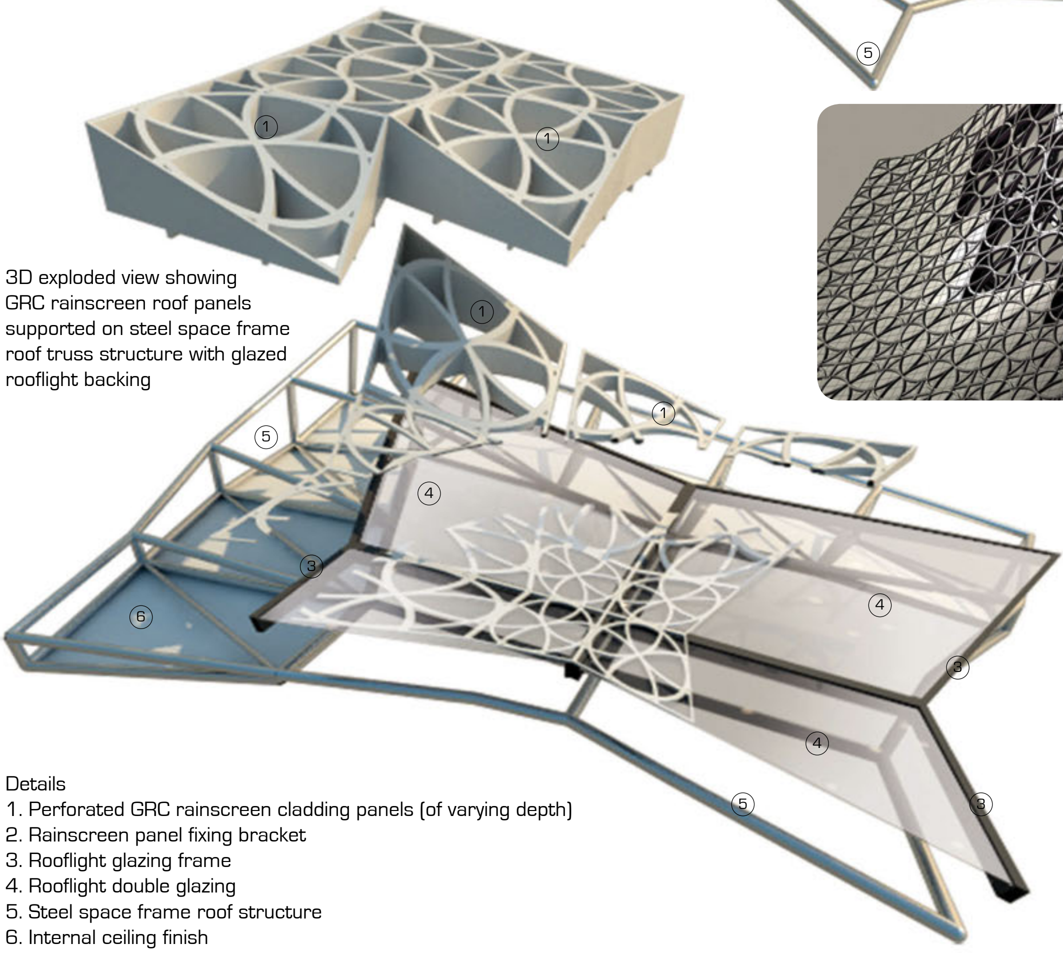




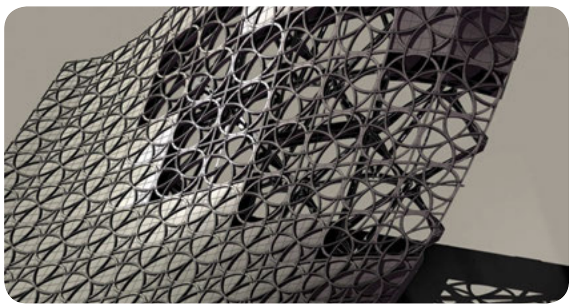
3D detail views showing tiled rainscreen cladding panels fixed to in-situ cast concrete primary structure with inset full-height unitised glazing

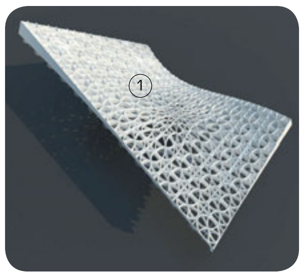


3D exploded view showing GRC rainscreen roof panels supported on steel space frame roof truss structure with glazed rooflight backing



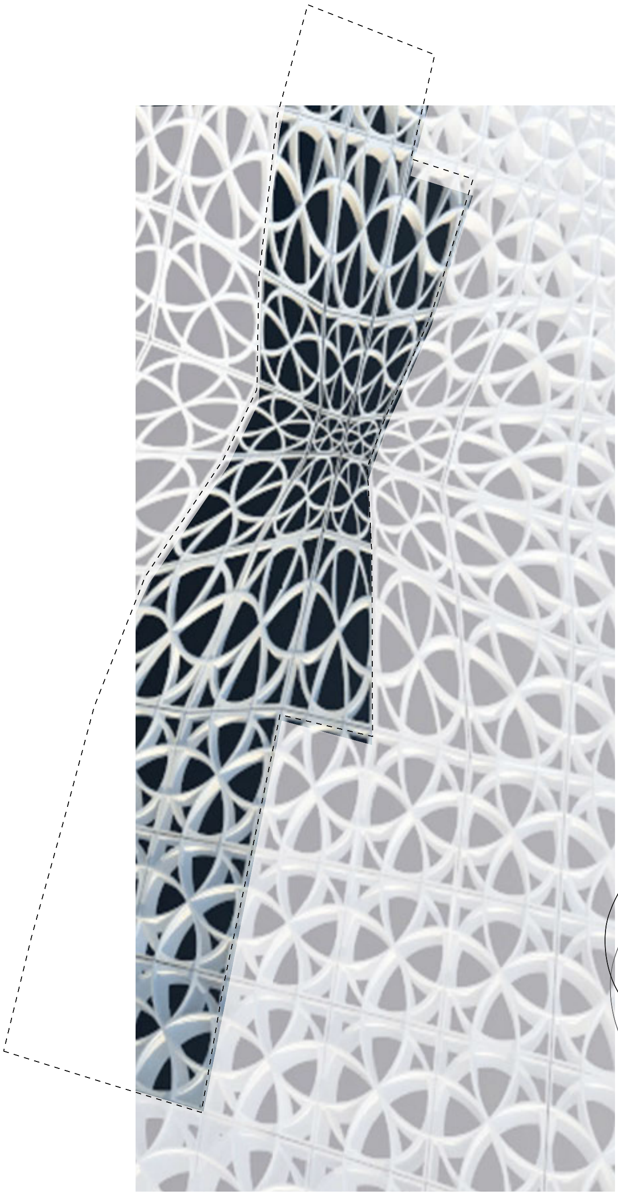
3D exploded view showing GRC rainscreen roof panels supported on steel space frame roof truss structure with glazed rooflight backing



