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Hygrothermal Risk on Building Heritage

A Methodology for a Risk Map

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Preface

The international heritage building is of great importance, justifying the need to safeguard it from extreme climatic phenomena such as floods and moisture degradation. For historical reasons, the most prestigious buildings were built near the natural water lines and are possibly threatened by the flood phenomenon.

Climate changes due to global warming have revealed an increasing vulnerability of urban and rural territories to the risk of flooding. It is therefore necessary to adopt preventive measures to control, minimise and mitigate these adverse effects, avoiding catastrophic consequences.

The subject of this book is to present a critical review of a criterion of risk, created to assess the flood risk of the international heritage building. In order to evaluate this criterion, it was applied to a sample of Portuguese building heritage. In a first approach, only a reduced number of parameters were adopted and grouped in two different groups of parameters: the monument location in relation to a waterway, and the behaviour of its construction material when in contact with water.

The main benefit of the book is that it discusses the importance of architectural heritage and justifies the need to safeguard it from extreme climatic phenomena such as floods. The book alert, one more time, the scientific community that the intensification of the global warming, climate change will worsen throughout the twenty-first century. It is therefore necessary to adopt preventive measures to minimise, mitigate and control these adverse effects, avoiding catastrophic consequences.

At the same time, this book will be going to the encounter of a variety of scientific and engineering disciplines, such as civil and architecture. The book is divided into several chapters that intend to be a synthesis of the current state of knowledge for benefit of professional colleagues.

The authors would acknowledge with gratitude the support received from the University of Porto-Faculty of Engineering, Portugal, namely the Laboratory of Building Physics (LFC). Finally, the authors would welcome reader comments, corrections and suggestions with the aim of improving any future editions.

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Contents

Nomenclature

A	Water absorption coefficient (–)
C_a'	Water vapour concentration in the air (kg/m^3)
C_s'	Water vapour concentration at the surface (kg/m^3)
D_w	Capillary transport coefficient (m^2/s)
D_ϕ	Liquid conduction coefficient (kg/ms)
$\mathrm{D_{WL}}$	Horizontal distance (m)
FR	Flood risk (–)
g	Flow density (kg/(m^{2}s)
MBV	Moisture Buffer Value (–)
n	Parameter of Eq. (2.5) (–)
Ob	Existence of obstacles (–)
P	Pressure (N/m^2 or Pa)
P_{air}	Air pressure (N/m^2 or Pa)
P_c	Capillary pressure (N/m^2 or Pa)
P_e	External pressure (N/m^2 or Pa)
P_i	Internal pressure (N/m^2 or Pa)
P_s	Saturation pressure (N/m^2 or Pa)
P_{water}	Water pressure (N/m^2 or Pa)
Q	Discharge (–)
RMS	Root mean square (%)
R_1, R_2	Radii of curvature (m)
$\mathrm{R_{si}}$	Indoor superficial resistance (m^2 · °C/W)
RH	Relative humidity (%)
s	Surface tension (N/m)
t	Time (s)
T	Temperature (K)
U	Thermal transmittance coefficient (W/m^2 · ºC)
u	Equilibrium moisture content (kg/kg)
$\mathrm{U_F}$	Existence of underground floors (–)
X_1	Parameter of Eq. (2.5) (–)

w	Water content (kg/m^3)
$w_{80\ \%}$	Water content at 80 % of relative humidity (kg/m^3)
w_f	Free water saturation (kg/m^3)
W_L	Waterway type (–)
Z_p	Diffusion resistance (–)
β	Surface moisture transfer coefficient (m/s)
ρ	Density (kg/m^3)
ϕ	Relative humidity (–)
λ_T	Thermal conductivity (W/mK)
μ	Vapour diffusion resistance factor (–)
δ_p	Vapor permeability (kg/msPa)
ΔL_H	Hydric Expansion (–)
θ	Temperature (°C)
θ_i	Indoor temperature (°C)
θ_e	Outdoor temperature (°C)
θ_h	humidification angle (°)
θ_{si}	Indoor superficial temperature (°C)

Chapter 1
Introduction

1.1 Motivation

Architectural heritage is of great importance therefore justifying the need to safeguard it from extreme climatic phenomena such as floods (see Fig. 1.1). The most prestigious buildings, for historical reasons, were built near the natural water ways and are frequently threatened by this flood phenomenon. Currently there is a majority trend in thinking within the scientific community which hold the view that climate change due to the intensification of the global warming, will worsen throughout the 21st century, thus causing an increase in extreme climatic phenomena (see, for example the Human Development Report 2007/2008 of the UNDP which is entitled precisely "climate change combat", articles about the causes and possible consequences). It is therefore necessary to adopt preventive measures to minimize, mitigate and control these adverse effects, avoiding catastrophic consequences.

This context of climate change has revealed an increasing vulnerability of urban and rural territories to the risk of flooding; this is one of the largest risks growing in frequency and intensity we can expect in the coming decades.

Intervening in old buildings requires extensive and objective knowledge. The multifaceted aspects of the work carried out on these buildings tend to encompass a growing number of specialities, with marked emphasis on those allowing to understand the causes of the problems that affect them and to define appropriate treatments (Freitas et al. 2007).

In this work the location study will be accomplished by making a synthesis document of the main information about the most important Portuguese historical buildings location (north of Portugal), constitution, etc.

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Fig. 1.1 Hygrothermal risk on building heritage (Freitas et al. 2007)

This effort will start with the definition of the most important historical buildings in Portugal, its location and a full study about its constitution considering not only the materials they are made to but also the layers and the influence of the porosity/porometry for the drying process. Then it will also crucial the classification of the flood risk occurrence having in mind the previous information. A mapping will be made with the classification here developed.

1.2 Moisture Transfer Fundaments

1.2.1 Introduction

The mechanisms that determine the moisture transport in building elements are very complex. Diffusion and convection motions affect the transport in the vapour phase, while in the liquid phase, capillary action, gravity and the pressure gradient effect control the moisture transfer (CSTC 1982; de Freitas 1992).

In practice, moisture transport occurs in the liquid and vapour phases simultaneously, being dependent of several parameters such as temperature, relative humidity, precipitation, solar radiation, wind effect, atmospheric pressure (which define the boundary conditions) and the characteristics of building materials used.

From the physical point of view it is generally accepted that there are three fundamental mechanisms for setting the relative humidity: hygroscopicity, condensation and capillary. These three mechanisms can explain, in most cases, the variation of the moisture content inside the building materials with a complex porous structure.

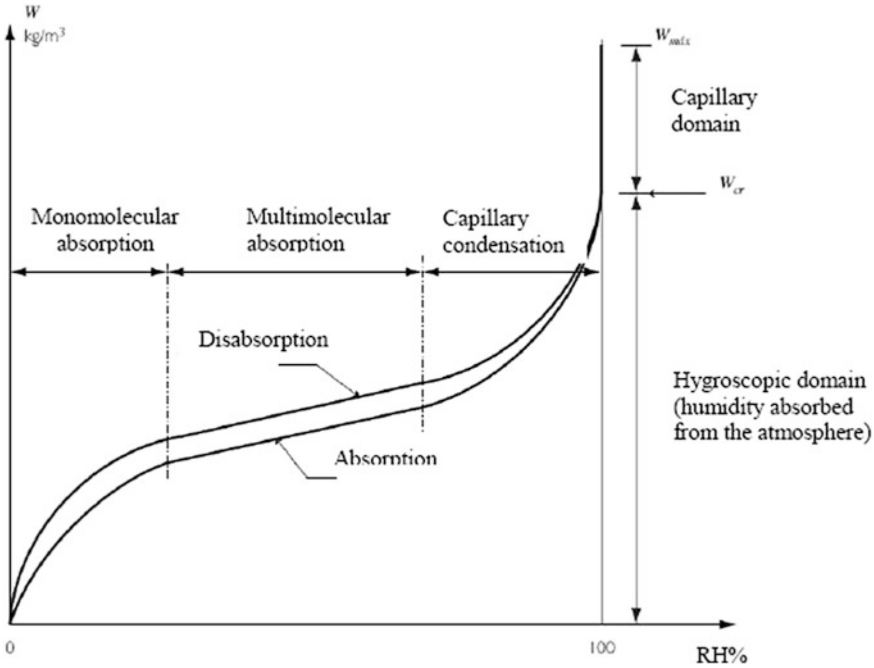


Fig. 1.2 Hygroscopic behaviour of building materials with relation to relative humidity

1.2.2 Hygroscopicity

The materials currently used in civil engineering are hygroscopic; this means that, when they are placed in an atmosphere where the relative humidity varies, their moisture content will also vary. The phenomenon, represented graphically in (see Fig. 1.2), is attributed to the action of intermolecular forces that act upon the fluid-solid interface inside the pores. The transfer of moisture between the wall surface and the atmosphere is also conditioned by hygroscopicity. This will be discussed further in Sect. 2.4.

1.2.3 Capillarity

Capillarity occurs when a porous material comes into contact with water in its liquid phase. The humidification of the material by capillary action is illustrated in (see Fig. 1.3).

This phenomenon results from the particular humidification properties of solid matrix, leading to the formation of curved interfaces between the fluid (water) and the air contained inside the pores. At the liquid-gas interface, a pressure gradient is

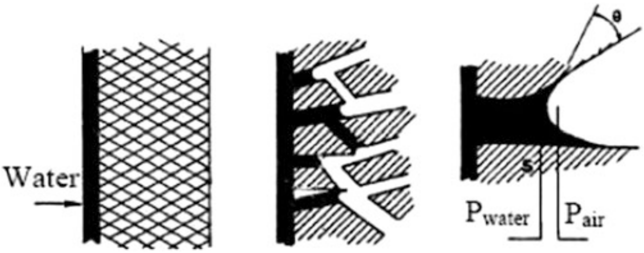


Fig. 1.3 Capillary action

established designated by capillary pressure, which is a function of interfacial tension s, the radii of the main curvature R and the humidification angle θ_h (1.1):

$$P_c = P_{air} - P_{water} = \sigma\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\cos\theta_h \quad [\mathrm{N/m^2}] \tag{1.1}$$

where

P_c is the capillary pressure (N/m^2 or Pa)
P_{air} is the air pressure (N/m^2 or Pa)
P_{water} is the water pressure (N/m^2 or Pa)
θ_h is the humidification angle (°)
s is the surface tension (N/m)
R_1, R_2 is the Radii of curvature (m)

Capillary pressure is a function of the temperature and moisture content, as s varies with temperature and R with the moisture content. The development of the capillary pressure curve (suction) depends upon the law of distribution, the radius of the pores and their variation. The higher the moisture content, the lower the suction, which is annulled when the moisture rate is equal to the maximum moisture content (see Fig. 1.4) (see de Freitas 1992).

1.2.4 Condensations

Condensations can occur at the building element surface being detectable by direct observation or inside the element usually in some interface between different layers—internal condensations. The internal condensations are sometimes dangerous being not detectable by observation.

Internal condensations can be identified according to Glaser proposed theory. In the vapour diffusion theory, whatever the point inside of the building element, vapour pressure, P, must necessarily be less than or equal to the saturation pressure, Ps.

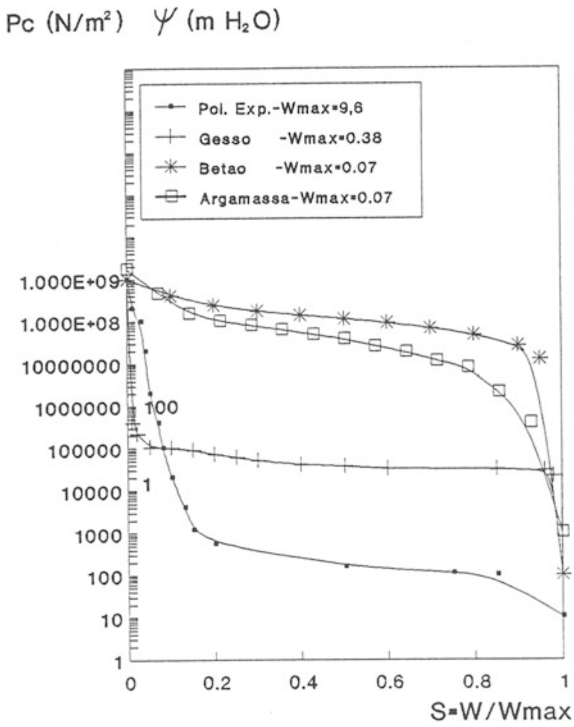


Fig. 1.4 Capillary pressure curve (de Freitas 1992)

When the pressure is equal to the saturation pressure condensation occurs, i.e. the transport that was made in the vapour phase creates the appearance of a liquid phase.

Known temperature distribution curve within a building element it may be determined through the psychometric diagrams (see Fig. 1.6), the saturation curve of pressure (see Fig. 1.5). If this curve has coincident points with the pressure curve the result will be the occurrence of internal condensations (see Berthier 1980; Delcelier 1989; de Freitas 1992; Henriques 1994; Torres 2004).

The condensate feed stream may flow from the first steam contained in this field and, above all, flow moving from the hot zone to the cold zone of the building elements. When the moisture content generated by the condensation are high, appear the moisture flow in the liquid phase and in the opposite direction to the steam flow.

The three mechanisms described are not separable and may also join the action of gravity and external pressures generated by the wind, which makes it a very complex analyse and modelling of the global movement of water within building materials (de Freitas 1992).

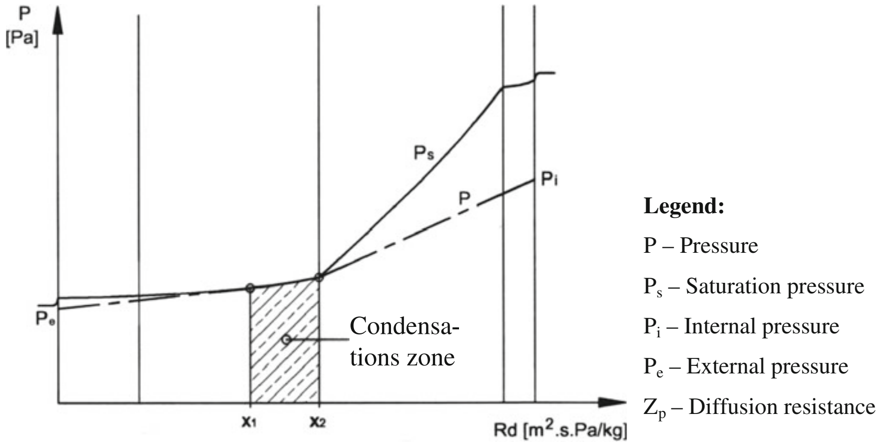


Fig. 1.5 Condensations zone (Freitas and Pinto 1998; Pinto 2002)

1.3 Moisture Manifestations

1.3.1 Vapour Phase and Liquid Phase

The knowledge of the different moisture manifestations is essential for the development of a correct diagnosis, to identify clearly the causes underlying the problems and propose appropriate methodologies for the work repair. In practice there is typically an isolated moisture event but the overlap of one or more different forms of moisture manifestations. However, it is possible to divide the different forms of moisture manifestations as follows:

• Higroscopicity of building materials	Vapour phase
• Superficial condensations	Vapour phase/liquid phase
• Internal condensations	Vapour phase/liquid phase
• Moisture in buildings	Vapour phase/liquid phase
• Infiltrations	Liquid phase
• Plumbing leaks	Liquid phase
• Rising damp	Liquid phase

1.3.2 Hygroscopicity of Building Materials

Hygroscopicity reflects the hygroscopic behaviour of the building materials and it is the ability to fix water molecules by adsorption from the surrounding environment or to free water molecules to the surrounding environment in function of the relative humidity variations.

