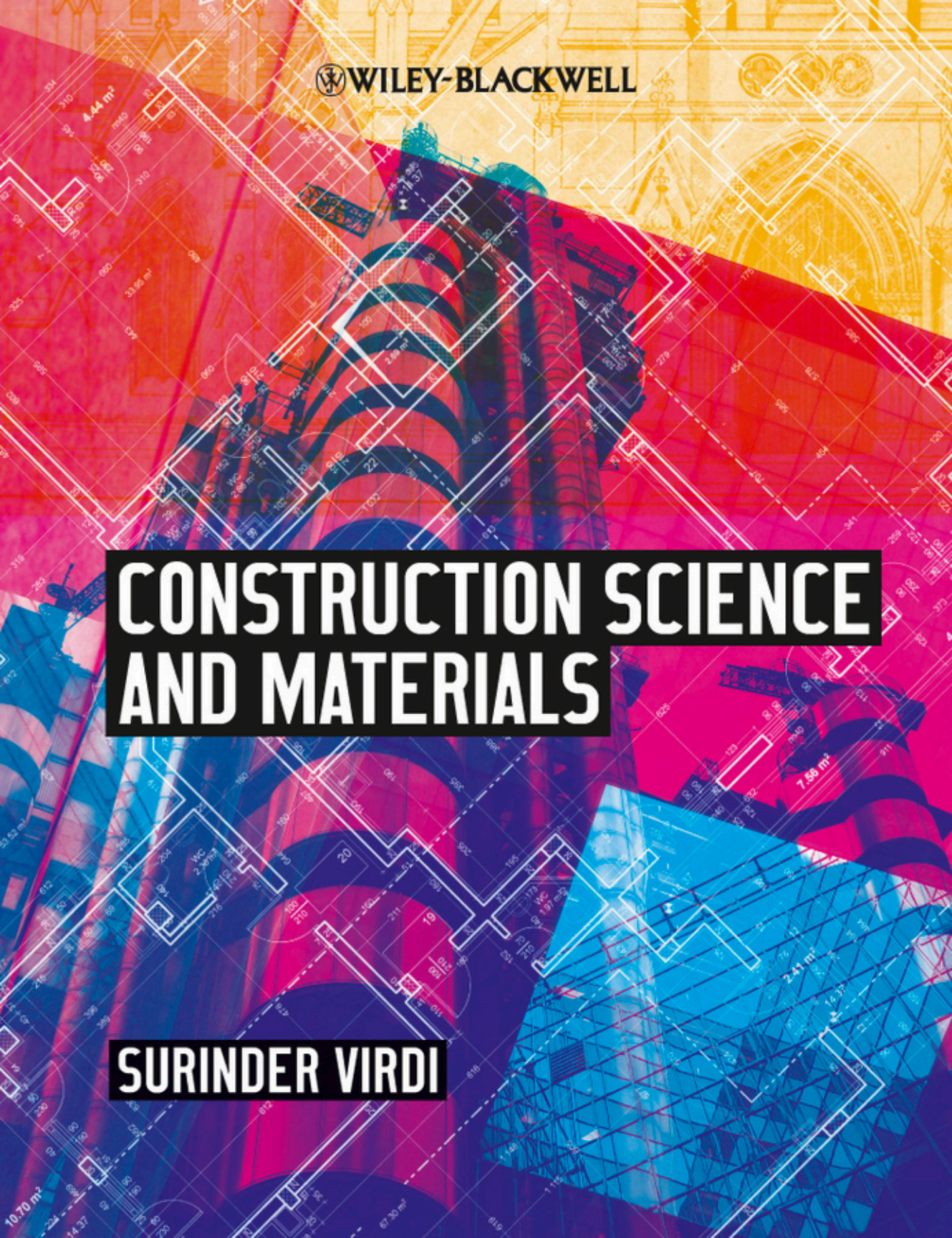




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CONSTRUCTION SCIENCE AND MATERIALS

SURINDER VIRDI

Construction Science and Materials

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the memory of my parents, Mr Amar Singh Virdi
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- fully worked solutions to the exercises at the end of chapters
- model answers for the assignment tasks set in Chapter 17
- explanation of settlement and consolidation in structures
- details on the design of building foundations
- daylight calculations
- a task + solution on the design of timber joists
- PowerPoint slides for lectures on: Hooke's Law; Forces & Their Effects; Temperature & Heat Loss

Construction Science and Materials

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- explanation of settlement and consolidation in structures
- details on the design of building foundations
- daylight calculations
- a task + solution on the design of timber joists
- PowerPoint slides for lectures on: Hooke's Law; Forces & Their Effects; Temperature & Heat Loss

Preface

This book has been written for students pursuing full-time/part-time studies in Level 2, 3 and 4 programmes in Construction, Civil Engineering and Building Services. The topics included cover most of the syllabus of the core subject of Construction Science and Materials. The information has been divided into sixteen chapters providing information on construction science and construction materials for the above courses. The book should also be informative for students on Level 2/3 construction craft courses.

Construction Materials is a subject on its own; in this book the discussion is focused on a selection of eight materials that are widely used in building and civil engineering projects. The text in this book is supported by a large number of illustrations and worked examples.

My thanks are due to my family, my students and colleagues for the interest they have shown in this project. John Wood, Robert Waters and Steve Spence provided valuable assistance.

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Surinder Singh Viridi

How to use this book

All students should spend some time on studying the first seven chapters.

Students pursuing Level 2 courses should focus additionally on Chapters 3, 8, 10 and 16, and part of Chapter 11.

Students pursuing Level 3/4 courses should study all chapters in this book.

Specimen assignment tasks are given in Chapter 17, which the students can try once they have studied the relevant topics. The model answers are given in the companion website www.wiley.com/go/virdiconstructionscience

The website also includes the solutions for questions at the end of chapter exercises; information on settlement and consolidation; design of building foundations; design of timber joists; daylight calculations; and PowerPoint presentations on some topics.

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List of units, prefixes and symbols

Units

Quantity	Name of unit	Symbol	Quantity	Name of unit	Symbol
Length	metre	m	Power	watt	W
Mass	kilogram	kg	Acceleration		m/s ²
Time	second	s	Velocity		m/s
Thermodynamic temperature	kelvin	K	Celsius temperature	degrees celsius	°C
Plane angle	radian	rad	Thermal conductivity		W/mK
Solid angle	steradian	sr	Heat capacity		J/K
Frequency	hertz	Hz	Moment of a force		kNm
Force	newton	N	Specific heat capacity		J/kg K
Pressure or stress	pascal	Pa	Potential difference		V
Luminous intensity	stress	N/m ²	Sound reduction index	decibels	dB
Luminous flux	candela	cd	Wavelength	metre	m
	lumen	lm			

Greek alphabet

Upper case	Lower case	Name	Upper case	Lower case	Name
A	α	Alpha	N	ν	Nu
B	β	Beta	Ξ	ξ	Xi
Γ	γ	Gamma	Ο	ο	Omicron
Δ	δ	Delta	Π	π	Pi
E	ε	Epsilon	Ρ	ρ	Rho
Z	ζ	Zeta	Σ	σ	Sigma
H	η	Eta	Τ	τ	Tau
Θ	θ	Theta	Υ	υ	Upsilon
I	ι	Iota	Φ	φ	Phi
K	κ	Kappa	Χ	χ	Chi
Λ	λ	Lambda	Ψ	ψ	Psi
M	μ	Mu	Ω	ω	Omega

Prefixes

Abbreviations/symbols

Name	Symbol	Factor	Description	Symbol
Tera	T	10^{12}	Approximately	Approx.
Giga	G	10^9	Change in length,	Δ
Mega	M	10^6	temperature etc.	
Kilo	k	10^3	For example	e.g.
Hecto	h	10^2	Greater than	>
Deca	da	10	Degrees, minutes, seconds	° ' "
Deci	d	10^{-1}		
Centi	c	10^{-2}	Less than	<
Milli	m	10^{-3}	Proportional to	$\propto$
Micro	μ	10^{-6}	That is	i.e.
Nano	n	10^{-9}	Therefore	$\therefore$
Pico	p	10^{-12}		

1

Using a scientific calculator

Learning outcomes:

- 1) Identify the keys of a scientific calculator.
- 2) Perform a range of simple and complex calculations.

1.1 Introduction

Before the development of scientific calculators, scientists and engineers used tables of logarithms (popularly known as log tables), slide rules and manual techniques to perform mathematical and scientific calculations. The use of electronic calculators, which became popular in Britain and elsewhere during the early 1970s, made calculations straightforward and saved a lot of time.

The exercises included in this book require the use of a scientific calculator; therefore this chapter deals with the familiarisation of its main keys. The procedure for performing calculations in all calculators is basically the same, however, with some complex calculations there may be some differences. The reader should consult the instructions booklet that came with their calculator, if there is any problem.

The order in which the keys of a modern calculator are pressed is the same as the order in which a calculation is written. Some of the commonly used keys are shown in the next section.

1.2 Keys of a scientific calculator

The keys of a typical scientific calculator are shown in Figure 1.1.