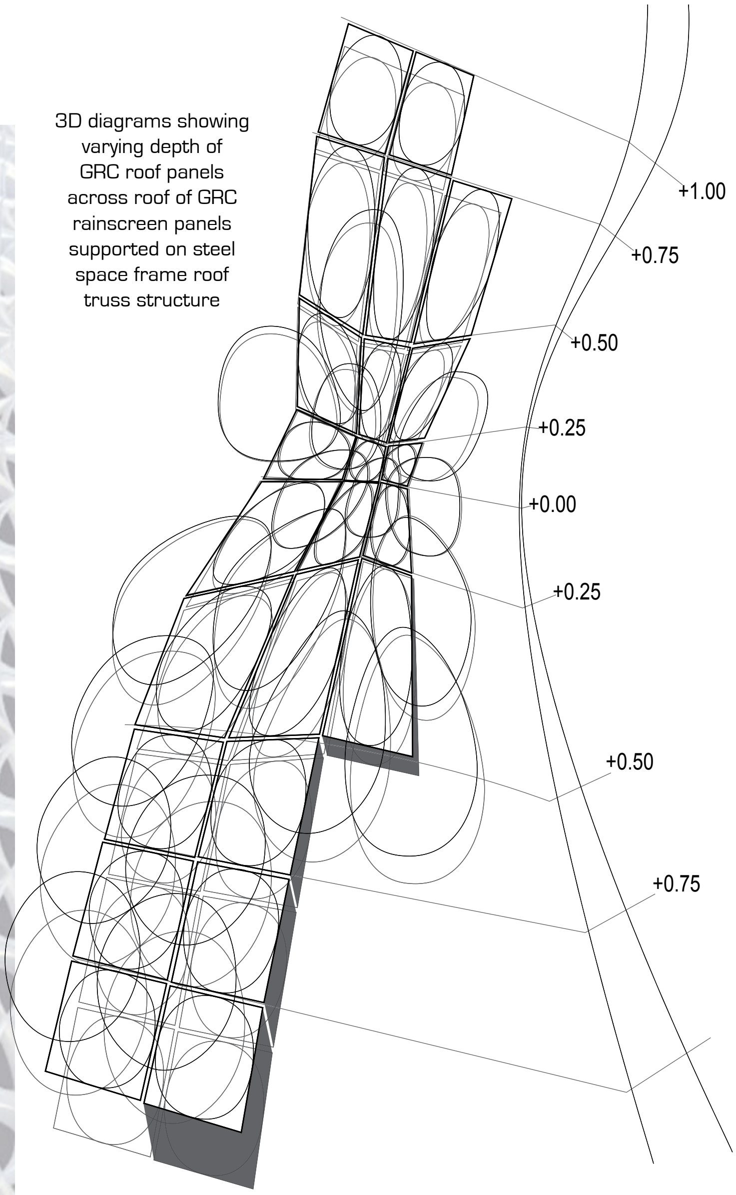


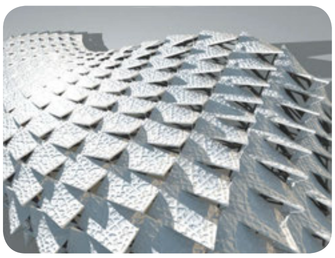
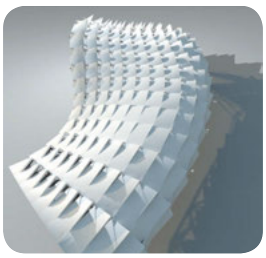
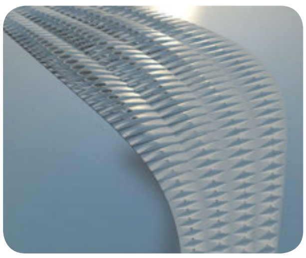
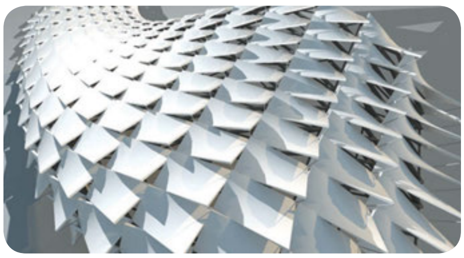
3D views showing GRC rainscreen roof panels supported on steel space frame roof truss structure with glazed rooflight backing

Details
1. Perforated GRC rainscreen cladding panels (of varying depth)
2. Rainscreen panel fixing bracket
3. Rooflight glazing frame
4. Rooflight double glazing
5. Steel space frame roof structure
6. Internal ceiling finish

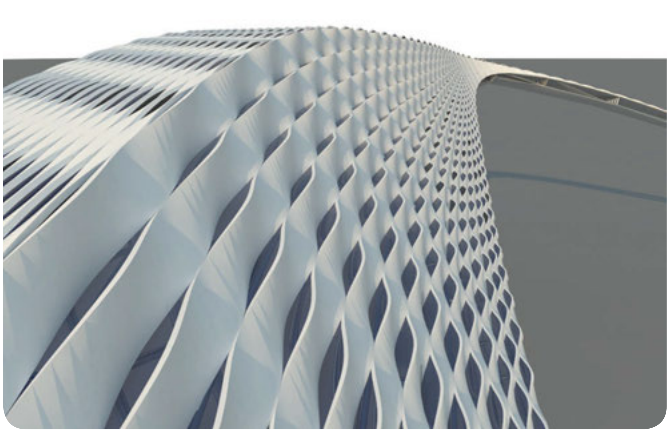
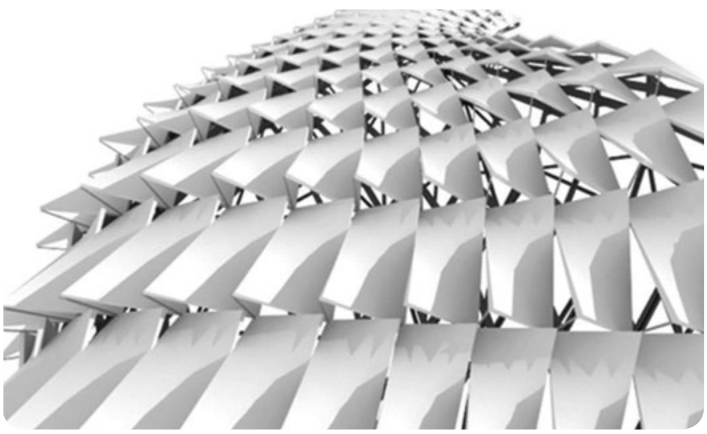


3D diagrams showing varying depth of GRC roof panels across roof of GRC rainscreen panels supported on steel space frame roof truss structure