There are hygroscopic and non-hygroscopic building materials. A hygroscopic building material, initially dry, absorb water vapour (water vapour sorption process) until it reaches its equilibrium moisture content, at certain ambient conditions. However the great majority of insulation materials present neither hygroscopicity nor capillarity, which means that an increased level of interstitial moisture occurs only in the event of condensation.

1.3.3 *Superficial Condensations*

At a given temperature, the air cannot contain a water vapour amount higher than saturation value. In winter the inner face of the building elements has a temperature, θ_{si}, below to the temperature of indoor air, θi.

$$\theta_{si} = \theta_i - \; U * R_{si} \; (\theta_i - \theta_e) \tag{1.2}$$

where:

θ_{si} is the indoor superficial temperature, (°C)
θ_i is the indoor temperature, °C
U is the thermal transmittance coefficient, $W/m^2 \cdot °C$
R_{si} is the indoor superficial resistance, $m^2 \cdot °C/W$
θ_e is the outdoor temperature, °C

Known temperature, θi, and the inside relative humidity it is possible to characterize the partial pressure of inside steam and determine, through psychometric diagram (see Fig. 1.6), the saturation temperature corresponding, θpo. To avoid condensations the following relations should be observed: θsi > θpo.

Fundamentally there are four processes to prevent surface condensation (Freitas and Pinto 1998):

- Increasing the thermal insulation by increasing the interior surface temperature inside, θsi;
- Increasing the interior temperature inside by increasing the interior surface temperature inside, θsi;
- Increase the flow ventilation and hygroscopicity coatings which reduces the interior relative humidity;
- Check the water production in the interior.

Everything described above refers to the condensation surface, i.e. the condensation occurring on the surface of the building elements and that are detectable by direct observation.

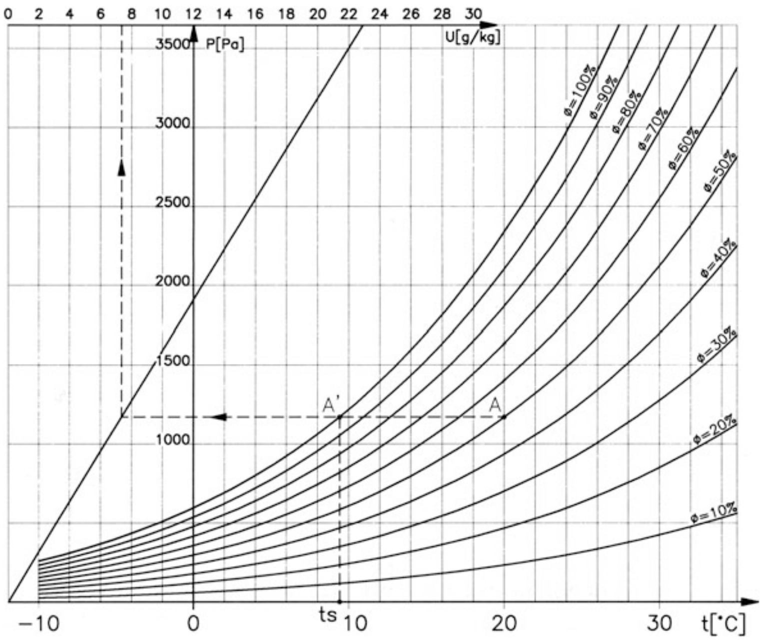


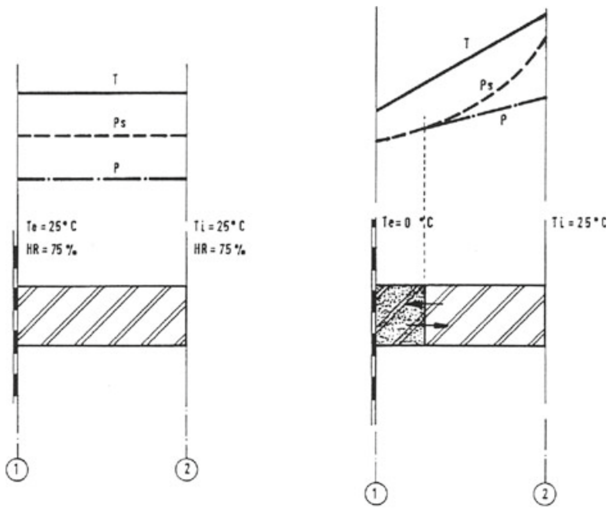
Fig. 1.6 Psychometric diagram (Freitas and Pinto 1998)

1.3.4 Internal Condensations

When condensation does not occur on the surface of the building elements this moisture manifestations are referred as internal condensation. At a given point of a building element, where the partial pressure of water vapour is equals to the saturation pressure, corresponding to the temperature in this point, condensation occurs inside the element. Thus, the carriage that was vapour creates the appearance of liquid water (de Freitas 1992; Freitas and Pinto 1998).

To illustrate this phenomenon for example consider a wall with a vapour impermeable layer placed on its outer face. Assuming that the temperatures and relative humidity's outside and inside are equal, there is no occurrence of condensation. There being a temperature gradient will be able to determine the saturation pressure curve as a function of temperature observed. If this curve yields points coinciding with the curve of the installed pressure (see Fig. 1.7), there will be occurrence of internal condensation (see de Freitas 1992; Freitas and Pinto 1998).

Internal condensation could influence the durability of building elements and components and contribute to the surface condensation deterioration and an important cause of building pathologies.



Legend:
θ – Temperature
P_s – Saturation pressure
P – Pressure
θ_i – Interior temperature
θ_e – Exterior temperature

Fig. 1.7 Internal condensations

1.3.5 Construction Moisture

During the building execution period a great amount of water are introduced in the construction. This water can be derived from the implementation process or else result in precipitation that may occur during construction.

In recent buildings, during construction time, are introduced thousands of litters of water, and the drying process should be slow which result in different pathologies. In a first phase a rapid evaporation of water surface is observed; in a second phase, occurs a slower evaporation of water contained in the pores with larger dimensions, and finally, in a third phase, the water evaporation process is very slow, during several years, and occurs in the pores of smaller size.

1.3.6 Infiltrations

Infiltrations results from water absorption by capillary in porous structures or percolation through the cracked areas. The infiltrations are linked to deficiencies in design or implementation or lack of maintenance, namely, cracking, deterioration of coatings, poor connection with the facade of the frames, application of materials with coefficients of very high water absorption, etc. It should be noted that the wind pressure causes the water path presents a horizontal component and reaches, in the most exposed areas, pressures of 2500 MPa.

1.3.7 Plumbing Leaks

This form of moisture manifestation is associated with water leaks due to defects in construction or operation of certain equipment and/or facilities.

The detection of such abnormality becomes relatively complicated since events often occur at different locations of their origin, in view of the fact that there is migration of water into the various building elements.

1.3.8 Rising Damp

Water seeping up from the ground may cause diminished performance in walls and floors. Most traditional building materials have a porous structure that leads to a high level of capillarity. This means water can migrate through capillary action, in the absence of any preventive barrier (CSTB 1985).

This water comes from two basic sources: groundwater and surface water. When it originates in groundwater aquifers, rising damp will manifest itself at a constant level throughout the year, as the source is active all year round. In this situation, damp stains reach a higher level on inside walls than on outside ones due to the fact that the evaporation conditions are less favourable.

When the source is surface water, the level reached by rising damp varies throughout the year. The height of the damp front may also vary from wall to wall, and is usually higher in the outside walls (Colombert 1985).

Rising damp is a major cause of decay in masonry materials such as stone, brick and mortar. The conservation of historical buildings has become important nowadays and has developed significantly in recent years. Rising damp in historical buildings may be considered one of the most important of all the different manifestations of dampness, leading to the destruction of stone materials due to frost/defrost cycles and the presence of salts associated with crystallization (Kunzel 1995) argues that in many cases increased salt content is interpreted as rising damp).

The mechanisms underlying the transportation of moisture through buildings are complex. During the vapour phase, diffusion and convection play a part, while capillary action, gravity and the pressure gradient effect control the transfer of moisture in its liquid phase (Guimarães et al. 2010).

In practice, transportation occurs in the liquid and vapour phases simultaneously, and is dependent upon conditions such as temperature, relative humidity, precipitation, solar radiation and atmospheric wind pressure (which define the boundary conditions) and the characteristics of the building materials used.

From the physical point of view, there are three main mechanisms involved in moisture transport: hygroscopicity, condensation and capillarity. In most cases, these three mechanisms account for variations in moisture content in building materials with a porous structure. Capillarity and hygroscopicity affect rising damp.

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Chapter 2
Hygrothermal Risk

One of the factors that contribute most directly to the degradation of the built heritage is the water from rain or soil in its liquid or vapour form.

Thus, hygrothermal behaviour of the building elements are an important risk factor for the monumental heritage buildings once they strongly influence its degradation. Hygrothermal behaviour is directly related to climatic conditions to which the heritage element is subdued, particularly in terms of precipitation, relative humidity, temperature, wind and sunshine.

Climate change is certainly a new risk that must be taken into account. The intensity and frequency of extreme events such as floods and droughts, possibly associated with climate change, have countless implications in contemporary societies, becoming increasingly pressing the prevention and mitigation of their effects, including regarding our built heritage.

Floods have always devastated large areas of Portugal, however, in recent years, there seems to be a trend of increased frequency and severity of their presence, giving rise to growing concerns about the exposure and the vulnerability of populations and heritage with this phenomenon. It is true that the floods have always existed as a natural phenomenon, after all, the presence of very intense or very long periods of precipitation have contributed to the intensification of floods, which rose exceptional frequent in many regions.

Portugal, due to its geomorphology, has a large and complex river system, increasing interest in the study of floods and the risk they pose to the built heritage.

Therefore, regarding our subject “the built monuments”, we analysed three major hygrothermal phenomena which, directly or indirectly, are related and dependent on changes and the presence of water.

2.1 Importance of Hygrothermal Behaviour

Once there is a vast and complex river network in Portugal, a lot of great heritage buildings are located close to water lines. Nevertheless, when the buildings are in equilibrium with the terms of the atmosphere, they can remain in good condition for hundreds of years. When this balance is affected by changing the internal conditions

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for border changes or significant changes in terms of external stresses, such as is the case of the occurrence of floods/droughts and fluctuations in the water table, degradation is inevitable.

The problem of moisture in buildings has always attracted great interest. However, the complexity of the phenomena involved do not always make easy the scientific explanation of various forms of events in which these problems are associated.

Moisture, in its various forms, is one of the primary causes of the degradation observed in buildings. Therefore, the development of studies aimed at identifying qualitative and quantitative rules for heritage protection is of great importance.

Normally, in practice there is not an isolated event, but the superposition of one or more forms of different events, either in liquid phase or in vapour phase. In this project we focus our attention only on the rising moisture that occurs in the liquid phase on the hygroscopicity of the materials and the dimensional variation that relate with the vapour phase.

2.2 Risk Associated to the Proximity of a Water Line

Natural flooding are extreme and temporary phenomena caused by moderate rainfall and permanent or sudden rainfall and intensity. This excess precipitation increases the volume of rivers, leading to extravasation of normal bed and flooding the banks of the river and adjacent areas.

Except in case of sudden flooding caused by intense and sudden rainfall associated with atmospheric instability difficult prediction, in general it is possible to provide a flood. This forecast is possible with the observation of meteorological comments and knowledge landfills dams, to try to minimize their impact quickly informing the population.

The public will be informed, however the built heritage cannot be moved, being the buildings subject to direct aggression of the flood by flood or by varying the water table. Thus it is necessary to create direct measurements in heritage to prevent or minimize degradation.

The envelope of the built heritage is the protective barrier of the building, and is subject to external aggression and internal stresses. The risk of the nearby heritage with water lines, is not only associated with the direct flooding due to flooding, but also, and more significantly shape, with the change of water level, or by the effect of flooding or by drought effect.

Parts in contact with the ground, generally used in this kind of building constructions, have great moisture transfer capacity, mainly due to capillary action, thus being subject to a series of downgrades by the moisture effect, due to the phenomenon of rising damp.

Moisture conditions of the building envelope condition the relative humidity of the indoor environment. If the change is significant, moisture equilibrium of

Fig. 2.1 Some examples of heritage degradation by hygrothermal behaviour (Guimarães et al. 2011)

materials can be seriously affected, such as in the case of wood, can handle a degradation of materials, coatings or even sculptures.

Figures reflect the following examples of impairments that built heritage is subdued due to hydrothermal origin actions (Fig. 2.1).

In this work we intend to give a contribution to knowledge, developing various studies in the following areas:

- Rising damp;
- Indoor materials hygroscopicity;
- Dimensional changes of the building materials.

2.3 Rising Damp in Building Heritage

Rising damp, a world-wide phenomenon, is a major cause of decay of masonry materials such as stone, brick and mortar. The conservation of historical buildings assumes, nowadays, a considerable importance and it has had a great development in the last few years (see Fig. 2.2).

The height that moisture will reach through capillary action depends upon factors such as the quantity of water in contact with the particular part of the building, surface evaporation conditions, wall thickness, building orientation and the presence of salts (Torres 2004; Torres and Freitas 2006). When atmospheric conditions are constant, the thicker the wall, the greater the height reached by the damp, as a greater quantity of water is absorbed (see Fig. 2.3).