Adds two or more numbers



Subtracts a number from another number



Figure 1.1



Divides a number by another number



Used to multiply two or more numbers



Cancels or clears an existing calculation



Press this key to use the second function of a key



Use this key to set the calculator for performing calculations in terms of degrees or radians



Calculates the square root of a number



Calculates the cube root of a number



Use this key to determine the square of a number



Use this key to determine the cube of a number

$x^{\square}$	x^y	A number can be raised to any power by pressing this key	
π		Use this key wherever π occurs in a formula	
$a \frac{b}{c}$		Enters a fraction into the calculator	
sin	cos	tan	Use the appropriate key to determine the sine/cosine/tangent of an angle
$\sin^{-1}$	$\cos^{-1}$	$\tan^{-1}$	If the sin/cos/tan of an angle is given, use the appropriate key to determine the angle
log		Use this key if the calculation involves logarithm to the base 10	
10^x		This key is used to calculate antilogarithms, i.e. the reverse of log	
EXP	or	$\times 10^x$	Use these keys to raise 10 to the power of a given number
ln		Used to calculate logarithm of a number to the base 'e'	
e^x		Use this key to raise the exponential e (2.718281 approx.) to any number It can also be used to calculate natural antilogarithms	
$^{\circ} ' ''$		This key is used to convert an angle into degrees, minutes and seconds	
(	)	These keys will insert brackets in the calculations involving complicated formulae	
DEL		Press this key to delete the number at the current cursor position	

Example 1.1

Calculate $37.60 - 40.15 + 32.57$

Solution: The order of pressing the calculator keys is:

3 7 . 6 0 - 4 0 . 1 5 + 3 2 . 5 7 = **30.02**

Example 1.2

Calculate $\frac{38.9 \times 57.5}{44.69}$

Solution: The sequence of inputting the information into the calculator is given below:

3 8 . 9 $\times$ 5 7 . 5 $\div$ 4 4 . 6 9 = **50.05**

Example 1.3

Calculate $\frac{87.2 \times 67.92}{23.96 \times 40.4}$

Solution: The answer to this question can be found in either of two ways:

a) $\boxed{8} \boxed{7} \boxed{.} \boxed{2} \boxed{\times} \boxed{6} \boxed{7} \boxed{.} \boxed{9} \boxed{2} \boxed{\div} \boxed{2} \boxed{3} \boxed{.} \boxed{9} \boxed{6} \boxed{\div}$

$\boxed{4} \boxed{0} \boxed{.} \boxed{4} \boxed{=} \mathbf{6.119}$

b) $\boxed{8} \boxed{7} \boxed{.} \boxed{2} \boxed{\times} \boxed{6} \boxed{7} \boxed{.} \boxed{9} \boxed{2} \boxed{\div} \boxed{(} \boxed{2} \boxed{3} \boxed{.} \boxed{9}$

$\boxed{6} \boxed{\times} \boxed{4} \boxed{0} \boxed{.} \boxed{4} \boxed{)} \boxed{=} \mathbf{6.119}$

Example 1.4

Calculate $\sqrt{4.5} \times \sqrt{5.6} + \sqrt{3.3}$

Solution:

The calculator operation is:

$\boxed{\sqrt{}} \boxed{4} \boxed{.} \boxed{5} \boxed{\times} \boxed{\sqrt{}} \boxed{5} \boxed{.} \boxed{6} \boxed{+} \boxed{\sqrt{}} \boxed{3} \boxed{.} \boxed{3} \boxed{=} \mathbf{6.837}$

Example 1.5

Calculate the value of πr^2 if $r = 2.55$

Solution: The sequence of pressing the calculator keys is:

$\boxed{\pi} \boxed{\times} \boxed{2} \boxed{.} \boxed{5} \boxed{5} \boxed{x^2} \boxed{=} \mathbf{20.428}$

Example 1.6

Find the value of $(2.1 \times 4.9) + (5.1 \times 3)$

Solution:

The sequence of calculator operation is:

(2 . 1 × 4 . 9) + (5 . 1 × 3) = **25.59**

Example 1.7

Evaluate $\frac{6^4 \times 4^3}{2^4}$

Solution: In this question $x^\square$ key will be used to raise a number to the given power.

Press the keys in this sequence:

6 $x^\square$ 4 $\times$ 4 $x^\square$ 3 $\div$ 2 $x^\square$ 4 = **5184**

Example 1.8

Calculate the values of: a) $(6.25)^{1/2}$ b) $216^{1/3}$ c) $25^{2/3}$

Solution:

Use the power key $x^\square$ to solve these questions:

a) 6 . 2 5 $x^\square$ 1 $\frac{b}{c}$ 2 = **2.5**

b) 2 1 6 $x^\square$ 1 $\frac{b}{c}$ 3 = **6**

c) 2 5 $x^\square$ 2 $\frac{b}{c}$ 3 = **8.55**

Example 1.9

Calculate: a) $\log_{10} 4000$ b) $\text{antilog } 5.8$ c) $10^{-6} \div 1.8$

Solution:

a) Use the $\boxed{\log}$ key to solve this question:

$$\boxed{\log} \boxed{4000} \boxed{=} \mathbf{3.602}$$

b) Antilog is the reverse of log; the sequence of inputting the information into the calculator is given below:

$$\boxed{\text{SHIFT}} \boxed{\log} \boxed{5.8} \boxed{=} \mathbf{630\ 957.34}$$

c) The $\boxed{\text{EXP}}$ key is used to raise 10 to any power:

$$\boxed{\text{EXP}} \boxed{(-)} \boxed{6} \boxed{\div} \boxed{1} \boxed{.} \boxed{8} \boxed{=} \mathbf{5.556 \times 10^{-7}}$$

Example 1.10

Calculate $10 \log_{10} \left(\frac{6 \times 10^{-7}}{3 \times 10^{-12}} \right)$

Solution: The $\boxed{\text{EXP}}$ and $\boxed{\text{Log}}$ keys will be used to solve this question:

$$\boxed{1} \boxed{0} \boxed{\log} \boxed{(} \boxed{6} \boxed{\text{EXP}} \boxed{(-)} \boxed{7} \boxed{\div} \boxed{3} \boxed{\text{EXP}} \boxed{(-)} \boxed{1} \boxed{2} \boxed{)} \boxed{=} \mathbf{53.01}$$

Example 1.11

Calculate $\frac{\sin 60^\circ}{\cos 50^\circ}$

Solution: Use the $\boxed{\text{MODE}}$ key to change the angle unit to degrees (D). Then press the following keys:

$$\boxed{\sin} \boxed{6} \boxed{0} \boxed{\div} \boxed{\cos} \boxed{5} \boxed{0} \boxed{=} \mathbf{1.347}$$

Example 1.12

- Find the angle if
- a) the sine of an angle is 0.4
 - b) the cosine of an angle is 0.71
 - c) the tangent of an angle is 0.65

Solution: Use the MODE key to change the angle unit to degrees. This question involves the determination of angles, therefore the process is the reverse of that used in Example 1.11. Instead of sin, cos or tan keys, use $\sin^{-1}$, $\cos^{-1}$ and $\tan^{-1}$.

- a) Use this sequence to determine the angle as a decimal number first, and then change to the sexagesimal system (i.e. degrees, minutes and seconds)

$$\boxed{\text{SHIFT}} \boxed{\sin} \boxed{0} \boxed{.} \boxed{4} \boxed{=} 23.5782^\circ \boxed{^\circ ' ''} \mathbf{23^\circ 34' 41.44''}$$

b) $\boxed{\text{SHIFT}} \boxed{\cos} \boxed{0} \boxed{.} \boxed{7} \boxed{1} \boxed{=} 44.7651^\circ \boxed{^\circ ' ''} \mathbf{44^\circ 45' 54.3''}$

c) $\boxed{\text{SHIFT}} \boxed{\tan} \boxed{0} \boxed{.} \boxed{6} \boxed{5} \boxed{=} 33.0239^\circ \boxed{^\circ ' ''} \mathbf{33^\circ 1' 25.92''}$

Exercise 1.1

1. Calculate $37.84 - 40.61 + 31.86 - 9.66$
2. Calculate $\frac{33.95 \times 56.25}{45.66}$
3. Calculate $\frac{67.30 \times 69.91}{25.91 \times 20.55}$
4. Calculate $\sqrt{4.9} \times \sqrt{8.5} + \sqrt{7.7}$
5. Calculate the value of πr^2 if $r = 13.15$
6. Find the value of:
 - a) $(3.2 \times 8.8) + (6.2 \times 5.3)$
 - b) $(4.66 \times 12.8) - (7.5 \times 4.95)$
 - c) $(4.4 \times 10.8) \div (7.3 \times 4.5)$
7. Calculate the values of: a) $(20.25)^{1/2}$ b) $2401^{1/4}$ c) $35.5^{2/3}$
8. Calculate: a) $\log_{10} 65000$ b) $\text{antilog } 3.45$
9. Evaluate:
 - a) $\frac{5^3 \times 3^5}{2^6}$
 - b) $\frac{4^3 \times 5^3}{4^4}$
10. Calculate $10 \log_{10} \left(\frac{8 \times 10^{-8}}{1.8 \times 10^{-11}} \right)$

11. Calculate: a) $\frac{\sin 80^\circ}{\cos 60^\circ}$
b) $\frac{\tan 55^\circ}{\cos 35^\circ}$
12. Find the angle if: a) the sine of an angle is 0.84
b) the cosine of an angle is 0.76
c) the tangent of an angle is 0.69
13. Calculate the values of: a) $\sin 52^\circ 42' 35''$
b) $\cos 42^\circ 22' 35''$
c) $\tan 75^\circ 10' 20''$
14. Calculate $\frac{\sin 84^\circ 35' 55''}{\tan 44^\circ 45' 50''}$

References/Further reading

Virdi, S. and Baker, R. (2006). *Construction Mathematics*. Oxford: Butterworth-Heinemann.