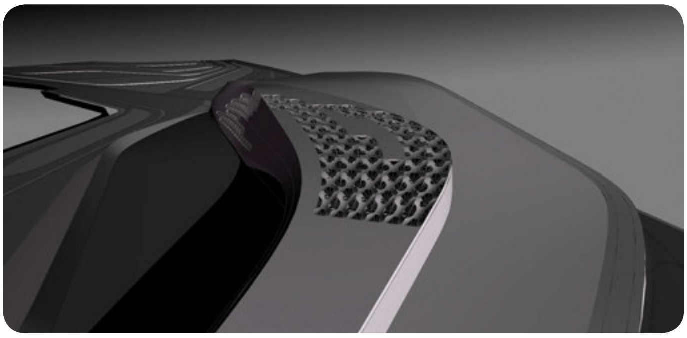


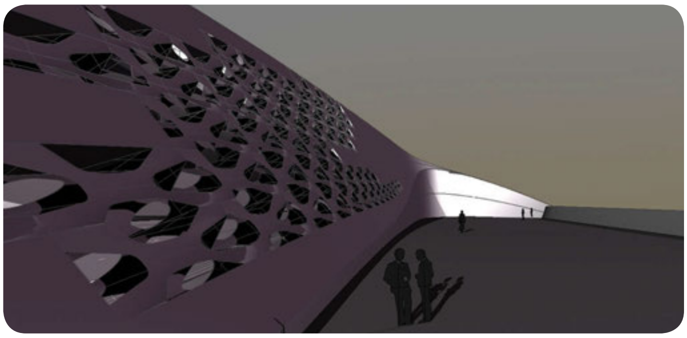





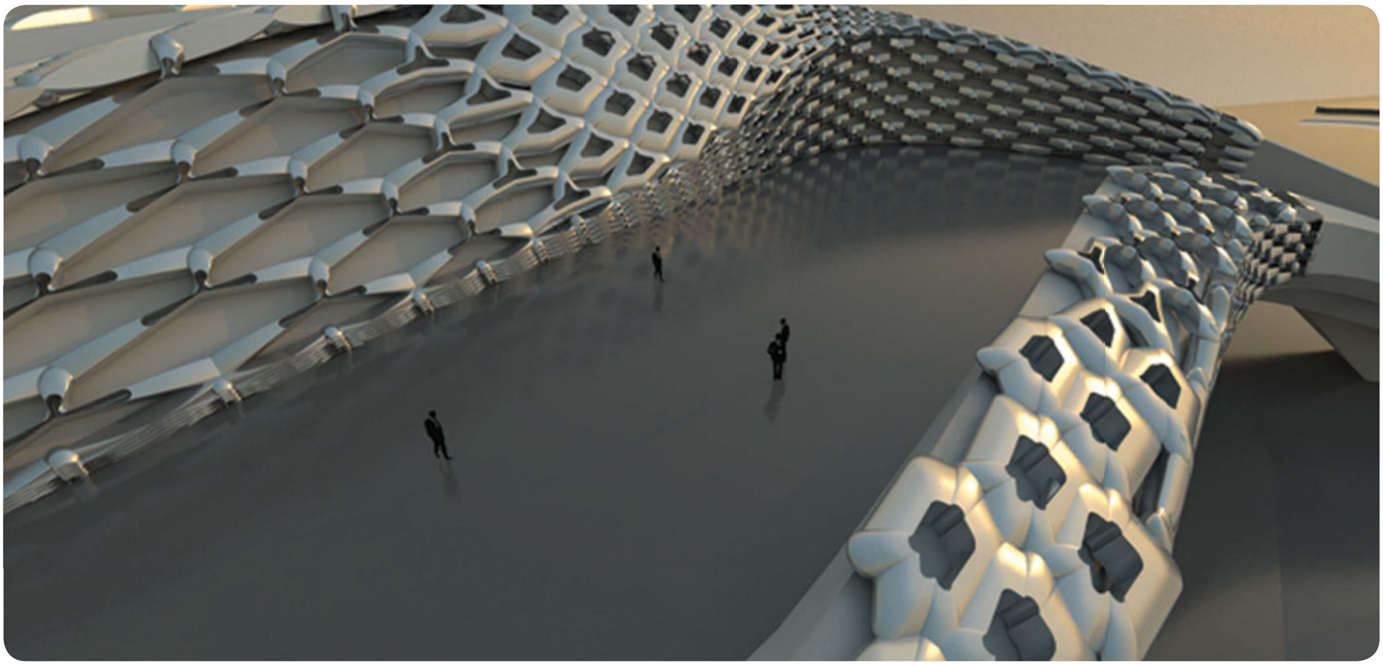
3D views showing GRC rainscreen roof panels in various geometric configurations supported on steel space frame roof truss structure

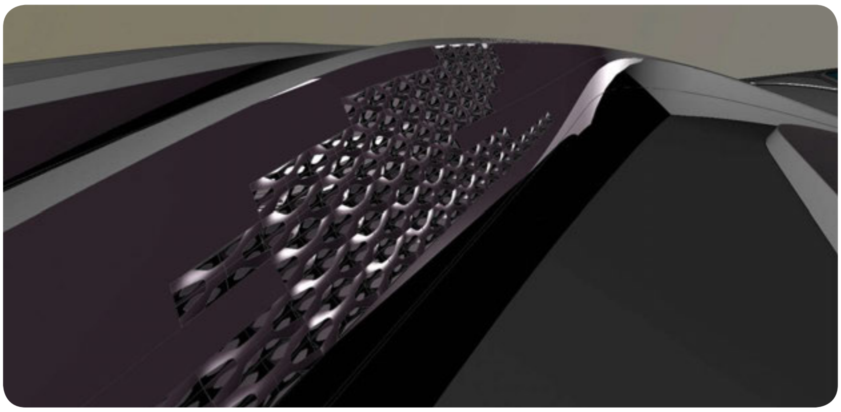
3D views showing GRC rainscreen roof panels in various geometric configurations supported on steel space frame roof truss structure