Another important factor to take into account is the presence of salts, which also increases the height achieved by rising damp. The salts are dissolved when the relative humidity of the air rises and they crystallise again when this humidity declines. This crystallisation/dissolution process causes the materials to decay. There are various water-soluble salts in the walls of buildings, contained in the building materials or emanating from the soil. These dissolved salts are transported

Fig. 2.2 Example of rising damp in a historical building

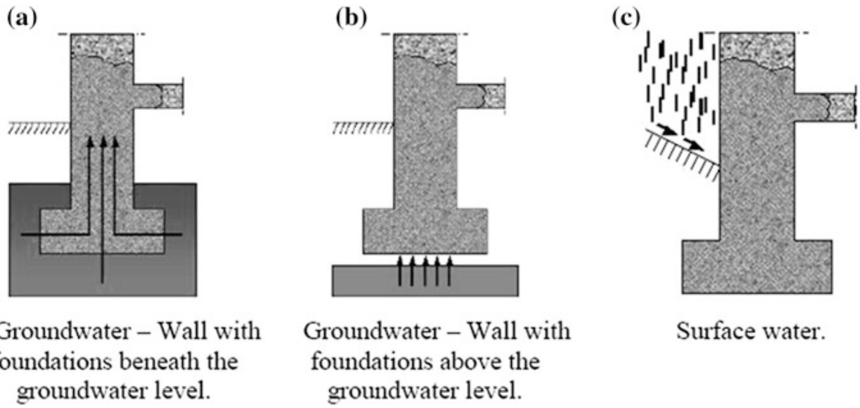

Fig. 2.3 Humidification of walls by groundwater and surface water

to the wall surface where they crystallise in the form of fluorescences or crypto fluorescences, depending upon whether the crystallisation takes place on the surface of the wall or beneath the wall renderings (Hens 2007).

Rising damp depends upon the following factors (Freitas et al. 2008):

- Ambient climate (temperature and relative humidity);
- Solar radiation;
- The presence of salts;
- The porosity and porometry of building materials;
- Wall thickness;
- The kind of materials used for wall renderings.

2.3.1 Climatic Conditions

The climatic conditions affect the drying process and exert great influence upon the level achieved by rising damp. In places with high relative humidity, evaporation is more difficult and there will consequently be greater progression of the damp front. Conversely, when relative humidity is low, evaporation will be greater and the damp front will progress more slowly. The drying flow may be defined by the following equation:

$$g = \beta.(C'_s - C'_a) \tag{2.1}$$

where:

g is the flow density (kg/(m^{2}s)

β is the surface moisture transfer coefficient (m/s)

C_s' is the water vapour concentration at the surface (kg/m^3)

C_a' is the water vapour concentration in the air (kg/m^3).

Where there is no great temperature difference between the air inside the building and the inner surface of the wall, for high relative humidity, the concentration difference $C_s'-C_a'$ tends to zero, as does the drying flow.

2.3.2 Solar Radiation

In a building with identical climate conditions throughout, the progression of the damp front may vary in accordance with the orientation of the building and amount of solar radiation received. Solar radiation and the radiation absorption coefficient alter the surface temperature and temperature distribution, bringing consequences for the drying process.

2.3.3 Salt Attack

Salt crystallization is one of the main mechanisms involved in stone degradation. This degradation mechanism is based upon the pressure exerted by salt formation in the porous structures, with an increase in volume. It is dependent upon the types of salts involved, their size and the arrangement of the pores.

Temperature may have some influence in the process, because salt solubility depends upon it.

When the pressure exceeds the material's resistance capacity, and, particularly, when the salt formations result in cycles of crystallisation and dissolution in response to humidity fluctuations, there will typically be material losses.

The most characteristic salts are:

- Chlorides, which absorb large amounts of water;
- Nitrates of organic origin, of which the most common is calcium nitrate, which crystallises at 25 °C and 50 % relative humidity;
- Sulphates, which are hygroscopic and soluble, and which increase in volume upon crystallization. The most common are sulphates of calcium, sodium and magnesium.

Anomalies caused by the presence of salts may result in a variety of symptoms of degradation in wall renderings. These include: surface alterations (fluorescences or damp patches); cracking; the formation of crusts; the separation of building materials into layers (delamination, exfoliation, the detachment of coatings, etc); loss of cohesion (eg. pulverulence of ceramic or stone brick elements, arenization of mortars, etc…), and the formation of voids (such as alveolization).

2.3.4 Porosity and Porometry

A material's porosity may be defined as the ratio between the total volume of voids (pores and channels) and its total apparent volume. Practically all building materials are characterised by open porosity, and their moisture imbibitions capacity is directly related to porosity. In the case of closed porosity, when there is no intercommunication between pores, the material is impermeable and water cannot penetrate.

Materials with closed porosity are of interest for the prevention of rising damp, as they may be used to form a water barrier. Materials with open porosity, on the other hand, conduct the moisture by capillary action. Capillarity increases the smaller the diameter of the pores. Thus, porometry studies are useful, as they enable the size of the pores to be assessed.

2.3.5 Wall Thickness

The progression of rising damp stabilises when the flow through the absorbent section is equal to the total wall evaporation; that is to say, the amount of water that enters the wall through absorption is the same as the amount of water that leaves through evaporation.

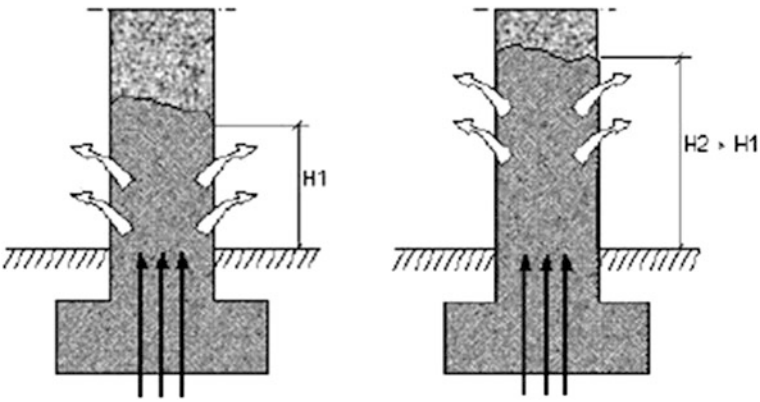

Fig. 2.4 Influence of impermeable materials placed on the wall surface at the level achieved by rising damp

2.3.6 Wall Renderings

The damp-proofing of walls generally reduces the evaporation conditions, which increases the level of rising damp, until a new equilibrium is achieved. This is shown in Fig. 2.4 as a schematic representation.

2.4 Materials Hygroscopicity

Hygroscopic moisture is moisture which a porous substance can absorb from the air and then release it into the air. The humidity will achieve balance with its environment, which means that the substance has hygroscopic balance moisture.

The hygroscopic qualities of building materials vary greatly. Wood-based materials are very hygroscopic; mineral-based materials are not very hygroscopic. The ability of a building material such as insulation to bind and release moisture is called the moisture capacity, and it is highly significant for the moisture-technical functioning of the structure. Large moisture capacity balances changes in moisture and reduces the risk of moisture damage.

Many materials and objects that are part of the internal heritage buildings are particularly sensitive to indoor relative humidity variations, being mainly affected by extremes, high or low relative humidity values. A low relative humidity can lead to contraction of the materials which in the case of small movements or objects consisting of different layers, implies the occurrence of tensions in an extreme case, may cause the cracking of the building material. The high relative humidity can lead to expansion of the material, involving tension, accelerates the reactions of degradation and makes favourable development organizations (mould and algae).

Once humans have the ability to sustain Relative humidity in a wide range of values, the concern of control occurs only in special-use buildings, such as museums. The use of coating materials with appropriate hygroscopic inertia, can help control the relative humidity of the indoor environment variations. The hygroscopicity reflects the hygroscopic behaviour of materials, which is characterized by the ability to bind water molecules adsorption and return them to the environment in which it is located, based on changes in relative humidity thereof. Hygroscopic material says if the amount of water that is capable of retaining adsorption is relatively large. Figure 2.5 shows the typical form of a porous hygroscopic material curve, which defines its ability to store water.

The practical application of the "hygroscopic inertia" concept in building design demands for a simple prediction strategy of the impact of interior renderings and furnishings. Significant aspects of the evaluation of finishing materials contribution to the hygroscopic inertia are presented.

On the NORDTEST Workshop on Moisture Buffer Capacity (Rode et al. 2003), the issue of how to characterize the ability of materials and structures to accumulate moisture was widely discussed. Although some definitions like moisture effusivity, available water and penetration depth, that hold an acceptable theoretical background, are available for characterizing building materials, they can't be easily used for structures or even coated materials. On that workshop, the MBC number was referred as a good alternative for the aimed characterization.

Based on the suggestions of the NORDTEST Workshop on Moisture Buffer Capacity—Summary Report (Rode et al. 2003), a laboratory test was prepared, where a specimen is submitted to a square wave in relative humidity, with 12 h steps, and constant temperature. This experiment simulates the cyclic variations in moisture loads and relative humidity levels that can be found in bedrooms, for instance, where during the night, there will be an increase in relative humidity due to vapour production by occupants. Some of the results of this work have already been presented (Ramos and Freitas 2004).

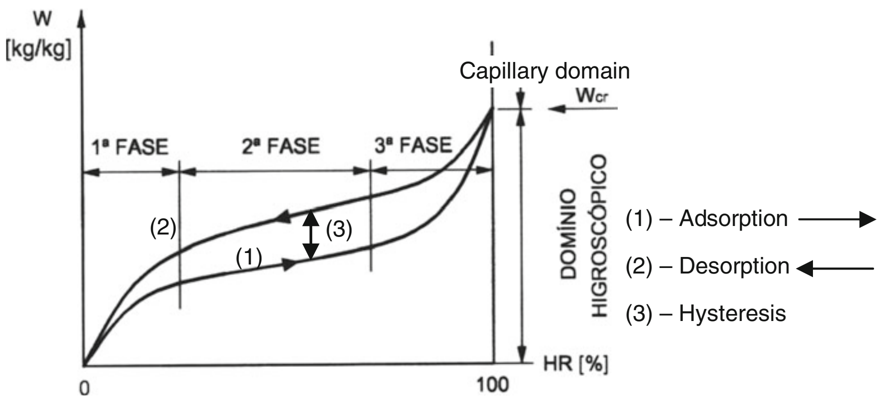

Fig. 2.5 Hygroscopic behaviour of building materials with relation to relative humidity

The specimens used in the tests were stabilized inside a climatic chamber at 20 °C and 65 % relative humidity. Afterwards, each specimen was tested for a few days period with a square wave of relative humidity, with 12 h steps, and constant temperature. The high value used for relative humidity was 85 % in the presented experiments. We can see in Figs. 2.6, 2.7, 2.8, 2.9 and 2.10 the mass variation of the

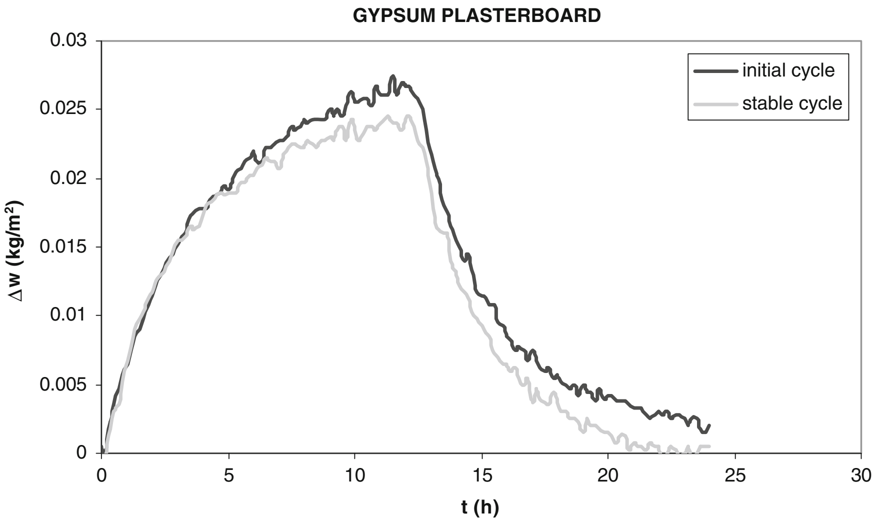

Fig. 2.6 Mass variation of the gypsum plasterboard specimen during laboratory tests

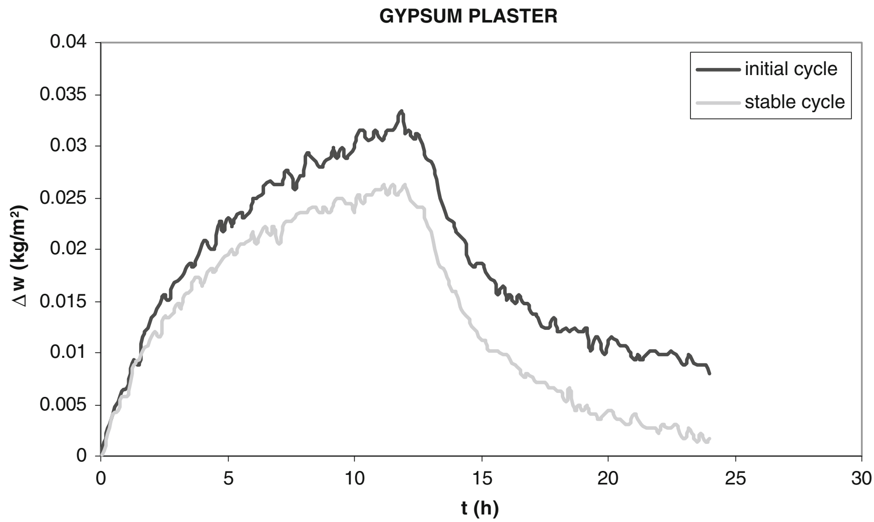

Fig. 2.7 Mass variation of the gypsum plaster specimen during laboratory tests

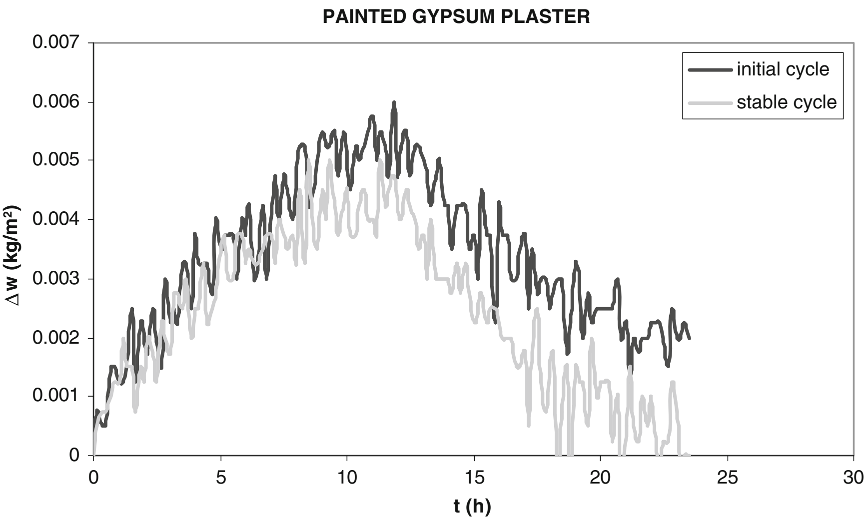

Fig. 2.8 Mass variation of the painted gypsum plaster specimen during laboratory tests

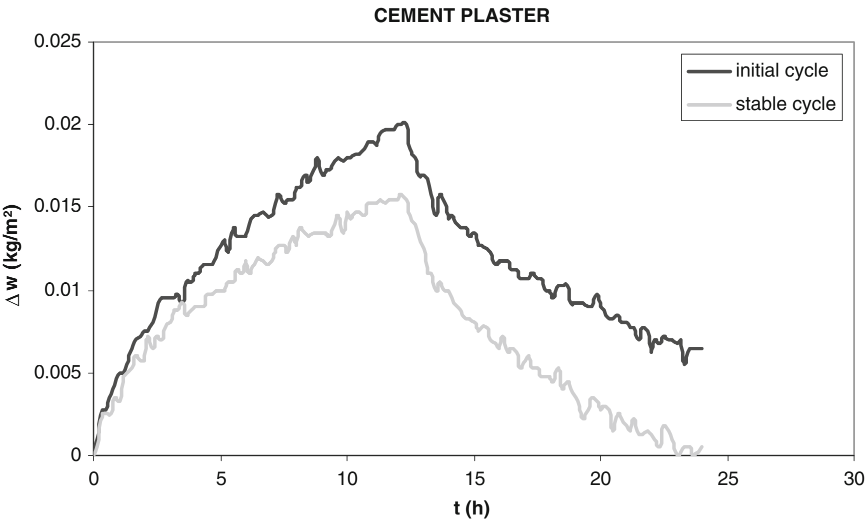

Fig. 2.9 Mass variation of the cement plaster specimen during laboratory tests

specimens, for the initial cycle and for what could be called the stable cycle, where the mass variation after its full length is zero.