2

Units and their conversion

Learning outcomes:

Use conversion factors to convert the units of length, mass, area and volume from CGS and SI system into FPS system and vice versa.

2.1 Introduction

Units of measurement, in one form or another, have been with us for many centuries. It is quite likely that the units for length and mass were the first ones to be invented. Early Babylonian, Egyptian and other records indicate that the length was measured with the forearm, hand or fingers. As civilisations evolved, units of measurement became more complicated to cater for trade, land division, taxation and other uses. In Britain, units from Egyptian, Babylonian, Anglo-Saxon and other European cultures evolved into the inch, foot and yard. In Britain and many other countries, the FPS system had been in use till the late 1950s. The basic units for length, mass and time were the foot, pound and second.

During the 1960s scientists and mathematicians started to use the metric system to simplify their calculations and promote communication across different nations. Even in the metric system two branches of systems coexisted for a long time: these are the CGS and the MKS systems. The base units for length, mass and time, in the two systems, are:

CGS system: the centimetre, gram and second.

MKS system: the metre, kilogram and second.

In 1960 the metric system was revised and simplified for international use. The metre, kilogram and second were kept as the basic units for length, mass and time. This system, which includes four other basic units, is called the SI system (International System of Units). A brief comparison of the metric systems and the FPS system is given in Table 2.1.

Table 2.1

	CGS/MKS system	FPS system
Length	Millimetre (mm), centimetre (cm), metre (m), kilometre (km)	Inch (in), foot (ft), yard (yd), mile
Mass	Gram (g), kilogram (kg), tonne (t)	Ounce (oz), pound (lb), stone, ton
Time	Second (s)	Second (s)
Temperature	Degrees Celsius (°C)	Degrees Fahrenheit (°F)
Capacity	Millilitre (ml), centilitre (cl), litre (l)	Pint, gallon
Volume	Cubic millimetre, cubic centimetre, cubic metre	Cubic foot, cubic yard

Table 2.2

1000 micrometres = 1mm	1cm = 10mm	1in = 25.4 mm
1mm = 0.1cm	1mm = 0.03937 in	1in = 2.54 cm
1mm = 0.001m	1mm = 0.003281ft	1ft = 304.8 mm
1cm = 0.01m	1cm = 0.3937 in	1ft = 30.48 cm
1m = 0.001km	1cm = 0.03281ft	1ft = 0.3048 m
1km = 1000 m	1m = 3.281ft	1ft = 12 in
1m = 1000 mm	1m = 1.0936 yd	1yd = 0.9144 m
1m = 100 cm	1in = 0.0254 m	1 mile = 1.609344 km

Although in formal work the metric units have replaced the British units, the inch, mile, ounce, pound, stone, pint, gallon etc. are still used in everyday life in Britain, and it becomes necessary sometimes to convert a unit from one system into the other.

Conversion of units may be done by using a range of methods:

- i) conversion factors
- ii) tables
- iii) graphs

Sections 2.2 to 2.4 give examples of converting the units of length, mass etc. based on the first method.

2.2 Length

The SI unit of length is metre, but millimetre, centimetre and kilometre are quite commonly used in technical and scientific calculations. The use of conversion factors gives the most accurate results but other methods may also be used.

Table 2.2 gives the conversion factors for some of the commonly used units in the metric as well as the FPS system.

Example 2.1

- Convert
- a) 66 mm into metres
 - b) 325 mm into metres
 - c) 5.75 m into centimetres
 - d) 2 ft 10 in into millimetres
 - e) 5 yd into metres
 - f) 8 in into metres

Solution:

- a) To convert millimetres into metres, use the conversion factor that has millimetre on the left and metre on the right, i.e. $1\text{ mm} = 0.001\text{ m}$. This technique will be used for other conversions as well.
If $1\text{ mm} = 0.001\text{ m}$, 66 mm will be equal to 66 times 0.001
 $66\text{ mm} = 66 \times 0.001 = 0.066\text{ m}$
- b) $1\text{ mm} = 0.001\text{ m}$
 $325\text{ mm} = 325 \times 0.001 = 0.325\text{ m}$
- c) $1\text{ m} = 100\text{ cm}$
 $5.75\text{ m} = 5.75 \times 100 = 575\text{ cm}$
- d) Convert 2 ft 10 in into inches first, then into millimetres
 $1\text{ ft} = 12\text{ inches}$
 $2\text{ ft} = 2 \times 12 = 24\text{ in}$
 $2\text{ ft } 10\text{ in} = 24 + 10\text{ in} = 34\text{ in}$
Now convert inches into millimetres using $1\text{ in} = 25.4\text{ mm}$
 $34\text{ in} = 34 \times 25.4 = 863.6\text{ mm}$
- e) $1\text{ yd} = 0.9144\text{ m}$
 $5\text{ yd} = 5 \times 0.9144 = 4.572\text{ m}$
- f) $1\text{ in} = 0.0254\text{ m}$
 $8\text{ in} = 8 \times 0.0254 = 0.2032\text{ m}$

2.3 Mass

The SI unit of mass is kilogram but gram and tonne are also used in mathematics, science and daily use. In Britain pounds and ounces, which are part of the FPS system, are still in common use. Table 2.3 gives the conversion factors for some of the commonly used units in the metric as well as the FPS system.

Table 2.3

1g = 0.001kg	16 oz = 1lb	1g = 0.03527 oz
1g = 0.000001 tonne	14 lb = 1 stone	1kg = 2.20462 lb
1kg = 1000 g	112 lb = 1 hundredweight (cwt)	1lb = 453.59237 g
1kg = 0.001 tonne	20 cwt = 1 ton	1lb = 0.45359 kg
1 tonne = 1000 kg	2240 lb = 1 ton	1oz = 28.3495 g
1 tonne = 1 000000 g		

Example 2.2

- Convert
- 0.070 kg into grams
 - 25500 kg into tonnes
 - 675 g into ounces
 - 85 kg into stones

Solution:

- To convert kilograms into grams, use the conversion factor that has kilogram on the left and gram on the right, i.e. $1\text{ kg} = 1000\text{ g}$
 $1\text{ kg} = 1000\text{ g}$
 $0.070\text{ kg} = 0.070 \times 1000 = 70\text{ g}$
- $1\text{ kg} = 0.001\text{ tonne}$
 $25500\text{ kg} = 25500 \times 0.001 = 25.5\text{ tonne}$
- $1\text{ g} = 0.03527\text{ oz}$
 $675\text{ g} = 675 \times 0.03527 = 23.807\text{ oz}$
- $1\text{ kg} = 2.20462\text{ lb}$
 $85\text{ kg} = 85 \times 2.20462 = 187.3927\text{ lb}$
 As $14\text{ lb} = 1\text{ stone}$
 $187.3927\text{ lb} = \frac{187.3927}{14}\text{ stones}$
 $= 13.385\text{ stones}$

2.4 Area, volume and capacity

For converting the units of area, volume and capacity, a small selection of conversion factors is given in Table 2.4.

Table 2.4

Area	Volume	Capacity
$1\text{mm}^2 = 0.01\text{cm}^2$	$1\text{mm}^3 = 0.001\text{cm}^3$	1000 millilitres (ml) = 1 litre (l)
$1\text{mm}^2 = 0.000001\text{m}^2$	$1\text{mm}^3 = 1 \times 10^{-9}\text{m}^3$	100 centilitres (cl) = 1 litre
$1\text{cm}^2 = 0.0001\text{m}^2$	$1\text{cm}^3 = 1 \times 10^{-6}\text{m}^3$	1ml = 0.001 litre
$1\text{cm}^2 = 100\text{mm}^2$	$1\text{cm}^3 = 1000\text{mm}^3$	1cl = 0.01 litre
$1\text{m}^2 = 1000000\text{mm}^2$	$1\text{m}^3 = 1 \times 10^9\text{mm}^3$	1 litre = 1000 cm^3
$1\text{m}^2 = 10000\text{cm}^2$	$1\text{m}^3 = 1 \times 10^6\text{cm}^3$	1000 litres = 1 m^3
		1 pint = 0.5683 litre
		1 gallon = 4.5461 litres
		1 litre = 0.21997 gallons

Example 2.3

- Convert
- a) 16204mm^2 into cm^2
 - b) 247000mm^2 into m^2
 - c) 6.15m^2 into mm^2

Solution:

- a) Use the conversion factor that involves mm^2 and cm^2
 $1\text{mm}^2 = 0.01\text{cm}^2$
 $16204\text{mm}^2 = 16204 \times 0.01 = 162.04\text{cm}^2$
- b) This question involves mm^2 and m^2
 $1\text{mm}^2 = 0.000001\text{m}^2$
 $247000\text{mm}^2 = 247000 \times 0.000001 = 0.247\text{m}^2$
- c) $1\text{m}^2 = 10^6\text{mm}^2$
 $6.15\text{m}^2 = 6.15 \times 10^6 = 6150000\text{mm}^2$