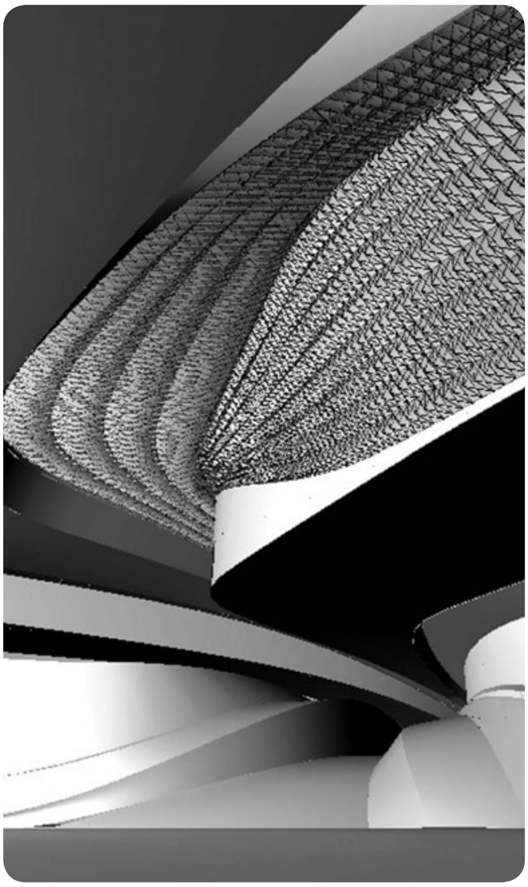


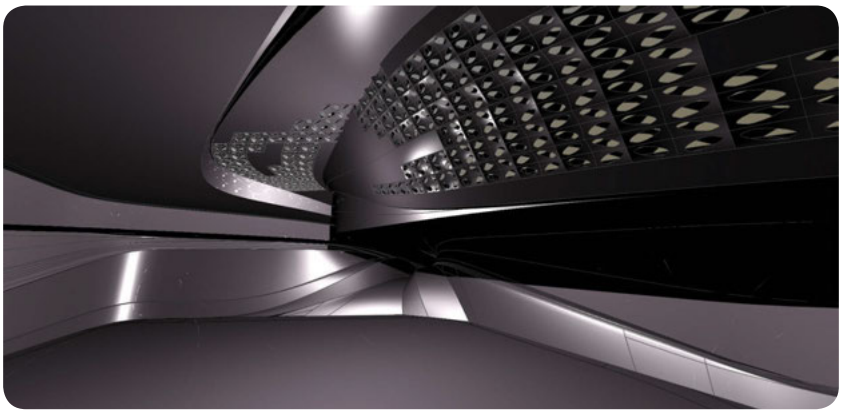


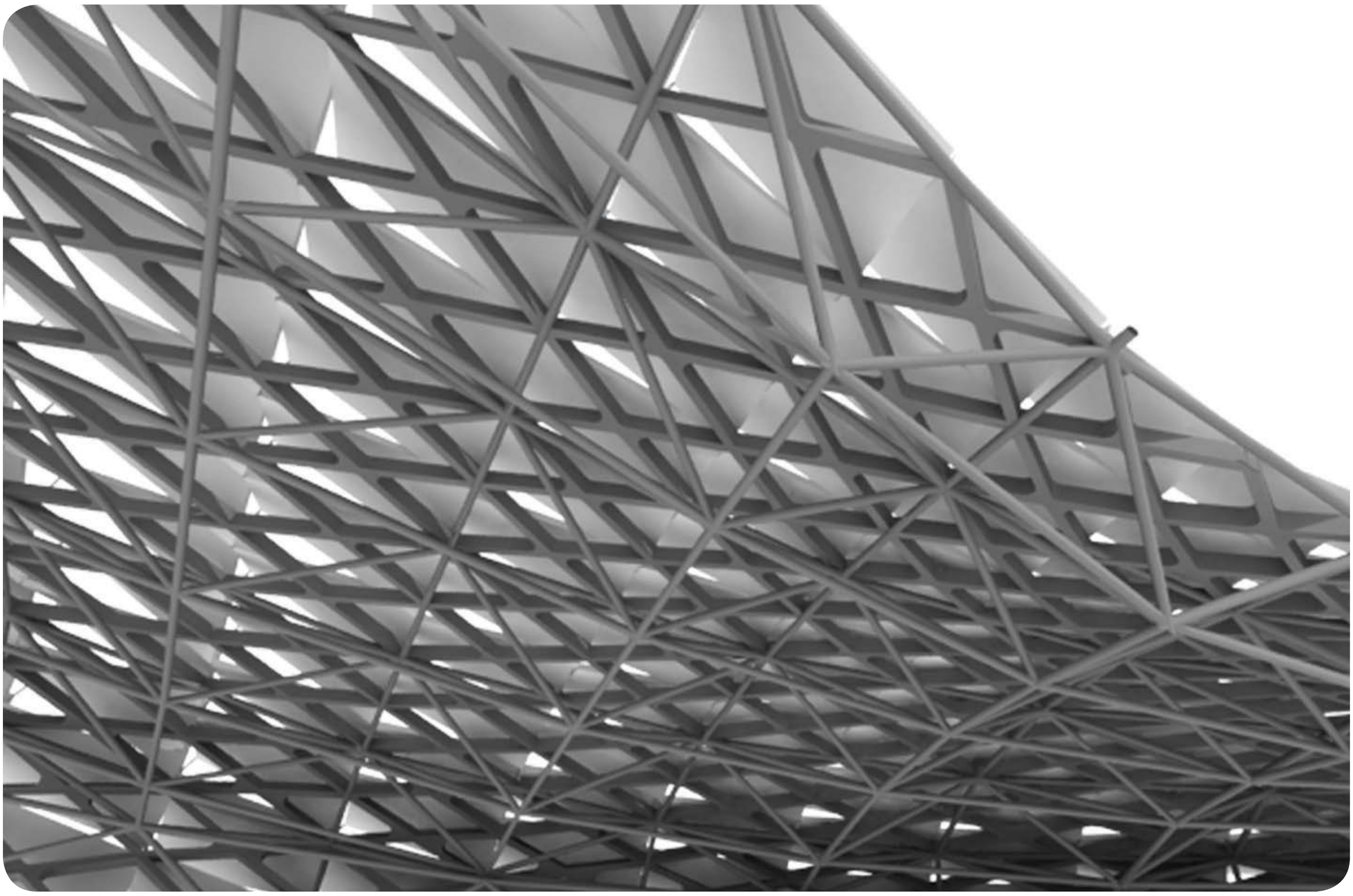


3D views showing GRC rainscreen roof panels in various geometric configurations supported on steel space frame roof truss structure