In Fig. 2.11 the maximum weight variation in each cycle is presented. We can see that there's always a decrease of that value from the initial cycle to the stable one. Also that decrease is different for each specimen. We believe that the stable

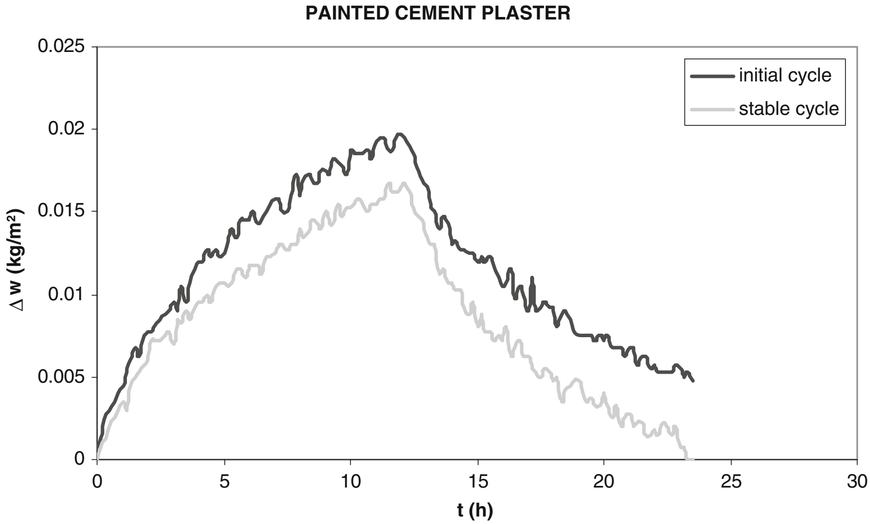

Fig. 2.10 Mass variation of the painted cement plaster specimen during laboratory tests

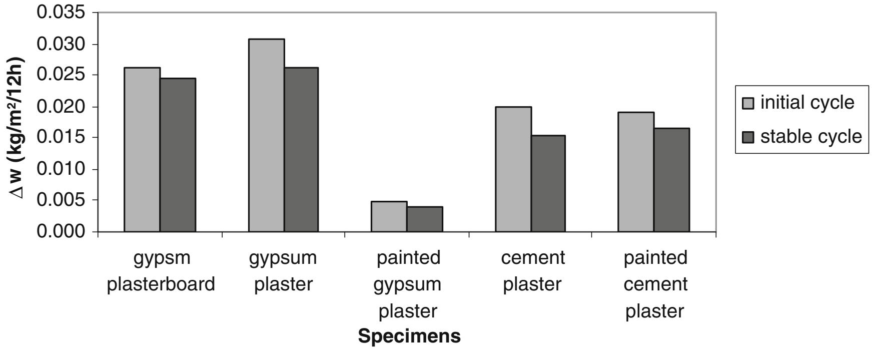

Fig. 2.11 Maximum weight variation

cycle should be the reference for the definition of a rendering's Moisture Buffer Capacity.

2.5 Dimensional Changes of Building Materials

Moisture is one of the most important causes for building pathology. Material's behaviour degradation can be affected by the presence of water both in vapour and liquid phase. Wood is a hygroscopic substance and this ability to absorb or to lose water is dependent on the temperature and the humidity of the surrounding atmosphere. This moisture relationship has an important influence on wood properties and performance. Many of the challenges of using wood as an engineering material arise from changes in moisture content or an abundance of moisture within the wood.

As a consequence, the amount of moisture in wood fluctuates with changes in the atmospheric conditions around it. All physical and mechanical properties of wood are greatly affected by the fluctuations of the quantity of water vapour present in wood. In using wood as a raw material, it is therefore essential to be able to evaluate its moisture content, and to understand where the moisture is located and how it moves through the wood.

Wood is dimensionally stable when moisture content is greater than the fiber saturation point. Below this point, wood changes dimension as it gains moisture (swells) or loses moisture (shrinks), because volume of the cell wall depends on the amount of bound water (Bergman et al. 2010). With respect to dimensional stability, wood is an anisotropic material. It shrinks or swells most in the direction of the annual growth rings (tangential), about half as much across the rings (radial), and only slightly along the grain (longitudinal). As with all wood properties, shrinkage is highly anisotropic, i.e., tangential shrinkage is 1.5–2.5 times greater than radial shrinkage.

2.5.1 Theory

An important variable that should be analysed is the rate of dimensional change. It is well-known that below the fiber saturation point, the rate of shrinkage can be expected to be directly proportional to moisture adsorption. The rate of dimensional change can be described by the initial linear rate (Mantanis et al. 1994) or by the two-parameter asymptotic regression model (Rypstra 1995), as

$$\frac{dy}{dt} = k(y_{\max} - y) \tag{2.2}$$

Integrating this equation for the initial and end conditions $t = 0$ to $t = t$ and $w = 0$ to $w = w$, Eq. (2.2) may be rearranged for linearized data plotting as shown by Eq. (2.3):

$$\ln\left(1 - \frac{y}{y_{\max}}\right) = -k.t \tag{2.3}$$

The isothermal adsorption data measured is given in Fig. 2.10. Several equations (GAB model, modified Oswin model and Hansen equation) were used to fit experimental data for water activity in the range between 0.33 and 0.91 (Machado 2006).

The three models referred above were applied to experimental data using SPSS 14.0 program and Levenberg-Marquardt algorithm, with no statistical relevant differences observed. The quality of the models was tested by using the "root mean square" (RMS, %):

$$RMS = \sqrt{\frac{\sum\left[(M^{\exp} - M^{\mathrm{calc}})/M^{\exp}\right]^2}{N}} \times 100\,\% \tag{2.4}$$

The results obtained were very similar and the authors decided to use the model proposed by Hansen (1986) and given by the following expression (Tables 2.1 and 2.2).

$$u = u_h\left(1 - \frac{\ln\phi}{A}\right)^{-1/n} = u_h \exp\left[-\frac{1}{n}\ln\left(1 - \frac{\ln\phi}{X_1}\right)\right] \tag{2.5}$$

The results of parameter estimation, for the experimental data, are summarized in Table 2.3. The fittings of the proposed model are very satisfactory for the examined building materials.

Table 2.1 Variables of Eq. (2.2)

Direction	RH (%)	Sample 1				Sample 2			
		$y_{\max}$ (mm)	k (h^{-1})	R^2 (%)	E (%)	$y_{\max}$ (mm)	k (h^{-1})	R^2 (%)	E (%)
Tangential	50	0.139	0.005	99.72	2.07	0.129	0.005	99.70	3.68
	75	0.414	0.004	99.95	1.67	0.382	0.003	99.92	2.67
	90	0.618	0.001	99.94	4.09	0.593	0.001	99.94	3.91
Radial	50	0.085	0.006	97.46	10.81	0.089	0.006	99.27	4.80
	75	0.235	0.005	99.22	7.32	0.238	0.005	99.52	4.81
	90	0.279	0.004	99.91	2.26	0.280	0.004	99.89	2.45

Table 2.2 Moisture content of the samples

Test period	Sample 1			Sample 2		
	m_h (g)	m_s (g)	u (%)	m_h (g)	m_s (g)	u (%)
Beginning	53.347	46.742	14.1	53.576	46.746	14.6
RH = 35 %	51.178	46.742	9.5	51.173	46.746	9.5
RH = 50 %	51.890	46.742	11.0	51.899	46.746	11.0
RH = 75 %	53.823	46.742	15.1	53.848	46.746	15.2
RH = 90 %	55.851	46.742	19.5	55.817	46.746	19.4

Table 2.3 Samples dimension in function of relative humidity

Relative humidity (%)	Sample 1		Sample 2	
	l_t (mm)	l_r (mm)	l_t (mm)	l_r (mm)
0	29.03	49.05	58.93	48.78
50	29.17	49.14	29.06	48.87
75	29.44	49.29	29.31	49.02
90	29.65	79.33	29.52	49.06

$$u(\%) = \frac{m_h - m_s}{m_s} \times 100 \tag{2.6}$$

and hygric expansion is given by

$$\varepsilon_h(\%) = \frac{l - l_0}{l_0} \times 100 \tag{2.7}$$

$$\alpha = \frac{\Delta\varepsilon_h}{\Delta u} \times 100 \tag{2.8}$$

$$\rho_{ref} = \rho \frac{(100 + 12)(100 + \alpha_v u)}{(100 + u)(100 + 12\alpha_v)} \tag{2.9}$$

2.5.2 Experiments and Results Analyse

An experimental device was planned and designed for testing wood samples (see Fig. 2.11). Displacement sensors were attached to a supporting tray and the complete set was installed in an existing climatic chamber.

The samples with 50 × 50 × 30 mm were, initially, stabilized at a relative humidity of 35 % and a temperature of 20 °C. At the beginning of each cycle, the samples were weighed and measured in three directions, so that it is possible to determine the curve hygroscopic and density. Figure 2.12 presents the geometry assumed for the specimens based on the NP-615 (1973) recommendations and shows the measurement points of the specimens: two measurements per side, in the axial (A), radial (R) and tangential (T).

The stopping criterion to consider that the wood samples had reached stabilization was to remain unchanged for 5 consecutive days.

Figure 2.13 shows the dimensional change in tangential and radial direction, observed for the 2 samples, in function of the variation of relative humidity (RH): [35,50], [50,75] and [75,90]%.

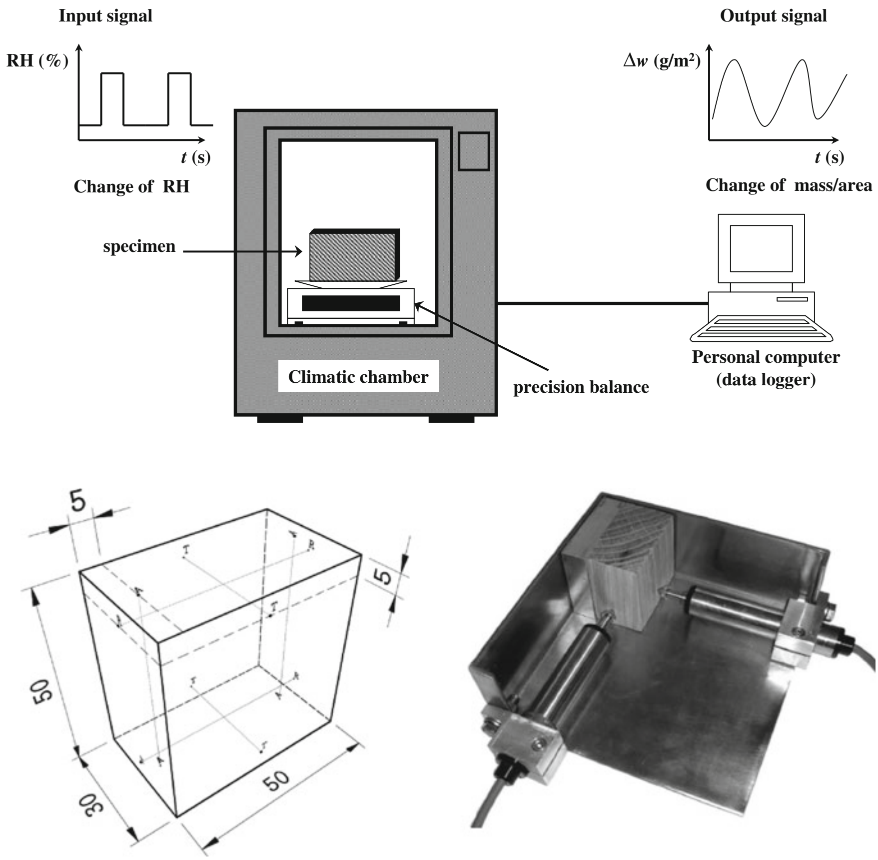

Fig. 2.12 Sketch of experimental set-up

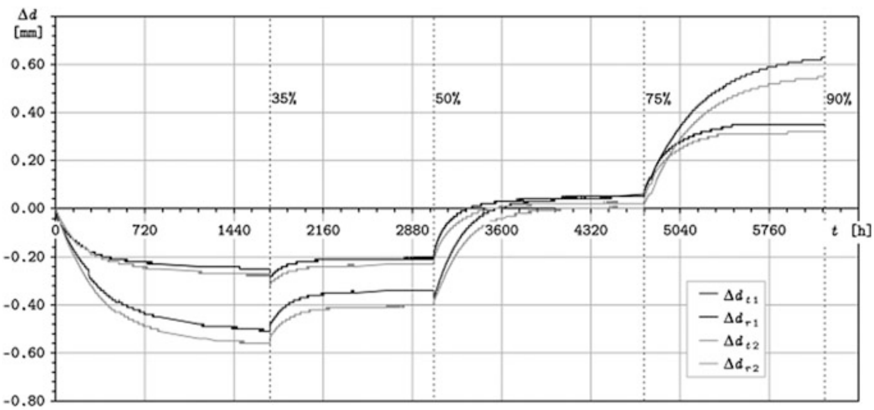

Fig. 2.13 Dimensional change in tangential and radial direction, for each relative humidity plateau