Example 2.4

- Convert
- a) 6780000mm^3 into m^3
 - b) 0.00032m^3 into mm^3

Solution:

- a) $1\text{mm}^3 = 1 \times 10^{-9}\text{m}^3$
 $6780000\text{mm}^3 = 6780000 \times 1 \times 10^{-9} = 0.00678\text{m}^3$
- b) $1\text{m}^3 = 1 \times 10^9\text{mm}^3$
 $0.00032\text{m}^3 = 0.00032 \times 1 \times 10^9 = 320000\text{mm}^3$

Example 2.5

- Convert
- a) 15500 ml into litres
 - b) 8.37 litres into centilitres
 - c) 0.0038 m^3 into litres
 - d) 25 litres into gallons

Solution:

- a) $1 \text{ ml} = 0.001 \text{ litre}$
 $15500 \text{ ml} = 15500 \times 0.001 = 15.5 \text{ litres}$
- b) $1 \text{ litre} = 100 \text{ cl}$
 $8.37 \text{ litres} = 8.37 \times 100 = 837 \text{ cl}$
- c) $1 \text{ m}^3 = 1000 \text{ litres}$
 $0.0038 \text{ m}^3 = 0.0038 \times 1000 = 3.8 \text{ litres}$
- d) $1 \text{ litre} = 0.21997 \text{ gallons}$
 $25 \text{ litres} = 25 \times 0.21997 = 5.499 \text{ gallons}$

2.5 Temperature

The two temperature scales used in building science are the Celsius temperature scale and the thermodynamic temperature scale. These are discussed in more detail in Chapter 8. The Fahrenheit scale is no longer used in scientific work.

One degree on the Celsius scale (symbol: $^{\circ}\text{C}$) is equal to one degree on the thermodynamic scale (symbol: K), however, the zero degree on the thermodynamic scale is approximately equal to -273°C . The conversion from one system to the other involves the addition or subtraction of 273.

$$\begin{aligned}\text{Therefore, } 0^{\circ}\text{C} &= 0 + 273 = 273 \text{ K} \\ 20^{\circ}\text{C} &= 20 + 273 = 293 \text{ K}\end{aligned}$$

Exercise 2.1

1. Convert:
 - a) 75 mm into metres
 - b) 335 mm into metres
 - c) 7.8 m into centimetres
 - d) 3 ft 6 in into millimetres
 - e) 60 yd into metres
 - f) 15 in into metres
 - g) 25 ft into metres
 - h) 3.3528 m into feet

2. Convert:
 - a) 0.060 kg into grams
 - b) 22500 kg into tonnes
 - c) 745 g into ounces
3. Convert:
 - a) 18.500 kg into pounds
 - b) 200 kg into pounds
 - c) 15 lb into kilograms
4. Convert:
 - a) 10580 mm^2 into cm^2
 - b) 695000 mm^2 into m^2
 - c) 3.65 m^2 into mm^2
 - d) 9.29 m^2 into cm^2
5. Convert:
 - a) 6545000 mm^3 into m^3
 - b) 12545 mm^3 into cm^3
 - c) 0.00096 m^3 into mm^3
6. Convert:
 - a) 14760 ml into litres
 - b) 16.65 litres into centilitres
 - c) 235 cl into litres
 - d) 0.06 m^3 into litres
 - e) 35 litres into gallons

References/Further reading

Virdi, S. and Baker, R. (2006). *Construction Mathematics*. Oxford: Butterworth-Heinemann.

3

Introduction to physics

Learning outcomes:

- 1) Define speed, velocity and acceleration.
- 2) Explain mass, gravitation and weight.
- 3) Explain Newton's laws of motion and solve numerical problems based on these laws.
- 4) Explain work, energy and power, and solve numerical problems.

3.1 Speed and velocity

In the study of moving objects, one of the important things to know is the rate of motion. The rate of motion of a moving object is what we call **speed**. It may be defined as the distance covered in a given time:

$$\text{Speed} = \frac{\text{distance covered}}{\text{time taken}}$$

If the distance covered is in metres (m) and the time taken in seconds (s), then speed is measured in m/s. If the distance is in kilometres (km) and the time in hours (h), the unit of speed is km/h.

When the direction of movement is combined with the speed we have the **velocity** of motion. Quantities that have both magnitude and direction are known as **vector** quantities. Velocity is a vector quantity; its magnitude and direction can be represented by an arrow. Speed, on the other hand, has magnitude but no direction, therefore, it is called a **scalar** quantity.

3.2 Acceleration

An object is said to accelerate if its velocity increases. The rate of increase of velocity is called the **acceleration**.

$$\text{Acceleration} = \frac{\text{increase in velocity}}{\text{time taken}}$$

If velocity is measured in metres and time in seconds, then acceleration is measured in m/s/s or m/s². If the velocity of a moving object decreases, it is said to decelerate, i.e. the acceleration is negative. The following relationships may be used to solve problems involving velocity and acceleration:

i) $v^2 - u^2 = 2as$

ii) $v = u + at$

iii) $v = ut + \frac{1}{2}at^2$

Where, u = initial velocity

v = final velocity

a = acceleration

t = time, and s = distance

3.3 Mass

The amount of matter contained in an object is known as its **mass**. The basic SI unit of mass is kilogram (kg).

1 gram (g) = 1000 milligram (mg)

1000 grams = 1 kilogram

1000 kilograms = 1 tonne (t)

The mass of an object remains constant irrespective of wherever it is.

3.4 Gravitation

Gravitation can be defined as the force of attraction that exists between all objects in the universe. According to Isaac Newton, every object in the universe attracts every other object with a force directed along the line of centres for the two objects that is proportional to the product of their masses and inversely proportional to the square of the distance between their centres.

$$F_g = \frac{G m_1 m_2}{r^2}$$

Where F_g = gravitational force between two objects

m_1 = mass of first object

m_2 = mass of second object

r = distance between the centres of the two objects

G = universal constant of gravitation

The value of constant G is so small that the force of attraction between any two objects is negligible. In 1798 Henry Cavendish performed experiments to determine the value of G and found it to be $6.67 \times 10^{-11} \text{ Nm}^2/\text{kg}^2$.

If we consider an object and the Earth, the mass of Earth is so large ($5.98 \times 10^{24} \text{ kg}$) that depending on the mass of the object there could be a considerable force of attraction between the two. That is why when an object is dropped from a height, it falls towards the Earth, not away from it. The initial velocity of the object is zero m/s, but as the distance increases, the velocity of the falling object also increases. The rate of increase in velocity is called acceleration and, in the case of a free falling object, it is known as the **acceleration due to gravity** (symbol: g).

The value of g is 9.807 m/s^2 , but for all calculations in this book it will be approximated to 9.81 m/s^2 (m/s^2 can also be written as ms^{-2}).

Example 3.1

Find the gravitational force between the Earth and:

a) An object having a mass of 1 kg

b) A person having a mass of 80 kg

Given: mass of the Earth = $6.0 \times 10^{24} \text{ kg}$; radius of the Earth = $6.4 \times 10^6 \text{ m}$;

$G = 6.7 \times 10^{-11} \text{ Nm}^2/\text{kg}^2$

Solution:

$$\begin{aligned} \text{a) } F_g &= \frac{G m_1 m_2}{r^2} \\ &= \frac{6.7 \times 10^{-11} \times 6 \times 10^{24} \times 1}{(6.4 \times 10^6)^2} \\ &= 9.81 \text{ N} \end{aligned}$$

$$\begin{aligned} \text{b) } F_g &= \frac{G m_1 m_2}{r^2} \\ &= \frac{6.7 \times 10^{-11} \times 6 \times 10^{24} \times 80}{(6.4 \times 10^6)^2} \\ &= 785.16 \text{ N} \end{aligned}$$

3.5 Weight

The **weight** of an object is the force with which it is attracted towards Earth. When an object falls freely towards Earth, the average value of the acceleration produced (g) is 9.81m/s^2 . The force (F) acting on the object due to Earth's gravitational pull (or the weight of the object) can be calculated as:

$$F = m \times g$$

where m is the mass of the object in kg.

The units of weight are the same as the units of force. If the mass is in kilograms, the unit of weight will be newtons (N).

The weight of 1kg mass will be:

$$F = 1 \times 9.81 = 9.81\text{N}$$

Similarly, the weight of a 5kg mass is:

$$F = 5 \times 9.81 = 49.05\text{N}$$

For larger forces, kilonewtons or meganewtons may be used.

$$1000\text{N} = 1\text{kilonewton (kN)}$$

$$1000000\text{N} = 1\text{meganewton (MN)}$$

The weight of a body is not constant but changes slightly when we move from the Equator to the North Pole. The Earth is not a perfect sphere: it bulges at the Equator. This affects the gravitational force, which varies from 9.78m/s^2 at the Equator to 9.83m/s^2 at the North Pole.

3.6 Volume

All substances, whether they are solid, liquid or gas, occupy space. The amount of space occupied by an object is called its volume.

$$\begin{aligned}\text{Volume} &= \text{length} \times \text{width} \times \text{height} \\ &= \text{area} \times \text{height}\end{aligned}$$

Units: m^3 , cm^3 and mm^3 .

3.7 Density

If equal volumes of bricks, concrete, timber and other materials are compared, the values of their mass will be different. This is because different materials do not have the same density.