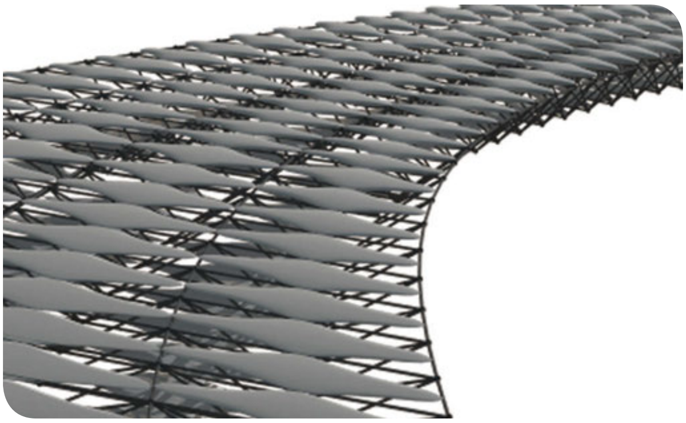


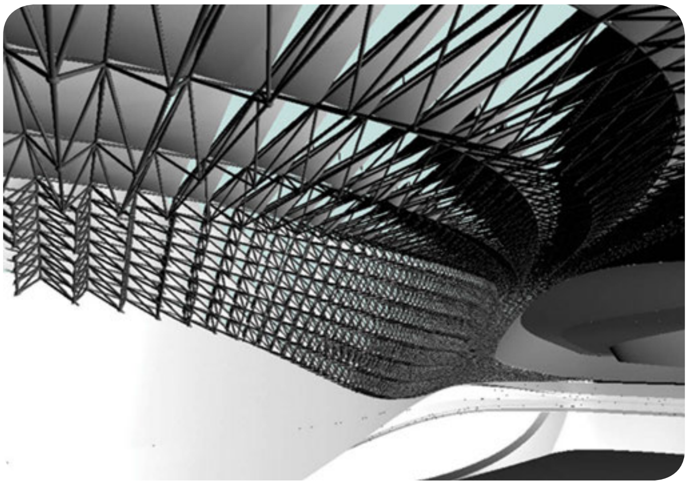


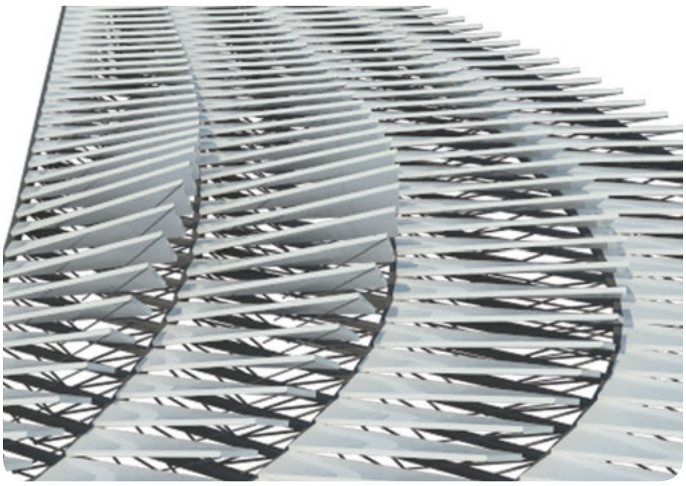


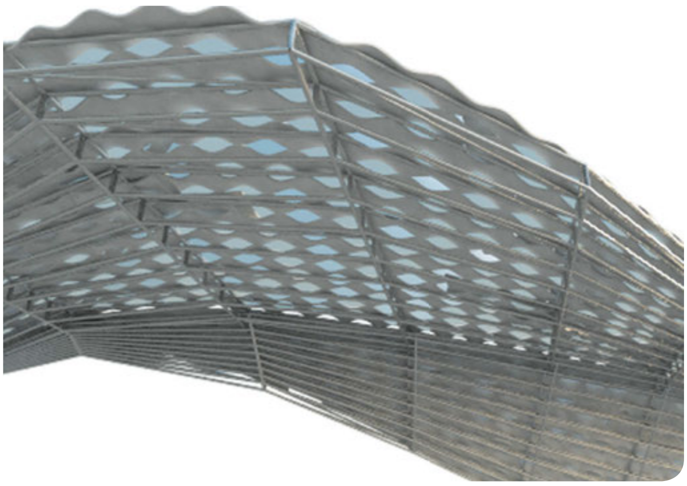


3D views showing GRC rainscreen roof panels in various geometric configurations supported on steel space frame roof truss structure









REFERENCES

The glossary of terms here is aimed to explain words used in the context of this book. These are not intended to be general definitions and should be used accordingly. Topics are arranged in alphabetical order.

BUTT JOINTS. These are a contemporary type of joint where two materials are brought together and sealed with a different material such as silicone, as in an external wall. Traditionally, joints in walls have been formed by some form of lapping or interlocking of materials, as in the corners of window frames. Butt joints have the advantage of allowing movement to occur in the joint, as where adjacent panels are supported separately. An example is the use of silicone sealant between bolt fixed glazed units, where double glazed units move independently and may experience considerable amounts of movement if secured to a structure that allows higher deflections than frames, such as cable net structures. An essential requirement of most butt joints is to ensure that the there is sufficient surface on either side of the joint for the sealant to seal against, allowing it to stretch in several directions without losing adhesion.

CAPPED SYSTEMS. Glazed walls or roofs which are fixed to a continuous framing system on all sides are referred to as being 'edge restrained'. Since most panels in glass or metal, for example, have four sides, these systems are generally called 'four edge restraint' systems, with the panels being held in place by pressure plates. Since the pressure plates have visible screws which are not always aligned neatly, an additional cover cap is set on top of the pressure plate. The cap is made in extruded aluminium and is coated, typically with a colour to match any adjacent metal panels or doors. Such systems are called 'capped systems' to differentiate them from those which have a silicone seal on the outside, such as 'toggle' glazing and 'silicone bonded' glazing, where only a silicone strip is visible from the outside. Sometimes a capped joint is used in one direction on a glazed wall, while a silicone seal is used in the opposite direction.

CAVITY WALL. This form of construction developed from the 1920s onwards in brick construction as an alternative to thicker loadbearing walls, which were both unreliable in their ability to keep out rainwater and vapour as well as being more expensive to construct. The cavity wall divides the wall into two halves, or 'skins'. The outer skin is the weather barrier, and is assumed to become completely soaked during a rain storm. The inner leaf is not in contact with the outer leaf, so it remains generally dry. The two skins are joined together with cavity wall ties, designed to encourage water in the cavity from dripping off the ties and down the cavity rather than being carried onto the face of the adjoining inner skin. The cavity wall has developed by setting thermal insulation either within the cavity, on the outer face of the inner skin, or within the inner leaf itself.

CLADDING. This term refers to non-loadbearing facade systems which are applied to a building envelope in a way which is independent of the building structure. Cladding may even be used to give a completely different expression to the building from that suggested by either the building structure or the organisation of spaces within the building. This independence of cladding from its supporting structure has been exploited by many contemporary architects to create textures and geometries which accept this independence of the technology of the building envelope, and work with the opportunities provided by the non-loadbearing nature of cladding. Since the primary structure of building is set behind the cladding, the external envelope can be configured to give precedence to other design considerations as primary forms of architectural expression, such daylight, solar control and the visual expression of individual spaces within a building without direct reference to the structural frame.

COMPOSITE MATERIALS. These have been developed to mix two or more different materials together in order to benefit from the strengths of each so as to overcome the weaknesses inherent in one or other of the materials. In wood, for example, where a length of timber can span only as long as can be cut from a tree, lengths of timber sections can be increased significantly by gluing strips or particles of timber to make board material. This combination uses the benefits of timber of lightness in weight and ease of working the material with increased size and greater stability to reduce the effects of moisture movement. Reinforced concrete can be regarded as a composite material, with steel reinforcement providing strength in tension which is lacking in regular concrete. GRP, or glass reinforced plastic, is a mixture of resins providing, conceptually at least, compressive strength with glass fibre giving tensile strength.