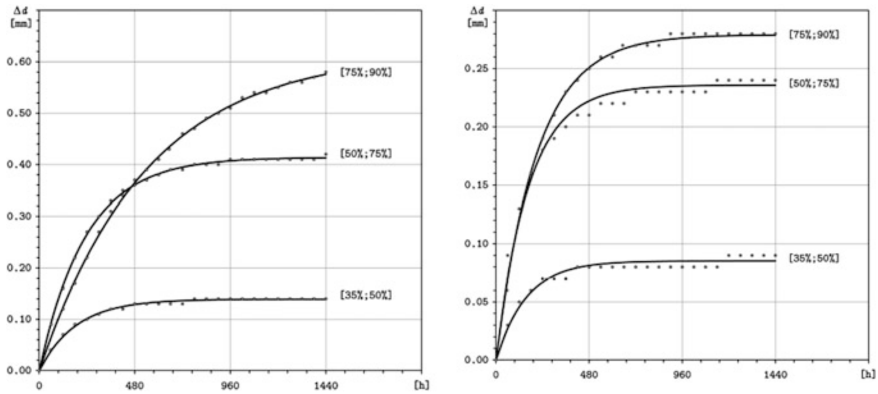

Fig. 2.14 Dimensional change in function of the time and relative humidity, in the **a** tangential and **b** radial direction of sample 1

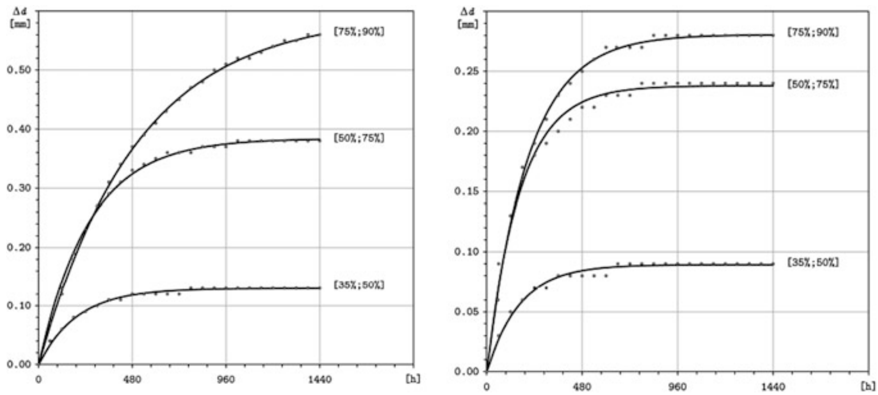

Fig. 2.15 Dimensional change in function of the time and relative humidity, in the **a** tangential and **b** radial direction of sample 2

Figures 2.14 and 2.15 show the wood dimensional change in function of the time at three different relative humidity's (50, 75 and 90 %), for the two samples analysed. Table 2.1 shows the coefficient values of Eq. (2.2) and the average relative deviation module. The analyse of the y_{max} values, of Table 2.1, with the values presented in Fig. 2.13, it is possible to observe that criteria reach 97 % of maximum dimensional variation defined in EN 13006:2000 was also achieved.

The hygroscopic curve was determined using Eq. (2.6). Table 2.2 shows the moisture content observed, for the two samples, at the beginning of the test and for different relative humidity's plateaus. Figure 2.16 shows the hygroscopic curves of the specimens tested for the moisture content values presented in Table 2.2. It is possible to observe that the two samples presenting very similar hygroscopic curves.

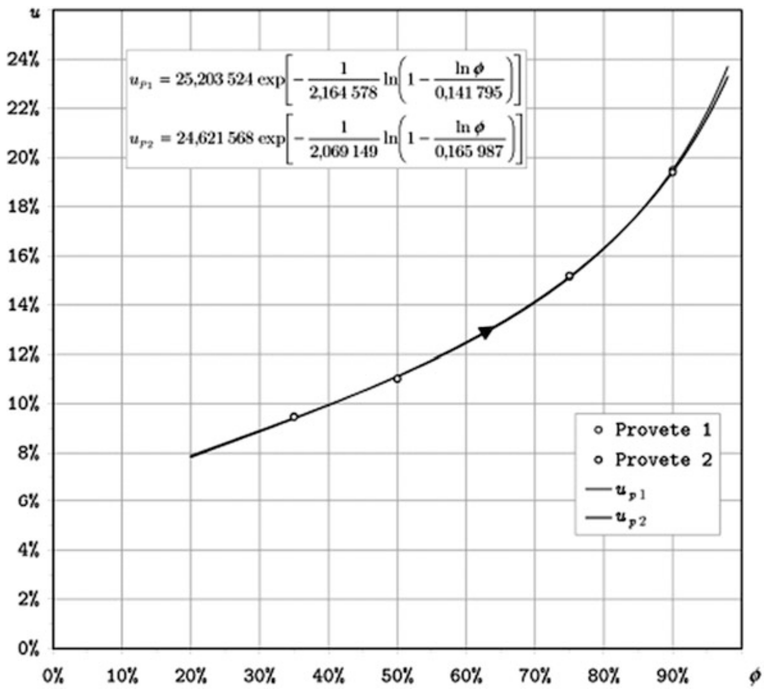

Fig. 2.16 Hygroscopic curve of the samples analysed

Table 2.4 Hygric extension for each relative humidity

Relative humidity (%)	Sample 1			Sample 2		
	u (%)	ε_t (%)	ε_r (%)	u (%)	ε_t (%)	ε_r (%)
50	11.0	0.48	0.17	11.0	0.45	0.18
75	15.1	1.43	0.48	15.2	1.33	0.49
90	19.5	2.13	0.57	19.4	2.05	0.58

Table 2.5 Hygric expansion coefficient determination

RH interval (%)	Sample 1						Sample 2					
	Δu (%)	$\Delta\varepsilon_t$ (%)	$\Delta\varepsilon_r$ (%)	$\Delta\bar{u}$ (%)	$\alpha_{h,t}$ (%)	$\alpha_{h,r}$ (%)	Δu (%)	$\Delta\varepsilon_t$ (%)	$\Delta\varepsilon_r$ (%)	$\Delta\bar{u}$ (%)	$\alpha_{h,t}$ (%)	$\alpha_{h,r}$ (%)
[35,50]	1.5	0.27	0.07	10.3	17.9	4.6	1.6	0.24	0.08	10.2	15.4	5.1
[50,75]	4.1	0.95	0.31	13.1	22.9	7.4	4.2	0.88	0.31	13.1	21.1	7.3
[75,90]	4.3	0.70	0.09	17.3	16.2	2.1	4.2	0.73	0.09	17.3	17.2	2.1

Table 2.3 presents the samples dimension in function of relative humidity and Tables 2.4 and 2.5 present the experimental values of hygric extension and hygric

Table 2.6 Density and reference density of the samples analysed

Test period	Sample 1		Sample 2	
	ρ (g/cm^3)	ρ_{ref} (g/cm^3)	ρ (g/cm^3)	ρ_{ref} (g/cm^3)
Beginning (%)	0.711	0.758	0.721	0.772
RH = 35	0.698	0.744	0.703	0.753
RH = 50	0.704	0.750	0.710	0.760
RH = 75	0.713	0.760	0.717	0.768
RH = 90	0.726	0.773	0.729	0.780

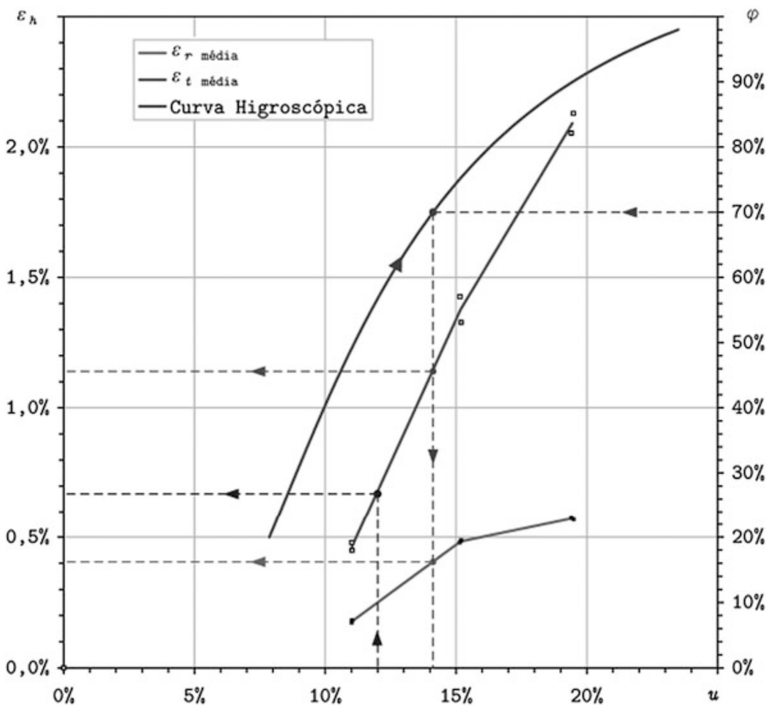

Fig. 2.17 Relationship between dimensional change and the relative humidity and moisture content

expansion coefficients, respectively. Finally, Table 2.6 shows the density values and reference density of the samples analysed (Fig. 2.16).

Above we presented the determination methods of several parameters that characterizing the wood in study. The main goal is to relate the three fundamental parameters of the dimensional variation phenomenon, which are the hygric extension (Eq. 2.7), the environmental relative humidity and the moisture content of the wood. Figure 2.17 presents an abacus with joint representation of those parameters.

This experimental work show the dimensional change of the red oak, an important material used in ceilings, floors and wall finishing's in function of interior moisture change. The experimental campaign resulted in the following conclusions:

- It was developed a prototype for determination of the hygric expansion;
- It was analysed the hygric expansion of the red oak at three different ranges of indoor relative humidity's, 35–50, 50–75 and 75–90 %;
- The hygric expansion coefficient presents a linear variation with the moisture content;
- It was possible to obtain a relationship between the dimensional change and the relative humidity and the moisture content.

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Chapter 3
Numerical Simulations Applied to Drying Out Buildings with Rising Damp Problems

Currently it is considered that climate change, caused by the intensification of the greenhouse effect, will worsen extreme weather events such as floods. One of the risks that will further increase in frequency and intensity in the coming decades is the risk of flooding. It is therefore very important to start thinking about taking measures to minimize and control its adverse effects, avoiding potentially catastrophic consequences.

After the occurrence of a flood building elements will see its moisture content suddenly increase, with all losses resulting therefrom. It is very important that, after the occurrence of a flood, the reduction in moisture level of the walls is achieved as quickly as possible.

The treatment of rising damp in historical buildings walls is very complex, due to the thickness of the walls and the fact that they are built from different materials. The traditional techniques used to deal with this kind of problem (such as watertight barriers, injection of hydrofuge products, etc.) sometimes prove ineffective or are expensive, justifying the need to find new approaches (see Guimarães et al. 2010).

3.1 Introduction

Rising damp, a world-wide phenomenon, is a major cause of decay in masonry materials such as stone, brick and mortar. The conservation of historical buildings has become important nowadays and has developed significantly in recent years. Rising damp in historical buildings may be considered one of the most important of all the different manifestations of damp, leading to the decay of stone materials due to frost/defrost cycles and the presence of salts associated with crystallization (in many cases increased salt content is interpreted as rising damp, as shown by Kunzel 1995), decay in elements in contact with the stone walls, such as wooden beams, wooden ceilings and other finishing's, and insanitary conditions caused by excess humidity associated with the development of fungus and mould.

J.M.P.Q. Delgado et al., *Hygrothermal Risk on Building Heritage*, SpringerBriefs in Applied Sciences and Technology, DOI 10.1007/978-3-319-19114-0_3

This chapter presents the results of our study, which consisted of a large number of numerical simulations on walls composed of different materials (granite and limestone), used to validate the analytical solution developed by Hall and his team. The main goal is to estimate the level achieved by the damp front in steady-state. It is very important to have an idea of the height of the rising damp front, to predict the improvements of some experimental treatment techniques. This paper presents the results of our study, which consisted of a large number of numerical simulations on walls composed of different materials (granite and limestone), used to validate the analytical solution developed by Hall and his team. The main goal is to estimate the level achieved by the damp front in steady-state. It is very important to have an idea of the height of the rising damp front, h_∞, to predict the improvements of some experimental treatment techniques.

3.2 Configurations Tested

Humidity is one of the main causes of decay in buildings, particularly rising damp. The treatment of this phenomenon in historical buildings is very complex due to the thickness and heterogeneity of the walls. Rising damp may usually be controlled by adopting one or more of the following treatment techniques as (Freitas et al. 2011):

- Adopting physical or chemical barrier, by reducing the absorbent section;
- Creating watertight barriers;
- Applying products;
- Creating electric potential and installing Knappen drainage;
- Applying coatings with controlled porosity;
- Hiding anomalies behind a new built wall;
- Ventilating the wall base.

In the analysis presented in this work, for the study of rising damp front, we selected the last two techniques, concealing wall anomalies and ventilating the wall base. The wall base ventilation system was developed by LFC-FEUP. This technique consists of ventilating the walls base through the installation of a hygro-regulable mechanical ventilation device. Wall base ventilation increases evaporation, which leads to a reduction in the level achieved by the damp front. This is possible only when the groundwater is lower than the base of the wall.

The configurations tested (boundary conditions) and used in the numerical analysis are shown in Fig. 3.1 (walls with a thickness of 200 or 500 mm and a height of 1500 mm, with sand, on the both sides, to a height of 450 mm). The only difference between Configurations 1 and 2 was that one side of the wall in Configuration 2 was completely covered with tiles. The aim of using these two boundary conditions was to analyze the influence of waterproof materials (such as tiles). In Configuration 3 a ventilation box was placed on both sides of the wall (see Fig. 3.1), immersed in the sand (for this configuration the sand height, h_s, was

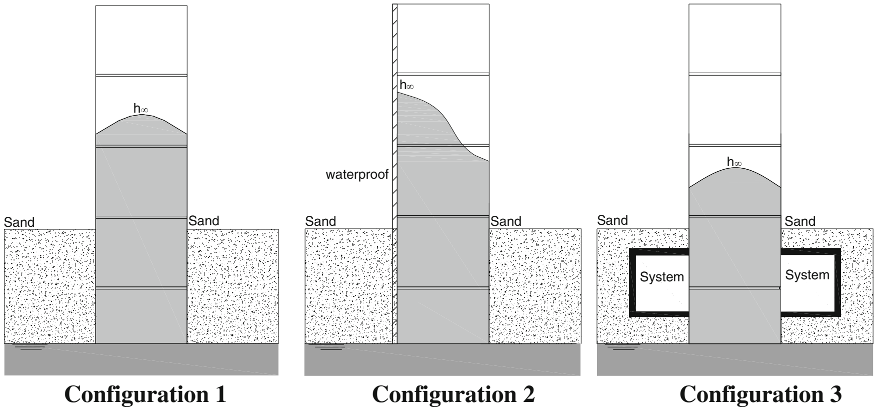

Fig. 3.1 Different boundary conditions studied

250 mm) and with an area of $200 \times 300\,\text{mm}^2$ (h_H = 200 mm). The sand was saturated (100 % RH) during the tests and the evaporation potential considered equal to zero.