The **density** of a material is defined as its mass per unit volume.

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

If the units of mass and volume are kg and m³ respectively, then the unit of density will be kg/m³. The density of pure water is 1000 kg/m³. The density of a material is an important property and is used in several areas of building technology, for example:

- a) To find the self-weight (dead load) of a component like a beam, column etc., its density must be known.
- b) The strength of a material, generally, depends on its density.
- c) The thermal insulation of a material is inversely proportional to its density.

Table 3.1 shows the densities of a selection of materials.

Table 3.1

Material	Density (kg/m ³)
Concrete blocks (lightweight)	450-675
Aluminium	2720
Brick (common)	2000
Brick (engineering)	2200
Cement	1500
Concrete	2400
Copper	8800
Cork	200
Glass	2500
Granite	2720
Gravel (coarse)	1450
Gravel (all-in)	1750
Lead	11300
Limestone	2250
Marble	2720
Mercury	13500
Mild steel	7820
Sand (dry)	1600
Sandstone	2250
Slate	2800
Timber (Oak)	600-900
Timber (Beech)	700-900

Example 3.2

The mass of a concrete block measuring 250 mm × 200 mm × 200 mm is 24.0 kg. Find the density of concrete.

Solution:

The dimensions of the concrete block are converted into metres to obtain the density in kg/m³.

$$250 \text{ mm} = \frac{250}{1000} \text{ m} = 0.250 \text{ m}$$

Similarly, 200 mm = 0.200 m

$$\text{Volume of the concrete block} = 0.250 \times 0.200 \times 0.200 = 0.010 \text{ m}^3$$

$$\begin{aligned} \text{Density} &= \frac{\text{mass}}{\text{volume}} \\ &= \frac{24}{0.010} = 2400 \text{ kg/m}^3 \end{aligned}$$

Example 3.3

The cross-sectional measurements of a 7.0 m long concrete beam are 0.3 m × 0.75 m. Find the mass and the weight of the beam. Density of concrete = 2400 kg/m³.

Solution:

$$\text{Volume of the beam} = 7.0 \times 0.3 \times 0.75 = 1.575 \text{ m}^3$$

$$\begin{aligned} \text{Mass} &= \text{Density} \times \text{Volume} \\ &= 2400 \times 1.575 = 3780 \text{ kg} \end{aligned}$$

$$\begin{aligned} \text{Weight} &= \text{Mass} \times g \\ &= 3780 \times 9.81 = 37081.8 \text{ N} \end{aligned}$$

3.8 Specific gravity

The specific gravity of a substance is defined as the ratio of the density of the material to the density of water.

$$\text{Specific gravity} = \text{Density of a material} \div \text{Density of water}$$

The specific gravity of a material remains the same, irrespective of the units of density.

3.9 Newton's first law of motion

In the seventeenth century Isaac Newton formulated three laws, which are known as Newton's laws of motion. The first law states that an object will remain in a state of rest or uniform motion in a straight line unless acted upon by an external force. This means that a book lying on a desk will lie there forever unless somebody applies an effort (external force) to pick it up. Similarly, imagine you are travelling in a car at, say, 60 km/hr and the ignition is turned off. The car will eventually come to a halt without the application of brakes. This is due to the friction between the car tyres and the road surface. Friction is a force that tries to stop moving objects. The car will not stop if there is no friction between the car tyres and the road surface. In space there is no influence of external forces. A spacecraft will continue to travel in a straight line at a constant speed. It does not need a force to keep it moving.

3.10 Newton's second law of motion

Newton's second law of motion states that when an unbalanced force acts on an object, the object will accelerate in the direction of the force. The acceleration is directly proportional to the force and inversely proportional to the mass.

$$a = \frac{F}{m} \quad \text{or, } F = ma$$

where F is the force (newtons)

m is the mass of the object (kg)

a is the acceleration produced (m/s^2)

A force of 1 newton gives a mass of 1 kg an acceleration of 1 m/s^2

Example 3.4

Calculate the acceleration of a 100 kg object if it is acted upon by a net force of 250 N.

Solution:

$$F = ma \text{ (a is the acceleration)}$$

$$250 = 100 \times a$$

$$\frac{250}{100} = a \text{ or, } a = 2.5 \text{ m/s}^2$$

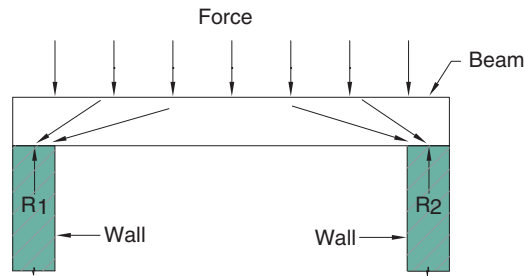


Figure 3.1

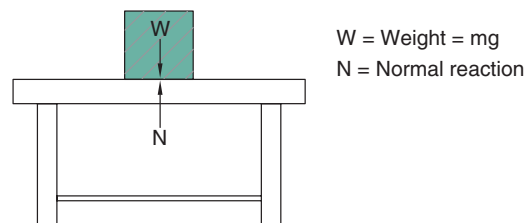


Figure 3.2

3.11 Newton's third law of motion

Newton's third law of motion states that to every action there is an equal and opposite reaction. Consider a beam resting on two walls as shown in Figure 3.1.

The weight of the beam plus any other force is the action. The reactions (R_1 and R_2) are offered by the walls as they support the beam and resist its downward movement. For the stability of the beam, the total reaction must be equal to the action.

$$\text{weight of the beam} + \text{forces acting on the beam} = R_1 + R_2$$

If the walls cannot support the beam, due either to some defect in the wall or to the use of weaker materials, the reaction will not be equal to the action and the beam moves away from its intended position. Depending on the magnitude of the movement, this might cause the failure of the component that the beam is supporting.

3.12 Friction

When an object rests on a surface, two forces act on it to maintain the balance: the weight acting downwards, and the reaction (or normal reaction) acting upwards, as shown in Figure 3.2. If a force F is applied to slide the object, the movement is resisted by another force that acts in the opposite direction, as shown in Figure 3.3. The opposing force is called the **friction force** (R) and is due to the roughness of the surfaces in contact.

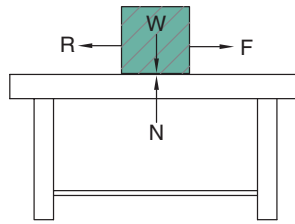


Figure 3.3

If the applied force is increased, the friction force increases as well. The maximum friction force is experienced when the object is about to move. This is called the static friction. The friction also acts when the object is in motion, but this friction (called the dynamic friction) is less than the static friction.

The amount of friction between two surfaces depends on:

- a) The normal reaction, which acts at right angles to the two surfaces
- b) The roughness of the surfaces in contact

The coefficient of friction (μ) is given by:

$$\begin{aligned}\mu &= \frac{\text{friction force (R)}}{\text{normal reaction between surfaces (N)}} \\ &= \frac{R}{N} = \frac{F}{W} \quad (R = F; N = W)\end{aligned}$$

Example 3.5

A horizontal force of 9.0 N moves a brick on a metal surface at a uniform speed. Find the weight of the brick if the coefficient of friction between the two materials is 0.45.

Solution:

$$R = F = 9.0 \text{ N}; N = W;$$

$$\mu = \frac{R}{N} = \frac{R}{W}$$

$$W = \frac{R}{\mu} = \frac{9.0 \text{ N}}{0.45} = 20.0 \text{ N}$$

3.13 Work

Work is said to be done when a force moves an object. The work done can be calculated from the following equation:

$$\text{Work done} = \text{force} \times \text{distance moved}$$

$$\text{or, } W = F \times s$$

The SI unit of work is **joule** (J), which can be defined as the work done when a force of 1 newton moves through a distance of 1m in the direction of the force.

Example 3.6

A 50 cm × 50 cm × 50 cm block of concrete rests on a concrete floor. The coefficient of friction between the two surfaces is 0.6. Calculate:

- The horizontal force necessary to move the concrete block.
- The work done in moving the block by 10 m.

The density of concrete is 2400 kg/m³

Solution:

$$\begin{aligned} \text{a) Mass} &= \text{density} \times \text{volume} \\ &= 2400 \times (0.5 \times 0.5 \times 0.5) \quad (50 \text{ cm} = 0.5 \text{ m}) \\ &= 300 \text{ kg} \end{aligned}$$

$$\text{Weight of the block (W)} = 300 \times 9.81 = 2943 \text{ N}$$

$$\text{Coefficient of friction, } \mu = \frac{F}{W} \quad (F \text{ is the horizontal force})$$

$$0.6 = \frac{F}{2943}$$

$$F = 0.6 \times 2943 = 1765.8 \text{ N}$$

$$\begin{aligned} \text{b) Work done} &= \text{force} \times \text{distance} \\ &= 1765.8 \times 10 \\ &= 17658 \text{ J or } 17.658 \text{ kJ} \end{aligned}$$

3.14 Energy

The capacity to do work is known as **energy**. Energy may be available in various forms but it is not possible to create or destroy energy. However, it may change from one form to another, for example, light energy into electrical energy, electrical energy into heat energy, heat energy into electrical energy etc.