CURTAIN WALLING. This refers historically to glazed wall systems which were 'hung' in panels or as a metal framework into which glass panels were set. While the concept is clear, these systems are not always hung in the manner of a curtain, and are not always spanning from floor to floor. Contemporary curtain walling is described as being either 'stick' systems, 'unitised' systems, or 'panelised' systems (explained under separate headings). Consequently, the term curtain walling is not referred to in this book as it is too generic, with 'glazed walls' used instead to allow the primary material to take precedence. Curtain walling was developed in the years following 1945, primarily in the United States where it was a practical way of enclosing tall buildings without the need for lifting heavy materials such as stone and brick high up, where they were slow and difficult to manage, making them far less economic in industrialised countries.

DOUBLE SKIN FACADES. These are essentially two skins of external wall which provide a thermal buffer in winter and natural ventilation in summer. The thermal buffer ensures that solar gain in winter months can be used to heat a building, while in summer, windows at high level can be opened into a void between inner and outer skins without experiencing the effects of wind gusts. Double skin facades can vary from 1000mm in width, with two walls separated by a maintenance walkway, to a thickness of 300mm, where the double skin is set within a single wall construction, typically as unitised panels. With the wider version, comprising two walls set apart, the cavity can be ventilated form the outside, either with open joints or with controlled louvres. Thin double skins are ventilated from inside the building, sometimes actually linking the void within the wall to the mechanical ventilation system.

EAVES. These are junctions between the top of an external wall and the underside of a sloping roof, which typically overhangs the wall. Where the external wall is made as a cladding system rather than a traditional loadbearing wall, the relative movements of wall and roof need to be taken into account in the weather tightness of the junction. There is also a need for continuity of thermal insulation from wall to roof, sometimes providing ventilation into the roof space and sometimes providing a complete seal from wall to roof. As an interface between primary elements of a building which are usually performing in quite different ways, using quite different forms of construction, eaves junctions require the lapping of the waterproofing for the roof to form a continuity with that of the wall. As an interface, an eaves detail usually requires one of the systems of wall or roof to take precedence from a visual point of view, so this becomes an additional requirement of their design.

EMBODIED ENERGY. This is the amount of energy required to construct a building or part of a building. No specific standards can be applied at this stage, as an essential component in the energy required to construct a building is the delivery of materials to site, which can vary enormously, but which favour as local a sourcing of materials as possible. In practice this can be difficult to agree on, as it needs to be established how far up the supply chain to go when calculating the energy required to make primary materials for a building. In the case of polymers, for example, the dependence on oil from different parts of the world being transported can create complicated scenarios for calculation. Timber is considered to have zero embodied energy as a material, but the energy used to fell, cut and transport the material is much higher, though not as high as that for the metals used in fixings which allow the timber to be made useful as a building material.

IN-SITU CAST CONCRETE. This method of working with concrete, also called cast-in-place concrete, is based on forming the material on site using formwork that is set up specifically for the casting process, before moved to the next stage of casting. The method can be used to create large scale concrete structures or walls. An important consideration is the formwork, which is used increasingly as a kit of parts that can be moved and re-assembled quickly for the next part of the work. If the concrete is to be a visible part of the construction, as in the case of columns or external walls, the provision of joints and junctions with adjacent elements needs to be considered carefully prior to starting on site. Since the casting of concrete reveals very closely the texture of the formwork from which it is cast, the choice of formwork board size, or tube size for columns, is an essential part of the design of the building, and is considered at an early stage of the design.

LAPPED JOINTS. This is the traditional method of forming junctions between materials in external walls. In order to ensure that water runs off timber boards, for example, the material is ship lapped, where one board is set over the other. More generally, this principle applies in tiled and slated roofs, and in brick walls where openings are formed so as to lap the external wall around window frames. Where render is used on top of masonry walls, the render forms, effectively, a lap between wall and window. Lapped joints are used in contemporary construction where a butt joint is either not appropriate in terms of its exposure or appearance, or alternatively where ventilation is required, as in rainscreen panel systems and roof coverings. An essential aspect of lapped joints is that they are oriented in a direction that ensures rainwater will run off the joint in a downward direction while allowing ventilation to occur in the upward or lateral direction.

MEMBRANES. These are single layer materials made in large sizes, typically 1000m to 2000mm in width and in long lengths, supplied in rolls. They are made primarily from polymers, and have the advantage of being possible to bond or weld together, often by heat rather than by naked flame, making them easy to install on site. Their use is mainly as reliable waterproof or vapour proof layers to large areas of wall or roof which experience relatively little thermal movement. Though reliable, they are relatively fragile unless designed specially for external use, as is the case with thicker, tougher roofing membranes. Mostly, however, membranes are required to be concealed beneath other materials to protect them from the effects of the sun and from suffering accidental damage, such as being walked upon for example. Membranes are usually fixed at points on their underside in order to avoid penetrating the membrane.

OPENINGS. This book shows examples of details around openings as they are often at the interface of different systems, or components from different systems. Windows and doors, for example, do not have obvious ways of being fitted into walls when a very watertight and airtight performance is required. Since facade systems are often developed and tested to quite different standards and with the intention of forming a complete building envelope as a single material system, combinations of two systems are dealt with on a project by project basis. In the case of windows and doors being designed within a single system, such as windows and doors, it is essential in order to understand the visual impact that they make on a facade, as well as how they can be accessed for cleaning and maintenance. Openings are required to be assembled in a particular order if made from different materials or systems, which can influence their appearance, so the sequence of construction is a consideration.

PARAMETRIC DESIGN. This is an approach to the design of a building, or part of a building, based on the idea of setting 'parameters' that can be changed dimensionally, while making other parts of the design 'fixed' which cannot be changed. This principle can be applied to the geometry of a set of floor slabs, for example, which may be allowed to change in one direction only, or be used for a set of components which might be changed. This approach suits geometrically complex or large-scale projects where the time required to rebuild the model would be uneconomic. Because parametric design software allows the design to make changes quickly, it allows the designers to try changes to see what happens to an overall building form, for example. This allows the behaviour of the component or building geometry to be understood, sometimes linking floor areas to a building geometry.

PANELISED SYSTEM. This is a general term covering large scale panels used primarily for external walls. Their use is in prefabricated wall systems where a building is required to be assembled on site quickly, or where the specific site does not make it easy to undertake complicated work; mainly where access is restricted. Where unitised panels in glazed walls are typically around 1500mm wide, panelised systems can be made up to around 7000mm long, depending on their weight, but are typically delivered to site on trailers, so that transportation is an important consideration in their design. These panels may comprise a mixture of systems, such as metal framed backing walls with windows installed, or even precast concrete panels with masonry fixed or forming an integral part of the panel. They are finding use as waterproofed or vapour proofed backing walls which can be installed quickly on site while the outer skin of the wall is applied later. This allows the building to become watertight at an earlier stage of construction.