The evaporation potential associated with the wall base ventilation system used was 0.75×10^{-4} mm/min (the same of the laboratory interior conditions), because the version of WUFI 2D used does not allow simulating the wall base ventilation system with a variable air flow rate.

3.3 Numerical Simulation

Simulation programs that evaluate changes in the moisture content and temperature inside walls are essential tools for simulating the behavior of walls in the presence of moisture dependent on internal and external climatic conditions (Bomberg 1974).

The calculation program used in the numerical simulations for the experimental and analytical validations was WUFI-2D v.2.1, developed by the Fraunhofer Institute for Building Physics. The governing equation for moisture transport is (Holm and Kunzel 2003; Kalamees et al. 2006)

$$\frac{dw}{d\phi}\frac{\partial\phi}{\partial t} = \nabla(D_\varphi \nabla\phi + \delta_p \nabla\phi p_a) \tag{3.1}$$

and the governing equation for heat transport is

$$\frac{dH}{dT}\frac{\partial T}{\partial t} = \nabla(\lambda_\mathrm{T}\nabla T) + h_\mathrm{v}\nabla(\delta_\mathrm{p}\nabla\phi p_\mathrm{a}) \tag{3.2}$$

where dH/dT is the heat storage capacity of the moist building material, $dw/d\phi$ is the moisture storage capacity, λ_T is the thermal conductivity, D_ϕ is the liquid conduction coefficient, δ_p is the water vapor permeability, h_v is the evaporation enthalpy of the water, p_a is the water vapor saturation pressure, T is the temperature and ϕ is the relative humidity (Evrard and De Herde 2010).

In the numerical analysis used to validate the analytical study only the change in relative humidity was considered important, since the experiments took place under isothermal conditions.

Hygrothermal modeling offers a powerful tool for predicting heat and moisture transport through multi-layer building assemblies. In this work, the hygrothermal model was used to compare the results of three configurations (see Fig. 3.1), with two types of monolithic walls, with different wall thicknesses and under different natural conditions. The simulations used two different climates, a controlled laboratory climate and the others with real climatic variables of Porto city, and actual material properties to determine the height of the rising damp front (see Table 3.1).

The numerical simulations, with real climate, were made using climate data for Porto provided by a software tool (METEOTEST 2008). This program calculates the hourly values for all parameters using a stochastic model and the resulting weather data files are produced in a variety of formats. The weather data used as input for the model was temperature (°C), relative humidity (–), precipitation (mm/h) and global solar radiation on a horizontal surface (W/m^2). The short wave

Table 3.1 Material properties (Torres and Freitas 2007)

		Limestone		Granite
Bulk density, ρ (kg/m^3)		2155		2550
Heat capacity, c_p (J/kgK)		1000		850
Porosity, ε (%)		19.7		12.5
Thermal conductivity, λ_T (W/mK)		1.33		2.30
Vapor diffusion resistance factor, μ (–)	Dry cup:	41		55
	Wet cup:	29		
Moisture storage function, w (kg/m^3)	ϕ (%)	*Adsor*	*Desadsor*	
	4.0	0.521	0.951	Generate by Eq. (3.3)
	11.2	0.593	1.150	
	34.8	0.872	1.239	
	58.6	1.043	1.628	
	76.3	1.237	2.360	
	80.0	1.334	—	
	84.2	1.584	—	
	92.1	2.831	4.144	
Capillary transport coefficient, D_w (m^2/s)	w = 1.7 kg/m^3	6.6×10^{-11}		Generate by Eq. (3.5)
	w = 188 kg/m^3	6.2×10^{-8}		
Water absorption coefficient, A (kg/m^{2}s$^{1/2}$)		0.024		0.012
Free-water saturation, w_f (kg/m^3)		177		112

radiation absorptivity and long-wave radiation emissivity considered were 0.4 and 0.9, respectively, and the initial conditions within the element were ϕ = 80 % and T = 20 °C.

The other numerical simulations used the climatic conditions inside the laboratory. The temperature and a relative humidity were considered constant, 20 °C and 60 %, respectively.

The vapor diffusion thickness value used was zero (no coating) and the interior heat transfer coefficient was constant and equal to 8 W/m^{2}K. The exterior heat transfer coefficient only contained the convective element and was considered independent of wind (at a constant value of 17 W/m^{2}K).

3.4 Results and Discussion

The simulation program provided the water content, relative humidity and temperature at all the points on the pre-defined grid and their evolution during the simulation. It also provided the heat and moisture flows along the surfaces. Figure 3.2 show an example of the variation in the rising damp front in terms of the relative humidity and water content for different boundary conditions, wall composition and thicknesses and climates. The graphical representation shows an infinitesimal section of the wall thickness in the center of the wall. It is important to bear in mind that in the numerical simulations with granite the following approximation for moisture storage function was used (Kunzel 1995)

$$w(\varphi) = w_f \frac{(b-1)\phi}{b-\phi} \tag{3.3}$$

with

$$b = 0.8 \frac{w_{80\,\%} - w_f}{w_{80\,\%} - 0.8 w_f} \tag{3.4}$$

and the capillary transport coefficient for the suction process is estimated by

$$D_{\mathrm{ws}} = 3.8 \left(\frac{A}{w_f}\right)^2 1000^{(w/w_f - 1)} \tag{3.5}$$

Table 3.2 shows the numerical results obtained for the three different boundary conditions (configurations) in Laboratory interior conditions and Porto climate. For configurations 1 and 3 the rising damp front was obtained in the middle of the wall ($x = b/2$), and in configuration 2 this value was obtained in the waterproof side ($x = 0$).

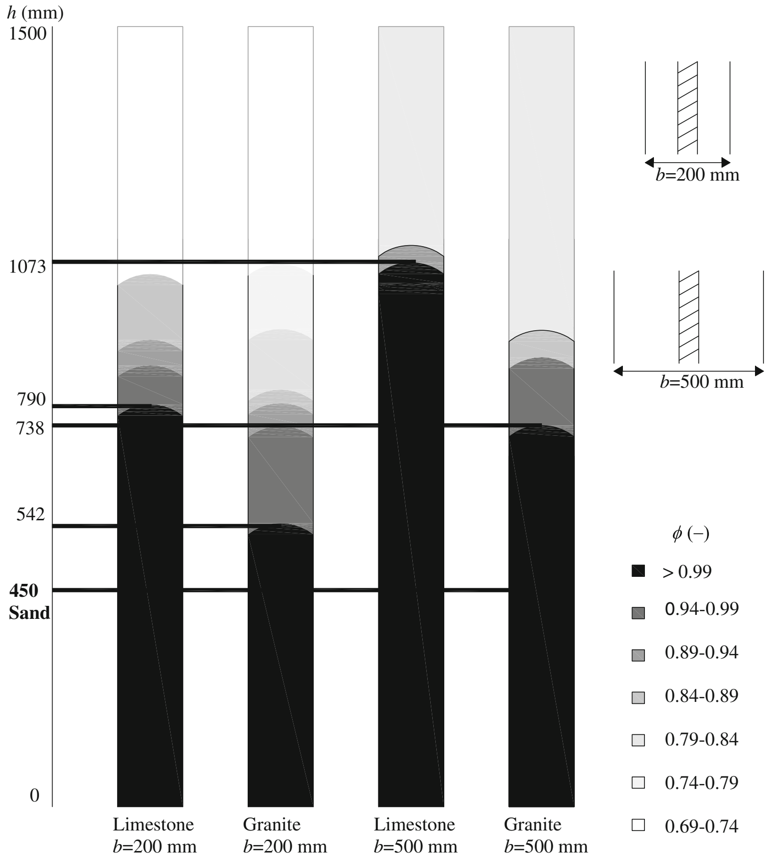

Fig. 3.2 Variation in rising damp front with relative humidity (Configuration 1), for limestone and granite, with different wall thicknesses, in Laboratory interior conditions

Table 3.2 shows that rising damp increases when drying conditions are hampered by extra waterproof coatings (see results obtained with Configurations 1 and 2). This result shows that the traditional techniques of applying coatings with reduced porosity or hiding anomalies behind a new built wall cannot be used as efficient techniques to treat rising damp. In addition, the presence of a wall base ventilation system on both sides entails a reduction of the damp front (Configuration 3).

The numerical results presented in Table 3.2, also, show that the steady-state heights of rise, h_∞, obtained in Laboratory conditions, were highest, when compared with the results obtained with the Porto climate. This is an expected result if we have in mind that, in laboratorial conditions, we have no solar radiation and lower values of evaporation potential.

Table 3.2 Numerical results obtained after a one-year simulation in Laboratory interior conditions and in Porto climate

h_∞ (mm)	b = 200 mm		b = 500 mm	
	Lime stone	Granite	Lime stone	Granite
Configuration 1				
Laboratory	790	542	1073	738
Porto	638	466	654	599
Configuration 2				
Laboratory	1025	655	1460	902
Porto	612	545	645	552
Configuration 3				
Laboratory	630	369	908	491
Porto	490	235	630	454

Related to the material properties, limestone presented a higher capillary ascension and granite a lower capillary ascension. This difference is explained by the fact that rising damp increases in materials with higher sorptivity values ($S \approx A/\rho_w$) and porosity values (water bulk volume is a function of porosity).

The comparison between the numerical results and the analytical solutions shows better results for a limestone wall than for a granite wall. These results could be explained by the granite properties adopted in the numerical simulations, namely the approximations for moisture storage function and capillary transport coefficient for the suction process, estimated by Eqs. (3.3) and (3.5).

The numerical results, presented in Table 3.2, show that the rising damp front increases with the wall thickness, b. Torres and Freitas (2007) obtained similar results in a previous experimental and numerical work. To analyze the relation between the rising damp front height and the wall thickness, several numerical and analytical results of a simple configuration were obtained and presented in Table 3.3. The results show that the dependence of h_∞ on b can be approximated by the regression, $h_\infty = A.b^n$, with exponents between 0.45 and 0.54 (see Fig. 3.3). This is an expected result if we consider the sharp front theory developed by Hall and Hoff (2002), where $h_\infty \propto f\left(\sqrt{b}\right)$. This simplified analytical model analyzes the capillary transport of liquids through porous media by the balance between absorption inflow and evaporation loss.

Table 3.3 The wall thickness influence in rising damp phenomenon

h_∞ (mm)/b (mm)	Limestone				Granite			
	200	400	600	800	200	400	600	800
Laboratory	553	752	924	1102	259	402	477	546
Porto	143	178	247	254	93	124	156	178

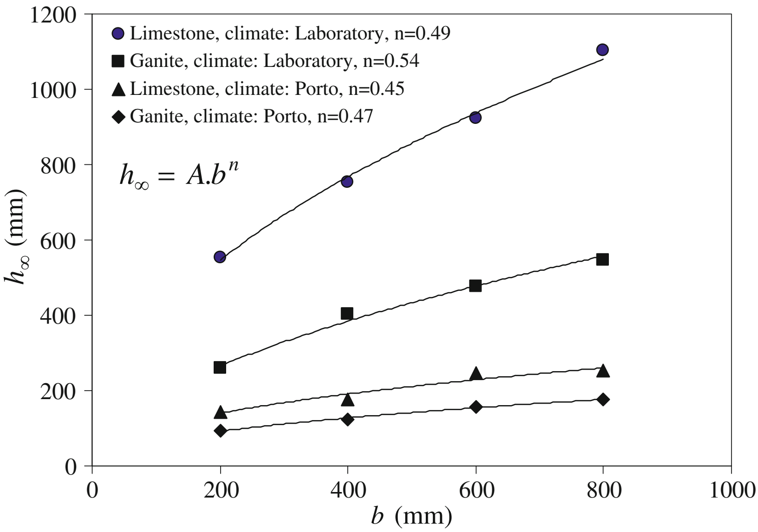

Fig. 3.3 The wall thickness influence in rising damp phenomenon

3.5 Conclusions

The main conclusions of this study, which set out to estimate the level achieved by the damp front, resulted on the following conclusions:

- It was presented the "Wall Base Ventilation System" design model to predict the damp front level based on some important and simple parameters. The evaporation potential inside the system is an important parameter of the design model.
- Regarding the influence of material properties, the most important parameter is the absorption coefficient of water, which was as expected, since this parameter best characterizes the movement of water in liquid phase within construction materials.
- The results obtained, also, show that the steady-state height of rise increase with the wall thickness as a function of the square-root of the thickness.
- The use of tiles (Configuration 2) presents as a bad solution to treat rising damp because the tiles reduce the evaporation area and the level achieved by the damp front increase.

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Chapter 4
Risk Map of Portuguese Building Heritage

The Portuguese building heritage is of great importance, justifying the need to safeguard it from extreme climatic phenomena such as floods and moisture degradation. For historical reasons the most prestigious buildings were built near the natural water lines and are possibly threatened by the flood phenomenon.

Climate changes due to global warming have revealed an increasing vulnerability of urban and rural territories to the risk of flooding. It is therefore necessary to adopt preventive measures to control, minimize and mitigate these adverse effects, avoiding catastrophic consequences.

This work presents a critical review of a criterion of risk, created to assess the flood risk of the Portuguese building heritage. In order to evaluate this criterion, it was applied to a sample of ninety monuments from the north of Portugal. In a first approach only two parameters were adopted: the shorter distance from the monument to the water lines and the height difference from the lowest point of the monument adjacent land to the plane of the closer water courses.

A final application exercise to a sample of northern Portuguese building heritage revealed a significant amount of monuments classified as medium or medium high risk of flood.

4.1 Introduction

Architectural heritage is of great importance therefore justifying the need to safeguard it from extreme climatic phenomena such as floods. The most prestigious buildings, for historical reasons, were built near the natural water courses and are frequently threatened by this flood phenomenon. Currently there is a majority trend in thinking within the scientific community which hold the view that climate change due to the intensification of the global warming, will worsen throughout the 21st century, thus causing an increase in extreme climatic phenomena (see, for example the Human Development Report 2007/2008 of the UNDP which is entitled precisely “climate change combat”, articles about the causes and possible consequences). It is therefore necessary to adopt preventive measures to minimize, mitigate and control these adverse effects, avoiding catastrophic consequences.