Some of the main forms in which energy exists are:

chemical energy, electrical energy, kinetic energy, light energy, nuclear energy, potential energy, sound energy and thermal energy. Potential energy and kinetic energy are discussed further in the next two sections.

3.14.1 Potential energy

Potential energy may be defined as the energy possessed by a body due to its position above the ground. If an object of mass m kilograms is raised to a height h metres, then the work done in doing so is given by:

$$\begin{aligned}\text{Work done} &= \text{force} \times \text{distance} \\ &= (m \times g) \times h = mgh\end{aligned}$$

The potential energy (PE) possessed by the object, at height h metres, is mgh .
The work done by the object, if it were allowed to fall, is also mgh .
The unit of energy is joule (J).

3.14.2 Kinetic energy

The energy possessed by a moving object is known as the **kinetic energy** (KE).

$$\text{Kinetic energy} = \frac{1}{2}mv^2$$

where m is the mass of the object in kg
 v is the velocity of the object in m/s

There are several uses of potential energy and kinetic energy in civil engineering, two of which are: hydroelectric power stations and the improvement of loose subsoil.

In hydroelectric power stations, water is stored in the form of a lake by constructing a concrete dam or an earth dam. The water level rises and, due to its height, possesses energy. The water is allowed to fall through a pipe (penstock), and its energy used to drive a turbine. The turbine in turn generates electricity.

Loose subsoils are not very strong and hence may not be able to support a building/structure satisfactorily. The strength of the subsoils may be improved by several techniques, one of which is called **dynamic compaction**. The method involves dropping a heavy block of steel from a suitable height (Figure 3.4). As the block falls on the ground, its energy is used to compact the soil. The compaction of a soil results in the improvement of its density and strength.

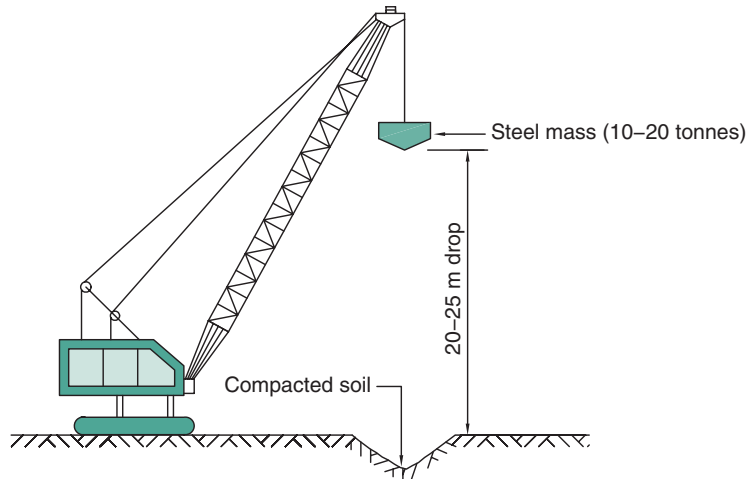


Figure 3.4 Dynamic compaction.

Example 3.7

A 10 tonne block of steel was raised to a height of 12.0m and then dropped. Calculate the energy possessed by the block at heights of 12m, 9m, 6m, 3m and when it hits the ground.

Solution:

$$10 \text{ tonnes} = 10000 \text{ kg}$$

The steel block is at rest at a height of 12m, i.e. its velocity, and hence the kinetic energy, is zero. The energy possessed by it is entirely due to its height above the ground surface.

$$\begin{aligned} \text{Total energy at 12 m height} &= \text{potential energy} = mgh \\ &= 10000 \times 9.81 \times 12.0 = 1177200 \text{ J} \end{aligned}$$

At a height of 9m: As the block is dropped, it accelerates due to gravitational force. The energy possessed by the block is a combination of kinetic energy and potential energy. Its velocity, v , can be determined from:

$$v^2 - u^2 = 2as \text{ or, } v^2 = u^2 + 2as \quad (\text{initial velocity, } u = 0)$$

$$v^2 = 0^2 + 2 \times 9.81 \times 3.0 = 58.86 \quad (s = 12 - 9 = 3 \text{ m})$$

$$\begin{aligned} \text{Kinetic energy} &= \frac{1}{2}mv^2 \\ &= \frac{1}{2} \times 10000 \times 58.86 = 294300 \text{ J} \end{aligned}$$

Table 3.2

Height (m)	$v^2 = 2as + u^2$	Kinetic energy $= \frac{1}{2}mv^2$ (J)	Potential energy = mgh (J)	Total energy = $P E + K E$ (J)
12	0	0	1177200	1177200
9	58.86	294300	882900	1177200
6	117.72	588600	588600	1177200
3	176.58	882900	294300	1177200
0	235.44	1177200	0	1177200

$$\begin{aligned}\text{Potential energy} &= mgh \\ &= 10000 \times 9.81 \times 9.0 = 882900 \text{ J}\end{aligned}$$

$$\begin{aligned}\text{Total energy at a height of 9.0 m} &= K E + P E \\ &= 294300 + 882900 = 1177200 \text{ J}\end{aligned}$$

The calculations at the other heights can be done in a similar way and are summarised in Table 3.2.

These calculations show that the total energy possessed by the steel block at 12m height is entirely due to the potential energy. The total energy is entirely due to its kinetic energy when the block hits the ground, i.e. at zero height. At other heights, the total energy of the block is a combination of kinetic and potential energies.

3.15 Power

Power is defined as the work done per second, i.e. the rate of doing work.

$$\text{Power} = \frac{\text{work done}}{\text{time taken}}$$

Power is measured in joules per second (J/s) or watts (W).

One watt = one joule of work done per second

or, $1W = 1J/s$

$$\begin{aligned}\text{also, Power} &= \frac{\text{work done}}{\text{time taken}} = \frac{F \times s}{t} \\ &= \text{force} \times \text{velocity} \left(\frac{s}{t} = \text{velocity} \right)\end{aligned}$$

Example 3.8

A crane lifts a block of concrete, having a mass of 2.0 tonnes, to a height of 8.0 m in 12 seconds. Find the work done in lifting the block and the power output of the crane.

Solution:

$$2.0 \text{ tonnes} = 2000 \text{ kg}$$

$$\begin{aligned} \text{Work done} &= \text{force} \times \text{distance} \\ &= (2000 \times 9.81) \times 8.0 \\ &= 156960 \text{ J} \end{aligned}$$

$$\text{Power} = \frac{156960}{12} = 13080 \text{ W}$$

Exercise 3.1

- Find the gravitational force between the Earth and:
 - An object having a mass of 10 kg
 - A person having a mass of 60 kg
 Given: mass of the Earth = 6.0×10^{24} kg; radius of the Earth = 6.4×10^6 m;
 $G = 6.7 \times 10^{-11} \text{ Nm}^2/\text{kg}^2$
- A block measuring 300 mm × 200 mm × 200 mm is made from concrete having a density of 2300 kg/m³. Find the mass of the block.
- The cross-sectional measurements of a 6.0 m long concrete beam are 0.3 m × 0.7 m. Find the mass and the weight of the beam. The density of concrete is 2400 kg/m³.
- Calculate the acceleration of an 80 kg object if it is acted upon by a net force of 960 N.
- A horizontal force of 85.0 N moves a concrete component on a metal surface at a uniform speed. Find the weight of the component if the coefficient of friction is 0.45.
- An 80 cm × 50 cm × 50 cm block of concrete rests on a concrete floor. The coefficient of friction between the two surfaces is 0.6. Calculate:
 - The horizontal force necessary to move the concrete block.
 - The work done in moving the block by 15 m.
 The density of concrete is 2300 kg/m³

7. An 8 tonne block of steel was raised to a height of 9.0 m and then dropped. Calculate the energy possessed by the block at heights of 9 m, 6 m, 3 m and when it hits the ground.
8. A crane lifts a block of concrete, having a mass of 2.5 tonnes, to a height of 10.0 m in 12 seconds. Find:
 - a) Work done in lifting the block.
 - b) Power output of the crane.

References/Further reading

1. Breithaupt, J. (2008). *AQA Physics A*. Cheltenham: Nelson Thornes.

4

Introduction to chemistry

Learning outcomes:

- 1) Define atom, electron, proton and neutron.
- 2) Explain electrovalency and covalency.
- 3) Explain the difference between elements, compounds and mixtures.
- 4) List a range of symbols and formulae.
- 5) Differentiate between acids and bases.

4.1 Introduction

The concept that matter is composed of tiny particles has been known to the scientists for many centuries. John Dalton, a British scientist, put forward his atomic theory in 1808 and suggested that matter is composed of minute particles called atoms, which cannot be created, destroyed or split. Another scientist, Marie Curie, and her husband Pierre, discovered two new elements called polonium and radium. The salts of these elements glowed in the dark and Marie Curie called this property 'radioactivity'.

An **atom** is the smallest particle that can exist on its own, and is made up of three types of particles:

Electrons, protons and neutrons.

The electrons carry a negative charge, protons a positive charge, but neutrons, as the name suggests, do not carry any charge. Many scientists, during the last century and earlier, assumed that in an atom, protons, electrons and neutrons are mixed up. Lord Rutherford, a British physicist, suggested that the protons and neutrons form the nucleus of an atom, with electrons surrounding the nucleus as shown in Figure 4.1.