PARAPETS. These are traditional elements of buildings which still form a prominent part of contemporary design. Parapets are formed when an external wall projects up in front of the base of the roof construction, requiring rainwater to be drained into a gutter behind the external wall rather than in front of it. This makes it essential to draw the rainwater down the pipes which are typically set outside the building rather than inside, where they can be difficult to access for maintenance and can be susceptible to damage, causing leaks. Parapets are detailed so as to form a gutter between wall and roof that can fill to capacity without the risk of leaking back into the building. Since parapet gutters can become blocked as a result of the outlet being accidentally covered, the design of these junctions, as well as the provision of overflows to the outside, are essential considerations in their design. The coping, or durable covering set on top of the parapet, has some visual presence on the facade and can be seen as a termination of the top of the building.

POINT FIXED GLAZING. This is a recent development that originated with clamped glazing systems of the 1960s, used mainly as shop front glazing at that time. The technique comprises either bolt-like fixings set near the corners of the glass, or clamps set on both sides of the glass along the edges of the glass, but not necessarily at their corners. An essential part of their design is to ensure that the glass is supported so that it can move in order to avoid putting additional stress into the glass. These systems are typically designed in conjunction with a manufacturer or facade designer who can ensure that the design is suitable both in relation to its supporting structure and for fabrication. Clamped glazing has become more popular in recent years since it is more economic than the bolt fixed method, as clamps can be set between the joints rather than requiring glazed units to be drilled to accommodate the bolt fixing.

PRECAST CONCRETE. This material is an alternative to in-situ cast (or cast-in-place) concrete. An essential aspect of precast concrete is that it can be used for structures, facades, roofs and interior building components, making the understanding of how the material is used an essential aspect of designing with the material. Because of the weight of concrete and the high amount of material required for its use in construction, its use as prefabricated components requires careful consideration, particularly in expected tolerances in its assembly, which can require wider gaps than those required in other materials. Although precast concrete is used for staircases, for example, these components are often covered up by finished work and so are not revealed. Consequently, the choice of precast concrete over in-situ cast concrete may not be of primary interest to the designer in such applications. Where the use of precast concrete will be of concern is where the material is visible, requiring careful attention to finish; mainly in terms of colour consistency and texture; as well as how the formwork will leave traces of the pouring method that may, or may not be required in the finished work.

PREFABRICATION AND SITE-BASED WORK. The choice between buildings constructed mainly on-site or off-site in a workshop or factory is based on issues primarily of cost and quality, though it has also to do with increased specialisation in construction. Projects of ambition often require specialist construction skills to undertake the construction. Such specialists are usually set up with their own working environment rather than being based on a succession of building sites. While prefabricated elements and systems are required to be assembled or set into position on site, this environment is too temporary for many specialists, who require a specific planned work environment for them to be effective both as an organisation and in order to produce work of high quality. Quantities of what can be transported to site are usually limited by the capacity and weight allowance of a trailer as well as storage facilities on site. However, some building work is more effectively undertaken on site, using the site as a workshop and storage facility for components. Structural frames and floor slabs in large scale construction are still mostly site-based, though the amount of prefabrication is increasing.

RAINSCREENS. These are facade and roof panel systems which allow small amounts of rainwater to enter the joints between panels and be drained down through the framing back to the outside, either at each floor level or at the lowest level of the system. The term was first used for curtain walling, where leaks in earlier forms of curtain walling were overcome not by attempting to exclude any water penetration, but by accepting that it is easier to ensure the water drains away safely when it penetrates joints. The term, in general use, is applied more to open joints in panel systems, typically metal, timber and, terracotta than to glazed curtain walls. When used in this context panels in these materials are generally fixed to a framing system which is secured to the building structure. A separate backing wall is typically used to provide thermal insulation and a waterproof layer. Rainscreen panels have grown in use as a visually refined finish to economic backing walls.

STICK SYSTEM. This is a method of constructing glazed walls on site from framing and glazed units. Stick glazing is often used in complex arrangements of curtain walling and for smaller projects. Larger projects such as apartment buildings often have many different conditions in their design on the external envelope, which would require many types of unitised panel both uneconomic and difficult to install. Smaller projects do not have a sufficiently large envelope to make unitising panels economic and are usually stick built regardless of their level of complexity. The advantages for designers are mainly the flexibility of design, which does not need to be made modular to suit repeated panels, and the narrower size of joint widths, which is usually 50mm to 70mm depending on project requirements. Stick systems can also be combined effectively with supporting steel frames such as those for atrium structures and double skin facades. Where steel frames are used, the aluminium extruded box section on the internal side of the framing can be omitted, allowing the front part of the stick system to be fixed directly to the supporting steelwork, which would typically also be in box sections.

THERMAL BRIDGING. This is also called ‘cold bridging’ but can occur in hot thermal conditions as well as cold conditions. Essentially, the design of different systems of wall and roof construction is gradually being developed to reduce thermal transmission through the build-up. Some parts of the system can perform considerably worse than others, creating a ‘bridge’ for the passage of heat or cold which is prevented elsewhere in the system. In glazed walling, for example, the thermal performance of the framing is significantly less than that of the glazed panels, and is improved by using a ‘thermal break’ so that the high thermal transmission of the frame is ‘broken’ with a polymer based component set between inside and outside. The thermal break may be a separating strip or may form an integral part of the construction, as is the case with aluminium framing to glazed walls.

U-VALUE AND THERMAL INSULATION. The U-value of a construction is a measure of the thermal transmission through the material, with systems of lower U-value having higher levels of thermal insulation. The U-value takes into account the thermal transmission of all the layers of construction that make up the wall, so walls of different build-up in section require separate U-value calculations. U-values can be used in calculating the rate of heat flow of spaces in the building, but are separate from the effects of solar gain through glazing, which may also cause thermal transmission. Consequently, double glazed units have a Low-E coating and vacuum in the cavity to provide thermal insulation, while a separate solar control coating provides protection against the effects of solar gain.

UNITISED SYSTEM. This is a prefabricated method of making facade panels, typically for glazed walls. Its advantage is primarily one of reduced cost for facades with considerable repetition resulting in few panel types; but another advantage is the use of silicone bonding, allowing frames to appear slim on the outside, and for opening lights to have their frames concealed internally. Applying silicone on site in stick systems can be very difficult to achieve due to the time needed, as well as the avoidance of dust around the edges of the bonds.

This book has been a team effort involving members of Newtecnic in London. Drawings were modelled and rendered by the Newtecnic team: Julianne Cassidy, Michael Clarke, Tom Donald, George Hintzen, Fabio Micoli, Rob Percy, Mandeep Singh, Alejandro Vicente Soto, Howard Tee, Andy Watts and Adam Willetts. The book was designed by Julianne Cassidy and Yasmin Watts. The text is by Andrew Watts, with contributions from Michael Clarke, who wrote the following texts for the environment chapter: Environmental Studies for envelopes, Analysis for Design 1-8, Green walls.

David Marold is Senior Editor for Architecture, Art and Culture at AMBRA | V Publishers in Vienna. He has driven this book from a set of basic layouts to a completed book. He has a passion for books and their design, ranging from their wider content to the quality of print paper.