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in Applied Sciences and Technology, DOI 10.1007/978-3-319-19114-0_4

This context of climate change has revealed an increasing vulnerability of urban and rural territories to the risk of flooding; this is one of the largest risks growing in frequency and intensity we can expect in the coming decades.

The Laboratory of Building Physics (LFC) of UPorto has devoted a significant portion of its resources to the experimental research in the humidity field, particularly in rising damp. In recent years it has developed and validated, experimentally, a treatment technique called "HUMIVENT", which is based on the walls base ventilation to treat the problem of rising damp on high thickness walls with heterogeneity, such as our historical buildings.

Intervening in old buildings requires extensive and objective knowledge. The multifaceted aspects of the work carried out on these buildings tend to encompass a growing number of specialities, with marked emphasis on those allowing to understand the causes of the problems that affect them and to define appropriate treatments (Freitas et al. 2007).

It is of utmost importance to accept that these buildings present some unique opportunities to implement the continuing research and development in this specific area. This contribution was just a step but we need now to continue our investigation to get all the characterization and the design of a new technique—HUMIVENT.

This technique can already be used, with the necessarily revisions, to treat building walls after a flood (Guimarães et al. 2011, 2012). In Portugal we have historical buildings near water courses with degraded walls due to the permanence of the water. Certainly the problem is not only the existence of water but also the presence of salts that cyclically crystallise and dissolve contributing to the quick degradation of the building materials (Gonçalves 2006; Gonçalves et al. 2006, 2007).

Portugal is an old country enriched by many buildings and monuments with cultural and architectural interest, from different periods of history. As such, it makes perfect sense the development of strategies in order to protect those buildings from the extreme climatic phenomena such as floods and moisture degradation, since the presence of water can be an actively contribute to the degradation of the built heritage (Freitas et al. 2007).

The main goal of this work is to create and evaluate a criterion of risk. At this stage, it will be made a synthesis document of the main information about the most important historical buildings location, constitution, etc. It is not intended to finalize this work, but only assess the criterion and the options made during the process.

It thus aims to explain the applicability of the criterion and the reasons of choice of the parameters involved and also explain some difficulties concerning the data gathering, some limitations of the criterion and the best way to develop it after these preliminary results. In addition, there will be done an application exercise, only focusing the northern Portuguese monuments, to illustrate these ideas.

The final goal will be the definition of the flood risk of those buildings, considering the location and the climatic changes, and the influence of its constitution in the performance of the treatment system we executed: the wall base ventilation system—HUMIVENT to dry the building walls water.

The risk analysis methodology will start with the definition of the most important historical buildings in northern of Portugal, its location; and, in the future, a full study about its constitution considering not only the materials they are made to but also the layers and the influence of the porosity/porometry for the drying process.

Then it will also crucial the classification of the flood risk occurrence having in mind the previous information.

4.2 Cultural Heritage and Flooding in Portugal

Rising damp, because of its high occurrence frequency, and floods, because of the seriousness of their consequences, represent both a high risk in terms of building humidity. Therefore, it is our intention that the HUMIVENT system is applicable to both cases.

As one of the main objectives is the evaluation of the risk of flood occurrence it is very important to know the history of the most important river flooding in Portugal (see Table 4.1).

It is well known that the architectural heritage is of great importance therefore justifying the need to safeguard it from extreme climatic phenomena such as floods

Table 4.1 Some of the most important river flooding in Portugal (ANPC 2014)

Date	Local	Flooding characteristics
December 1909	Douro river	Régua reached with a flowrate of 16,700 m^3/s
January 1948	Several rivers	–
January 1962	Mondego and Douro river	Second largest flood of 20th century
November 1967	Tejo river	Fast rising flood
February 1978	Tejo and Sado rivers	Slow rising flood
February 1979	Tejo river	The largest flood of 20th century Fast rising flood, during 9 days
November 1983	Tejo river	Fast rising flood
1983	Cascais	–
December 1989	Tejo and Douro rivers	Santarem and Vila Real were very reached with a flowrate of 12,000 m^3/s
October 1997	Monchique	Fast rising flood
November 1997	Low Alentejo	Fast rising flood in Ourique, Aljustrel, Moura and Serpa
2000/2001	Tejo and Douro rivers	Several flood during 4 months (Dec–Mar) in Porto, Vila Real and Santarem
January 2001	Mondego river	Flood caused by flow increase and levees rupture
February 2010	Madeira island	Fast rising flood

as we can see on Patrimoine Culturel et risques naturels: Les méthodologies d'évaluation et réduction des risques volcaniques, biologiques et hygrothermiques (Freitas et al. 2007).

A list of Portuguese monuments with some of their characteristics that are considered to influence the degradation of national heritage has been compiled. It is important to collect all the available characteristics that are relevant for this study (and future coming studies) and for the complete characterization of buildings: GPS coordinates, district, municipality and parish, the composing materials, the elevation, the distance to the nearest water line, a description, among others (Monumentos 2014).

This developing monuments spreadsheet database should be gradually improved with some new supplementary information relevant to the optimization of the criterion of risk.

About ninety northern Portuguese monuments have been listed. For that selection some exclusive criteria were considered, in order to create the final sample. As for the exclusive criteria, it is recommended to analyse the following scheme (see Fig. 4.1).

The first step of selection was made by considering all the monuments classified as National Monument in northern districts—310 monuments. According to NUTS division some monuments (from Aveiro, Guarda and Viseu districts) were excluded once they belong to the central region of Portugal (according to the municipality where they belong)—248 monuments effectively belonging to the northern region of Portugal. Monuments without habitable ground floor (as archaeological monuments, pillory or castles) were also excluded—123 monuments with habitable ground floor. As there are some missing or unclear information, some monuments were excluded, and the final selection is composed by 94 monuments.

The compilation of monument characteristics has resulted in a data spreadsheet, where the information is synthetized and organized. An example of the spreadsheet is presented in Fig. 4.2.

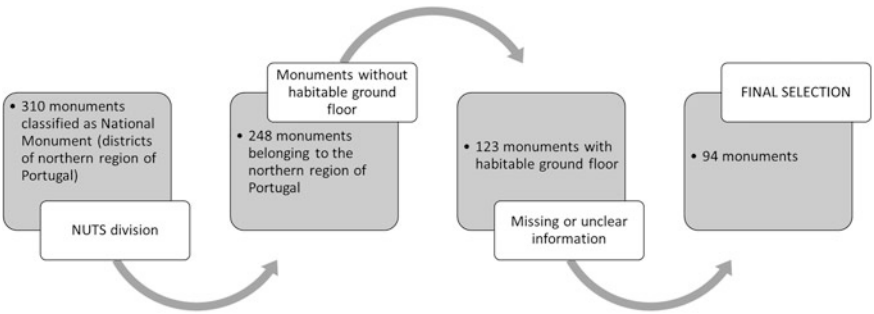

Fig. 4.1 Exclusive criteria for the selection of monuments

General number	Designation	Region	District	Municipality	Parish	Latitud	Longitude	Water line reference	Distance [m]	Height difference [m]	D range level	H range level	RISK LEVEL

Fig. 4.2 Example of data spreadsheet

The relevant information to the correct implementation of monuments is the following: general number, designation, region, district, municipality, parish, latitude, longitude, distance, height difference, water line reference, D range level, H range level, risk level (classification of risk degree).

The location data were found in SIPA Information (Monumentos 2014) and confirmed by google earth. After that, the information was transposed by a command to a Geographic Information System. On the other hand, some information, namely elevation and distance, were collected from the software and added to the text file. This methodology enables the constant data updating.

After that, the Portuguese map was introduced and used as basis for the implementation of the data collected.

The location of Portuguese water lines was imported from the SNIRH website (SNIRH 2014). A compatible shape file was added to all the information previously collected. The superficial water lines and the principal lines of Portuguese water line map from SNIRH were added to this work in order to confirm the information available in the cartography. The SNIRH information just helped the location of water lines that sometimes was not easily or clearly seen in the cartographic map. All distances were measured from the monument to the closer water line seen in the cartographic map.

There is no full assurance about this option once the seasonal changes on riverbeds have been not considered and the principal water lines chosen may be not the most relevant to assess the risk of flooding in some cases. Without statistical and hydraulic information, it is difficult to choose between a closer line with minor relevance and a faraway line with major relevance.

The subsequent step was to gather all the information in free software with adequate cartographic basis. The software chosen was QGIS (a user friendly Open Source Geographic Information System) but any different software of Geographical Information System (GIS) could have been used (QGIS 2014).

The Geographical Information System software offers the possibility to open digital maps, to add some new spatial information and to create printed maps. With this kind of software it was possible to compile all the data collected in a single place and, after that, export new spatial information, as distances, elevation and others (see Fig. 4.3).

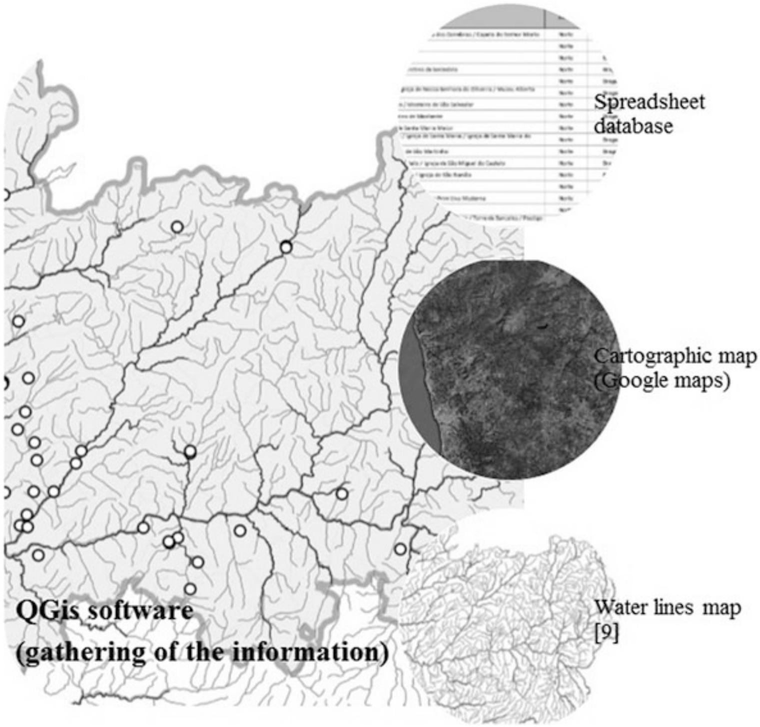

Fig. 4.3 Gathering of information

4.3 Methodology

The Portuguese territory, due to its geomorphology, has a wide and complex drainage system, which means that buildings are often located next to a waterway. The proximity to waterways, either in terms of horizontal or vertical distance, is the dominant factor in the calculation of the probability of a building to be affected by floods. However, if the water actually reaches a certain building, the factor that will determine the consequences that result therefrom, is the behaviour of the material when in contact with water. Thus, in this study, two main components were used to calculate the flood risk of a certain building: the monument location in relation to a waterway and the behaviour of the material when in contact with water.

4.3.1 Proximity to Waterways

4.3.1.1 Horizontal Distance—D_{WL}

The horizontal distance was measured in a straight line from the central point of the monument to the water's edge in the closest waterway, as shown in Fig. 4.4.

The risk classification for the horizontal distance was based on the combination of two aspects: a record of the distances achieved in historical Portuguese floods and the personal knowledge of the territorial positioning of some of the monuments. Accordingly, it was possible to refine the criteria and obtain the values shown in Table 4.2.

4.3.1.2 Vertical Distance—ΔH

The altimetry analysis was performed based on the difference in altitudes between the same two points used for measuring the horizontal distance, as shown in Fig. 4.5. The choice of criteria for the risk classification was made re-sorting the same two classification parameters previously used for the horizontal distance.

Fig. 4.4 Scheme of the measurements

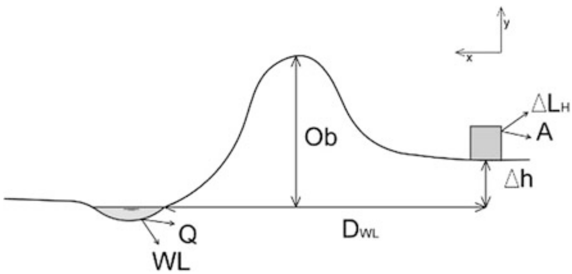

Table 4.2 Risk criteria and classification for the flood risk main factors

Flood risk main factors	Risk Criteria	Risk classification
Horizontal distance—D_{WL} (m)	>150	1
	$50 < D_{LA} \leq 150$	1.5
	≤50	2
Vertical distance—Δh (m)	>20	1
	$5 < D_{LA} \leq 20$	1.5
	≤5	2
Waterway type—*WL*	Type 4, 5 and 6	1
	Type 3	1.5
	Type 1 and 2	2
Water absorption coefficient—A (kg/m^{2}s$^{1/2}$)	>0.0333	2
	<0.0333	1

Very High Risk	**FR ≥ 2.0**
High Risk	**1.75 ≤ FR < 2.0**
Medium Risk	**1.25 < FR < 1.75**
Low Risk	**FR ≤ 1.25**

Fig. 4.5 Flood risk classification

The existence of underground floors in the building should be taken into account in the altimetry analysis, once it increases flood risk. In case of flood, the full removal of the water and drying of construction elements becomes more complex, making it is important to consider this variable in the risk model—*UF*. Therefore, a secondary factor was added, associated with the Δh factor, which increases the risk by 20 %. During the measurements of horizontal and vertical distances, the presence of obstacles between buildings and waterways was detected. The geomorphology of the terrain is considered as an obstacle between the Monument and the waterway. Obstacles resulting from humans' occupation were excluded.

n response to this issue, a secondary factor was introduced in the model, named *Ob*, in order to decrease the risk established by the vertical distance. The risk value of the Ob factor depends on the height of the obstacle that is measured as shown in Fig. 4.4. The higher the obstacle, the smaller is the value assigned to the factor Ob. Factor Ob can assume the value 1 if there is no obstacle or a value between 0.1 and 0.5 depending on the obstacle's height (see Table 4.3).

4.3.1.3 Waterway Type—W_L

Each drainage system is constrained by topography, climate and the lithology of the environment in which it is inserted making it that all drainage systems have distinct drainage characteristics. The consequences of floods caused from different waterlines will also be different. For example, the bifurcation ratio of a drainage basin

Table 4.3 Risk criteria and classification for the flood risk secondary factors

Flood risk secondary factors	Risk criteria	Risk classification
Underground floors existence—*UF*	Yes	1.2
	No	1
Obstacle existence—*Ob*	Yes	[0.1–0.5]
	No	1
Building location in relation to the waterway—*Q*	Upper course	1
	Middle course	1
	Lower course	1.2
Hydric Expansion—ΔL_H (mm/m)	>1	1.5
	$0.5 < \Delta L_H \leq 1$	1.2
	≤0.5	1

and the waterway dimensions are important parameters to take into consideration when anticipating flood consequences. Thus, in order to develop the risk model closer to reality as possible, it is relevant to create a hierarchy that orders the importance of the waterways.