Figure 4.1 is a highly enlarged representation of an atom. Atoms can be of different sizes, the diameter of an average atom being 0.5×10^{-9} m. The mass of a proton and a neutron is the same as that of an atom of hydrogen. This is known as 1 atomic mass unit and is equal to 1.67×10^{-27} kg. The mass of an atom depends on the number of protons

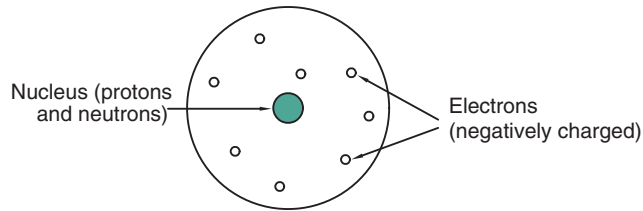


Figure 4.1

Table 4.1 Atomic numbers of some elements

Element	Atomic number	Number of protons	Number of electrons
Oxygen	8	8	8
Aluminium	13	13	13
Calcium	20	20	20
Copper	29	29	29
Iron	26	26	26

and neutrons. The mass of electrons is very small, as compared to that of protons and neutrons, hence they do not contribute to the mass of an atom.

The electrical charge carried by a proton and an electron is +1 unit and –1 unit, respectively. One unit of charge is equal to the charge on the nucleus of a hydrogen atom. Another important feature of the modern atomic theory is that the number of electrons in an atom is the same as the number of protons: this is responsible for the neutral charge on an atom. The number of protons or electrons in the atom of an element is called its atomic number. Table 4.1 summarises the atomic numbers of some elements.

The number of protons and neutrons is called the mass number. Sodium has 11 protons and 12 neutrons. The mass number is $11 + 12 = 23$. The mass number and the atomic number are written above and below the chemical symbol for the element, e.g. $^{23}_{11}\text{Na}$.

According to the atomic theory, the electrons are in constant motion around the nucleus in paths called **orbits**. As all electrons do not possess the same energy, those having less energy circle the nucleus in an orbit of smaller radii whereas the electrons having more energy move around the nucleus in orbits of larger radii.

Orbits of similar energy level can be grouped together, each group being known as a **shell**. There can be several shells around a nucleus, each capable of holding a maximum number of electrons. The shells can be represented by the letters K, L, M etc. as shown in Figure 4.2.

Most of the volume of an atom is space. The protons and neutrons are at the centre of an atom known as the nucleus. The electrons are present in the space surrounding the nucleus and are in constant motion. The electron configuration of an atom can be worked out if the atomic number of the element is known. Figure 4.3 shows the electron configuration of aluminium. The atomic number of an atom of aluminium is 13, which means that there are 13 electrons in an atom. The first shell can hold 2 electrons, the second shell 8, and the third shell has 3.

The electron configurations of carbon, oxygen and calcium are shown in Figure 4.4.

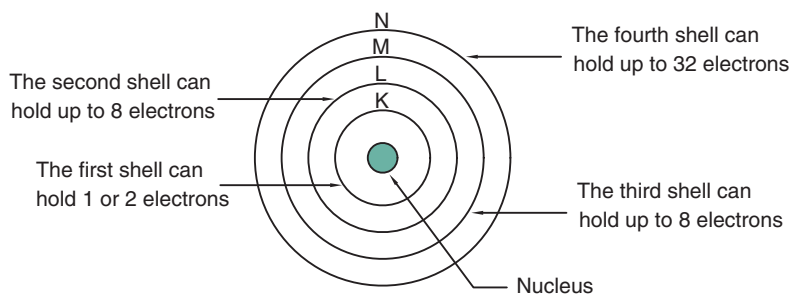


Figure 4.2

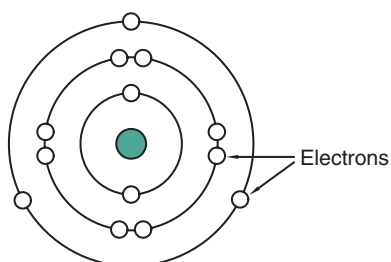


Figure 4.3 Electron configuration of aluminium.

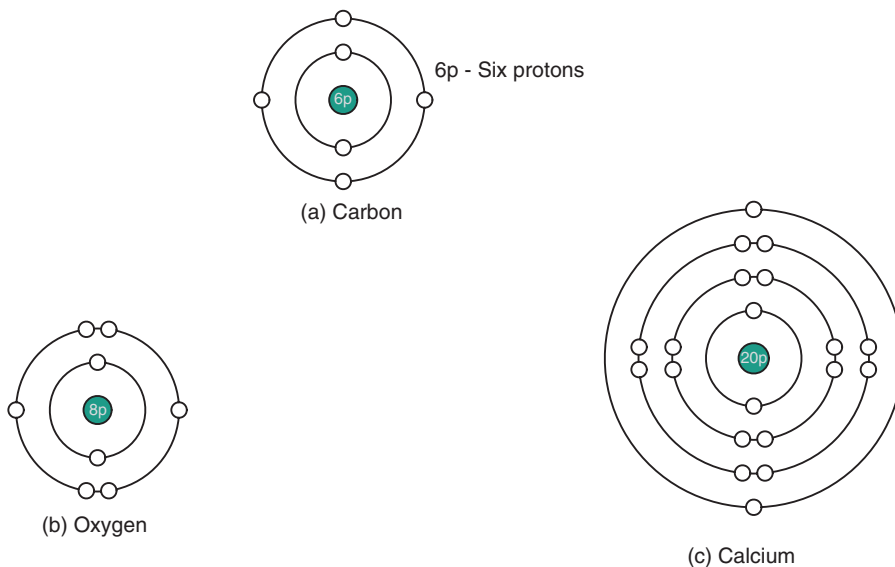


Figure 4.4 Electron configuration of carbon, oxygen and calcium.

4.2 Electrovalency and covalency

The electron configurations of some of the elements have already been discussed in the previous section. Many elements have incomplete outside shells. When two of these elements are mixed, they react in order to have complete outside shells. Metal atoms (aluminium, copper, iron etc.) lose the extra electron(s), which are gained by the non-metal atoms. In this way the outside shells of both the metal, as well the non-metal, atoms become complete.

Originally a metal atom, like all other atoms, is neutral as the number of protons (positive charge) is the same as the number of electrons (negative charge). On losing the spare electrons from the last shell, the atom has more protons than neutrons, hence it carries a positive charge. On the other hand, the atoms of non-metals gain electrons to complete the last shell. This makes them negatively charged as the number of electrons exceeds the number of protons. Atoms, which carry either a negative or a positive charge, are known as **ions**. The compounds made by elements by gaining or losing electrons are called **electrovalent compounds**. To understand the phenomenon of electrovalency, the structure of potassium chloride is considered here. Potassium and chlorine combine to give potassium chloride:

Potassium + chlorine = potassium chloride

When potassium and chlorine react, the potassium atom can lose the electron in the last shell. The third shell now has 8 electrons and is, therefore, complete and stable. The electron lost by the potassium atom is gained by the chlorine atom to complete its last shell. Thus, both elements end up with complete outer shells (see Figure 4.5). Potassium becomes positively-charged potassium ion (cation) after losing one electron. Similarly, chlorine gains one electron and becomes negatively-charged chloride ion (anion). The oppositely-charged ions attract each other, i.e. cations attract anions, and vice versa. The bond between anions and cations is called an ionic bond or **electrovalent bond**. The number of electrons gained or lost by an atom, when two elements react, is known as its electrovalency or, in short, **valency**. The valencies of potassium and chlorine are:

Valency of potassium = 1(positive); written as K^+

Valency of chlorine = 1(negative); written as Cl^-

4.2.1 Covalent bond

Some elements do not form ions, but can still combine with other elements making covalent compounds. A chlorine atom has seven electrons in the outermost shell. When two atoms of chlorine combine, both atoms want to gain electrons to complete their outermost shells. This is achieved as the atoms share two electrons (Figure 4.6).

One pair of electrons is shared by both atoms of chlorine, therefore each atom has eight electrons in the outermost shell. The bond between the two atoms due to sharing of the electrons is called a **covalent bond**. The valency of the element is the same as the number of pairs of electrons that one atom shares with the other.

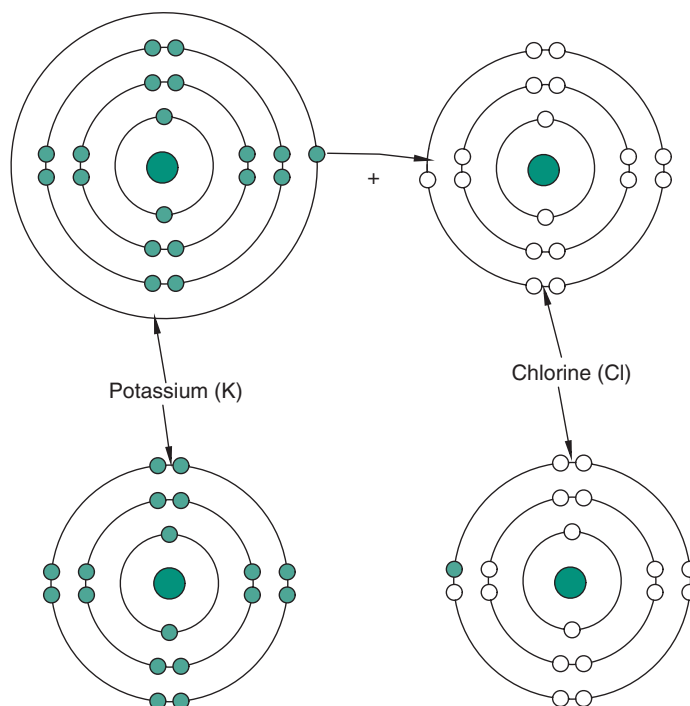


Figure 4.5 Formation of compound potassium chloride.