Newtecnic is a firm of London-based facade designers who create facades in collaboration with leading architects. The firm practices internationally on architecturally and technically challenging projects and has a particular interest in developing new facade systems and the use of complex geometries. Newtecnic follows principles of rapid prototyping as a method of developing facade systems that can be manufactured quickly and with a high degree of accuracy and precision. The office's current work ranges from large scale developments in Moscow, Dubai, Kuwait City, St Petersburg, Baku, Cairo and Rabat to educational projects in London, where Newtecnic are working with design teams to develop innovative technical solutions and optimise complex designs for digital fabrication.

Before establishing their own practice specialising in facades, Newtecnic principals Andrew and Yasmin Watts worked extensively both in the U.K. and abroad. During this time they were involved in a range of significant projects including Federation Square, Melbourne with LAB Architects, the Millennium Bridge, London for Foster and Partners, Euralille and Institut du Monde Arabe, Paris for Ateliers Jean Nouvel, and Cite Internationale, Lyon and the New Caladonia Cultural Centre for Renzo Piano Building Workshop. They have produced a number of volumes on contemporary building technology which provide reference material for students and professionals. The *Modern Construction Series* is published by AMBRA | V Publishers. In addition, the *Facades Technical Review*, from RIBA Publications was published in spring 2007.

Much of Newtecnic's work is informed by a specific response to climate and to the technical performance of the external envelope. In projects where climate control and natural ventilation are primary design criteria for the facades in temperate climates, double skin facades are often used. Rather than follow rectilinear design, the outer skin of the facades of projects where Newtecnic are involved are increasingly required to be shaped geometrically in response to specific environmental issues. These resulting facade forms are typically twisted, curved, tapered, or a combination of these forms. These pages aim to illustrate some of the research undertaken by Newtecnic in recent projects which exhibit these tendencies in terms of possible solutions for the design of the cladding in both temperate and hot climates.

The Newtecnic team investigates material systems that are explored through 3-D modelling rather than 2-D drafting. The engineering aspects of the design, both structural and environmental, are developed through an investigation of the behaviour of construction systems when modifed geometrically. Rather than develop a series of options to solve a design, a single parametric model is used with fixed criteria and criteria which can be stretched and pulled until an optimum solution is found. This allows a single design model to provide a 'range' of solutions which can be explored through rapid prototype models, using a range of modelling tools from 3-D printers to laser cutters. Strands of fabrication, context, site specificity, language of the base 'component' of the design and spatial organisation are developed in parallel for each project.

Images are credited per page, left to right, and from top to bottom:

P10 first left. Photo: Adrian Pingstone from Wikipedia.
P20 second from left. Photo: Michael Reeve from Wikipedia.
P21 bottom second from left. Photo: Julian Nitzsche from Wikipedia.
P21 second from left: Photo: Adrian Pingstone from Wikipedia.
P28 Photo: Aedas
P38 second from left. Photo: Finlay McWalter from Wikipedia.
P38 third from left. Photo: Enrique Cornejo from Wikipedia.
P40 first left. Photo: Lucas B. Salles from Wikipedia.
P40 third and fourth from left: Photo: Yoshito Isono from Structurae.
P44 bottom second from left. Photo: Adrian Pingstone from Wikipedia.
P45 top third from left. Photo: Adrian Pingstone from Wikipedia.
P46 top second from left. Photo: Chris McKenna from Wikipedia.
P47 top second from left. Photo: Olaf Davis from Wikipedia.
P50 top second from left. Photo: Raúl Polanco Montiel from Wikipedia.
P51 first from left. Photo: Walter Horvath from Wikipedia.
P54 top first from left. Photo: Marion Schneider & Christoph Aistleitner from Wikipedia.
P56 top second from left. Photo: Richard Bartz from Wikipedia.
P62 third from left. Photo: Parliamentary copyright images are reproduced with the permission of Parliament.
P62 fourth from left. Photo: Parliamentary copyright images are reproduced with the permission of Parliament.
P63 Photos: Don Evans
P65 Photo: Architen Landrell Associates Ltd
P84 Jewish Museum, Berlin, Germany.
Photo: Studio Daniel Libeskind.
P84 Usera Public Library, Madrid. Photo: Roland Halbe.
P85 Sun Tower Office Building, Seoul.
Photo: Youngill Kim.
P87 Matsunoyama Natural Science Museum, Japan.
Photo: Katsuhisa Kida
P205 top second from left. Canopies.
Photo: Architen Landrel Associates Ltd.
P205 bottom second from left. ETFE images.
Photo: Vector Foiltec Ltd.
P289 Lerner Hall Student Center,
Columbia University, New York, U.S.A. Photo: Lydia Gould.
P290 Museum of Contemporary Art, Los Angeles, U.S.A.
Photo: Yasuhiro Ishimoto.
P291 Jewish Museum, Berlin, Germany.
Photo: Studio Daniel Libeskind.
P393 Strawbale classroom at Avon Tyrrell, New Forest, England, U.K.
Photo: New Forest Park Authority.
P394 top second, third and fourth from left. The Redding Residence, Kendle Design Collaborative, Scottsdale, Arizona Community, U.S.A.
Photo: www.eartharchitecture.org
P400 Government Training Centre, Herne-Sodingen, Germany.
Photo: Christian Richters.
P401 Daggett Solar Farm, California, U.S.A.
Photo: G. Donald Bain, Geo-Images Project, University of California at Berkeley, U.S.A.
P401 Solarchis Solar Houses, Japan.
Architecture Studio and Maeta Concrete.
Photo: Solar.
P402 Kitakame Canal Museum, Japan.
Photo: Kengo Kuma and Associates.
P402 Furniture House, Yamanashi Prefecture, Japan.
Photo: Hiroyuki Hirai.
P403 International Housing Exhibition, Fukuoka, Japan.
Photo: Kwano, courtesy of the Office for Metropolitan Architecture.
P403 Freshwater Pavilion, Neeltje Jans, Holland.
Photo: Lars Spuybroek, NOX Architects.
P404. Offices, DaimlerChrysler Projekt, Potsdamer Platz, Berlin, Germany.
Photos: Robert Peebles.
P408, 410. Photos: Robert Peebles.

All other photographs have been provided by courtesy of Newtecnic Ltd.

Author
Andrew Watts
London, England

AMBRA | V is part of Medecco Holding GmbH, Vienna
Printed in Austria

Layout and Cover Design: Yasmin Watts, London, England
Cover photo: Newtecnic Ltd
Proofreading: Andrea Lyman and Alun Brown, Vienna, Austria
Printing and binding: Holzhausen Druck GmbH, Vienna, Austria

Printed on acid-free and chlorine-free bleached paper

With numerous coloured figures

1st Edition 2001: SpringerWienNewYork
2nd Edition 2010: SpringerWienNewYork

ISBN 978-3-99043-454-3 AMBRA | V