In order to take the waterway type into consideration, a classification system similar to the most commonly used—the Strahler stream order—was created. According to Maia (2014), the Strahler order assigns a number to a waterway which reflects the degree of ramification or bifurcation existing within a drainage basin, based on discharge, drainage basin area and stream bed width. The classification proposed in this study was established on the basis on the information about the Portuguese drainage system available in the SNIRH database, however this information is not sufficient to assign a Strahler number to each waterway. Thus, the waterways order was attributed based on the subdivision level of the network. The stream order varies between 1 and 6, wherein the main waterlines have order 1, tributaries have order 2 and so on up to order 6.

Along the course of a river, the fluvial morphology is not always the same. Some areas are more susceptible to the occurrence of floods than others. In the lower course of a river, slopes are less accentuated with floodplains reach many kilometers (Sousa 2012). According to this, the variation of the discharge is more evident in the lower course of the river, i.e. at the end of the waterway the adjacent areas have a higher flood risk than at the beginning or middle of the waterway. Furthermore, there is an interaction between the flood discharge and tide conditions at the final section of watercourses, near estuaries, lagoons and coastal areas. The simultaneous occurrence of a flood discharge and a high tide can raise the water level and aggravate flood consequences (Portela 1990). This fact justifies the need to add a secondary factor associated with the waterway type factor described above that indicates the location of the monument with respect to the course of the waterway: upper, middle or lower course. This secondary factor is designated by Q and increases the risk by 20 % when the monument is located at the end of the watercourse.

4.3.2 Construction Materials

4.3.2.1 Water Absorption Coefficient—A

The water absorption coefficient A (kg/m^2.s$^{1/2}$) characterizes the property of a material to absorb liquid water by suction when in contact with water (Silva 2011). The most commonly used materials in civil engineering, such as wood, stone and brick, have certain properties like porosity that makes them to absorb water and change their behaviour in the presence of it. Therefore, for each monument the effect of the water on the material was considered by adding a factor that evaluates the water absorption coefficient of the most harmful material, without distinction from wall and floor materials. According to the German standard DIN 4108-4

(1995), building materials can be classified into four categories, depending on the value of the coefficient of water absorption. Table 1 submits a proposal for the risk classification based on the classification of the aforementioned standard.

4.3.2.2 Hydric Expansion—ΔL_H

Once the materials were characterized regarding the water absorption coefficient, it was necessary to add a secondary factor to evaluate the behaviour of materials when in contact with water. The materials that absorb more water, *i.e*. those having a higher water absorption coefficient, are not always those who suffer greater damage by the presence of water. This is the case of wood, a commonly used material in Portuguese buildings, which is exposed to dimensional changes when in contact with water. Those changes are visible to the naked eye and yet wood does not have a very high water absorption coefficient.

The construction materials have the ability to expand, due to water absorption, which causes considerable deformations. Cycles of expansion/retraction of materials cause some of their properties to change. Consequently, they may become damaged and lose their mechanical resistance (Siedel 2010). Thus, a secondary factor was introduced that relates the risk classification associated with water absorption reflecting the possible expansion that can occur from this same absorption. The risk classification of factor ΔL_H was based on previous experiences from weathering researches on building stones performed by several authors cited in (Siedel 2010). Table 4.3 presents a proposal for the risk rating of this factor.

4.3.3 Risk Classification

To analyse the flood risk of each monument, four main factors and four secondary factors were chosen. The first ones may take the values of 1.0, 1.5 or 2.0, depending on the degree of influence of each factor on flood risk. The second ones act as a mean of increase or decrease of the risk value chosen for the main factors to which they are associated, whereby they appear multiplied by the respective main factor.

However, assuming that the main risk factors do not all have the same importance, it was necessary to use a weighted formula to calculate the risk (see Eq. 4.1). The risk factor associated with the materials cannot have a very representative weight, since you must first get together certain conditions before the water reaches the building materials. Thus, 90 % of the risk was associated with the proximity to the waterlines and 10 % to the materials. From the three risk factors related to waterways—the horizontal and vertical distance to the waterway and the type of waterway—it was considered that the vertical distance should be the decisive risk factor in the flood risk determination. The water, due to gravity, cannot overcome great height differences. The weight of 60 % was attributed to the vertical distance between the monument and the waterway, 20 % to horizontal distance and 10 % to the type of waterway:

$$FR = 0.2D_{WL} + 0.6\Delta h \times UF \times Ob + 0.1WL \times Q + 0.1A \times \Delta L_H \quad (4.1)$$

where, FR is the flood risk, D_{WL} is the horizontal distance to the waterway, Δh is the height difference between the building and the waterway, UF is the existence of underground floors, Ob is the existence of obstacles, WL is the waterway type, Q is the discharge, A is the water absorption coefficient and ΔL_H is the hydric expansion.

The result is displayed as a numerical value, which does not allow immediate identification of the flood risk associated with the Monument. However, a flood risk classification was created as shown in Fig. 4.5. It divides the flood risk into four categories associated with a numerical range and a colour.

4.4 Results and Discussion

4.4.1 Risk Map Applied to the North of Portugal

The classification of the National monuments located in Northern of Portugal was developed based on the risk criterion presented above, and each monument was identified according to the criterion and coloured complying that.

The results were presented in a map (see Fig. 4.6) that shows the distribution of monuments in this region and their flooding risk level. As soon as the criterion of flood risk is stabilized, more detailed maps can be presented.

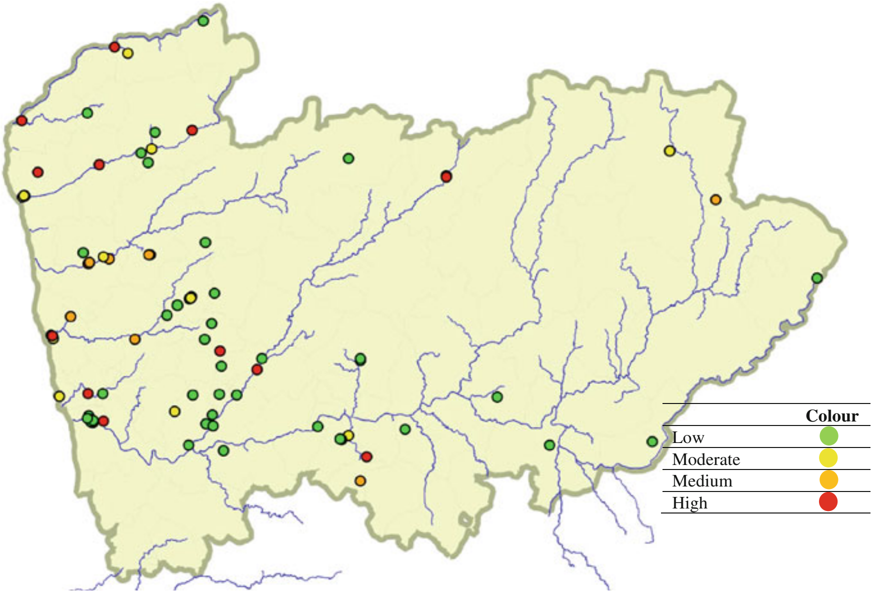

Fig. 4.6 Risk map of national monuments located in Northern of Portugal

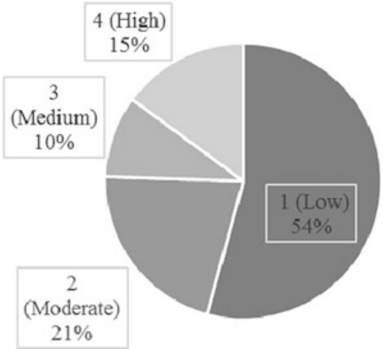

Fig. 4.7 Statistics of the national monuments classified

A simple statistical analyse of the preliminary results were done and it is possible to observe that approximately one quarter of the full sample is classified as medium or high flood risk and about three quarters as low or moderate flood risk (see Fig. 4.7).

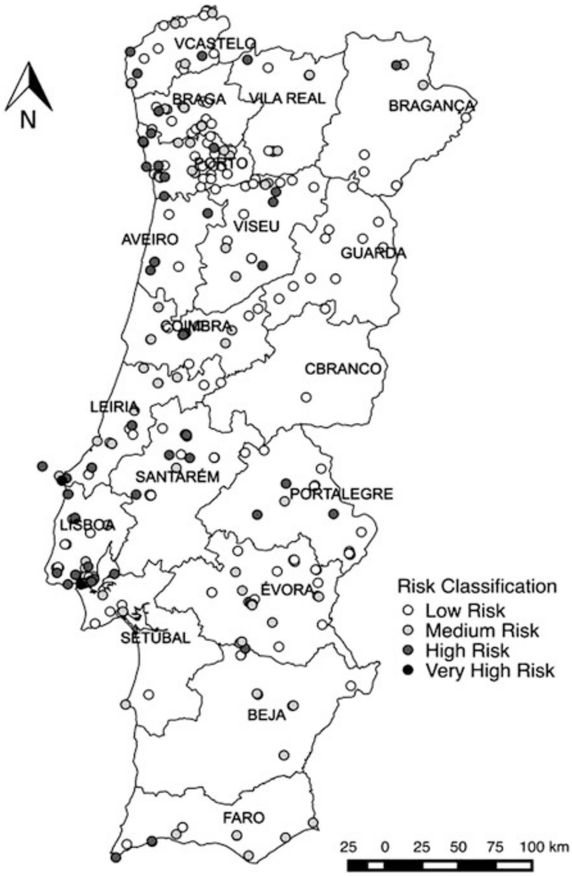

Fig. 4.8 Portuguese map of flood risk

4.4.2 *Risk Map of Portuguese Building Heritage*

Flood risk maps are a powerful auxiliary tool in control and prevention of floods, because they provide a more effective risk communication and, consequently, may lead to an adequate response on the occurrence of this phenomenon. Thus, to have a better perception of the flood risk in the Portuguese territory there was created a flood risk map (see Fig. 4.8) using the results that were obtained through the application of the risk model described above. About 40 % of the sample of 397 monuments that were analysed in this study are classified as medium to high risk of flooding.

4.5 Conclusions

The flood phenomenon is well studied in the hydrology field. However, there are not many studies related to the impact created by floods on historical buildings, particularly in the Portuguese territory. The presented model was developed in the Laboratory of Building Physics and has been tested in some academic works with some particular differences between them. It is intended to analyse the model by some sensibility tests.

In the present work, the model is applied to a sample of monuments. In this first approach, it is not intended to finalize this work, but only to assess the criterion and the options made during the process and also explain some difficulties concerning the data gathering, some limitations of the criterion and the best way to develop it after these preliminary results. This work proposes an analytical model of flood risk. It was applied to Portuguese heritage buildings. Overall, the flood risk model showed good and promising results. The main conclusions observed are:

- The height difference, Δh, is the most influent factor in the definition of the risk flood of a building;
- The lower the values of the absorption coefficient and the hydric expansion are, the lower is the impact created by the water in the buildings materials;
- Approximately 40 % of the analysed monuments show medium or high flood risk. Therefore, it is necessary to create preventive and protective measures to control the effect of floods.

For future developments it is suggested to:

- For heights greater than 20 m the distance maybe should be neglected and the risk level considered low;
- Consider the existence/nonexistence of underground floor and account the increased risk;
- Achieve a greater accuracy in the gathering of heights of buildings and water lines—find more appropriate work bases;

- Study the topography surrounding the monument and the waterline (elevations, valleys or others between the monument and the water line);
- Incorporate the possibility that the same river may have seasonally variable flow;
- Consider the relative location of the monument in the river course (river source/river mouth/other);
- Incorporate the constitution of buildings (building systems/materials) and, when applicable, account for the added risk;
- Apply the criteria to well-known monuments by collecting some in situ information.
- Apply the flood risk model to another territory to validate and calibrate the weights given in the flood risk formula;
- Develop a flood risk model with a larger number of parameters and apply it to a percentage of the sample analysed in this work. The results of the new model should be compared to the ones obtained in this work;
- Collect more information about the existence of underground floors and the characteristics of the building materials and waterways. It is believed that increasing the accuracy and number of risk parameters, the percentage of monuments with medium and high flood risk would be higher than estimated.

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Chapter 5
Conclusions and Recommendations

Architectural heritage is of greatest importance, which justifies the need to safeguard it from extreme climatic phenomena such as floods. The most prestigious buildings were built, for historical reasons, near natural waterways and are frequently threatened by the flood phenomenon. Currently, the scientific community holds the view that, due to intensification of the global warming, climate change will worsen throughout the 21st century. It is therefore necessary to adopt preventive measures to minimize, mitigate and control these adverse effects, avoiding catastrophic consequences.

Climate change has revealed an increasing vulnerability of urban and rural territories to the risk of flooding; this is one of the greatest hazards, growing in both frequency and intensity, we can expect in the coming decades.

The flood phenomenon is well studied in the hydrology field. However, there are not many studies related to the impact created by floods on historical buildings, particularly in the Portuguese territory.

This work presents a critical review of the main information related with the Portuguese monuments classified as "National Monuments". It also proposes an analytical model of flood risk. In the model proposed it was consider two different groups of parameters: the monument location in relation to a waterway, and the behaviour of its construction material when in contact with water. Equation 4.1 takes into account all of the factors defined as the most influent in flood risk determination. It was applied to Portuguese heritage buildings. Overall, the flood risk model showed good and promising results. The main conclusions observed are:

- The height difference, Δh, is the most influent factor in the definition of the risk flood of a building;
- The lower the values of the absorption coefficient and the hydric expansion are, the lower is the impact created by the water in the buildings materials;
- Approximately 40 % of the analysed monuments show medium or high flood risk. Therefore, it is necessary to create preventive and protective measures to control the effect of floods.
- A risk map (Fig. 4.8) was created on the basis classification developed where it will be possible to observe that a significant amount of Portuguese monuments are classified as medium to high risk of flooding.

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For future developments it is suggested to:

- Apply the flood risk model to another territory to validate and calibrate the weights given in the flood risk formula;
- Develop a flood risk model with a larger number of parameters and apply it to a percentage of the sample analyzed in this work. The results of the new model should be compared to the ones obtained in this work;
- Collect more information about the existence of underground floors and the characteristics of the building materials and waterways. It is believed that increasing the accuracy and number of risk parameters, the percentage of monuments with medium and high flood risk would be higher than estimated.