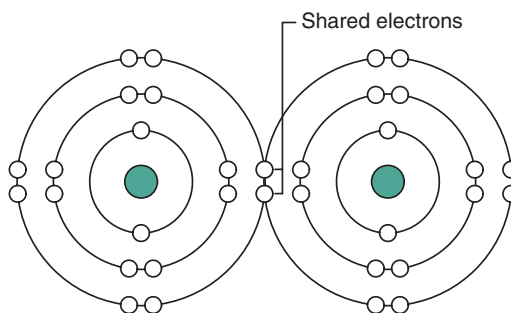


Figure 4.6 Covalent bond.

Similarly, water is also a covalent compound. An oxygen atom has six electrons in the outermost shell; a hydrogen atom has one. Two atoms of hydrogen and one atom of oxygen combine as shown in Figure 4.7. A hydrogen atom shares one pair of electrons, an oxygen atom shares two, therefore, the valency of hydrogen is one and that of oxygen is two. The valencies of ions of some of the metals and non-metals are given in Table 4.2. Copper ions have a positive charge and a valency of 2; this is shown in Table 4.2 as Cu^{2+} . Similarly, chloride ions, which have a negative charge and a valency of one, are shown as Cl^- .

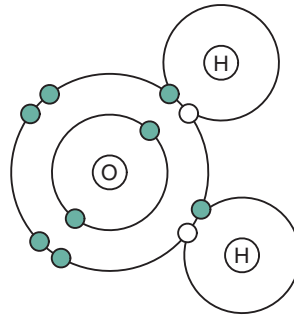


Figure 4.7

Table 4.2

Ions with positive charge	Valency
Sodium	Na^+
Potassium	K^+
Hydrogen	H^+
Calcium	Ca^{2+}
Magnesium	Mg^{2+}
Copper	Cu^{2+}
Lead	Pb^{2+}
Zinc	Zn^{2+}
Iron (Ferrous)	Fe^{2+}
Iron (Ferric)	Fe^{3+}
Aluminium	Al^{3+}
Ions with negative charge	Valency
Hydroxide ion	OH^-
Nitrate	NO_3^-
Chlorine	Cl^-
Carbonate	CO_3^{2-}
Oxide	O^{2-}
Sulphate	SO_4^{2-}

4.3 Elements and compounds

An **element** is a substance that cannot be decomposed into simpler substances. There are more than 100 elements, some of which are:

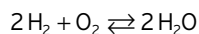
Calcium, copper, zinc, aluminium, chlorine, oxygen, carbon, sulphur etc.

In chemistry each element is given a symbol, which makes representation of chemical reactions very convenient. Table 4.3 shows the symbols of a selection of elements.

Table 4.3 Symbols of elements

Element	Symbol
Aluminium	Al
Calcium	Ca
Carbon	C
Chlorine	Cl
Chromium	Cr
Copper	Cu
Fluorine	F
Gold	Au
Helium	He
Hydrogen	H
Iodine	I
Iron	Fe
Lead	Pb
Magnesium	Mg
Manganese	Mn
Mercury	Hg
Nickel	Ni
Nitrogen	N
Oxygen	O
Phosphorus	P
Potassium	K
Silicon	Si
Silver	Ag
Sodium	Na
Sulphur	S
Tin	Sn
Zinc	Zn

Hydrogen + oxygen $\rightleftharpoons$ Water



Water is produced by combining hydrogen and oxygen gases. Also, by passing current through acidified water, it can be split into hydrogen and oxygen.

A compound is different from a mixture. A **mixture** can contain its components in any proportion, whereas in a **compound** the component elements are always in a fixed proportion. There are also other differences between a compound and a mixture:

- No chemical action takes place when a mixture is made. When a compound is made, a chemical action takes place.
- The components of a mixture can be separated easily by physical means, whereas a chemical reaction is required to separate a compound into its components.

Table 4.4

Compound	Formula
Aluminium oxide	Al_2O_3
Calcium sulphate	CaSO_4
Calcium carbonate	CaCO_3
Calcium chloride	CaCl_2
Magnesium carbonate	MgCO_3
Sodium chloride	NaCl
Sodium carbonate	Na_2CO_3
Copper chloride	CuCl_2
Copper sulphate	CuSO_4
Zinc oxide	ZnO
Ferrous sulphate	FeSO_4

4.4 Symbols and formulae

In chemistry symbols and formulae are used to represent elements and compounds, respectively. For elements, either one or two letters are used, e.g. the letter I is used for Iodine, Al for aluminium and Zn for zinc. For some elements, the symbols are chosen from their Latin names, for instance:

Fe from Ferrum (iron)

Na from Natrium (sodium)

Au from Aurum (gold)

The formula of a compound shows the ratio of its component elements. The formula for water is H_2O , which means that for every atom of oxygen, two atoms of hydrogen are required to form one molecule of water. The reason for this is that the valency of hydrogen is 1 (H^+) and that of oxygen is 2 (O^{2-}).

The valency of copper ion is 2 (Cu^{2+}) and that of chloride ion is 1 (Cl^-). Therefore, one copper ion combines with two chloride ions to form CuCl_2 (copper chloride).

Symbols used for some of the elements have already been given in Table 4.3; the formulae of some of the compounds are given in Table 4.4.

4.5 Acids and bases

Acids and bases are substances that have corrosive action on skin, metals and other building materials. The labels of bottles/containers containing acids/alkalis show the following sign:



Figure 4.8

Table 4.5

Organic acid	Formula	Mineral acid	Formula
Oxalic acid	CH_3COOH	Hydrochloric acid	HCl
Ethanoic acid	$\text{CH}_3\text{CO}_2\text{H}$	Nitric acid	HNO_3
		Sulphuric acid	H_2SO_4

4.5.1 Acids

There are two types of acids: organic acids and mineral acids. An organic acid is obtained from plant and animal sources; for example, citric acid is obtained from oranges and lemons, and ethanoic acid from vinegar. Organic acids are weak as compared to mineral acids. Mineral acids, which are strong and highly corrosive, include sulphuric acid, hydrochloric acid and nitric acid.

The chemical formulae of some of the acids are given in Table 4.5.

In general, acids have the following properties:

1. They change the colour of substances called indicators. Blue litmus, an indicator, becomes red when added to an acid.
2. They have sour taste.
3. Hydrogen ions are released when an acid is added to water.
4. There is a reaction between acids and a large number of metals producing hydrogen gas.
5. They also react with other materials like cement/concrete.

The reactions between acids and some metals/materials are given below:

Zinc + dilute hydrochloric acid $\rightarrow$ Zinc chloride + hydrogen gas

Zinc + dilute sulphuric acid $\rightarrow$ Zinc sulphate + hydrogen gas

Zinc + dilute nitric acid $\rightarrow$ Zinc nitrate + water + dinitrogen oxide gas

Copper + dilute nitric acid $\rightarrow$ Copper nitrate + water + nitrogen oxide gas

Table 4.6

Base	Formula
Aluminium oxide	Al_2O_3
Copper oxide	CuO
Sodium hydroxide	NaOH
Calcium hydroxide	Ca(OH)_2
Ammonia solution	NH_3
Copper hydroxide	Cu(OH)_2

Iron + dilute hydrochloric acid $\rightarrow$ Ferrous chloride + hydrogen gas

Iron + dilute sulphuric acid $\rightarrow$ Ferrous sulphate + hydrogen gas

Aluminium + dilute hydrochloric acid $\rightarrow$ Aluminium chloride + hydrogen gas

Lead + dilute hydrochloric acid $\rightarrow$ Lead chloride + hydrogen gas

(A layer of lead chloride will protect the metal from further acid attack.)

Calcium carbonate (marble) + dilute sulphuric acid
 $\rightarrow$ Calcium sulphate + water + carbon dioxide gas

4.5.2 Bases

A base is a substance that can neutralise an acid to produce a salt and water. Metal oxides, hydroxides and carbonates neutralise acids and are called bases. Alkalis are those bases that dissolve in water, for example, sodium hydroxide and calcium hydroxide. Some of the bases and their formulae are given in Table 4.6.

The properties of bases are:

1. Soluble bases can change the colour of red litmus to blue.
2. They neutralise the acids forming a salt and water.
3. Soluble bases react with oils to form soap.
4. Hydroxide ions are released when an alkali is dissolved in water.

The following reactions show how bases neutralise acids resulting in the formation of a salt and water:

Sulphuric acid + sodium hydroxide $\rightarrow$ Sodium sulphate + water

Copper sulphate + sodium hydroxide $\rightarrow$ Sodium sulphate + copper hydroxide

Bases can also react with some metals:

Aluminium + concentrated sodium hydroxide + water $\rightarrow$ Sodium aluminate + hydrogen gas

Exercise 4.1

1. Explain the difference between an element and a compound.
2. Write down the chemical symbols of the following elements:
 - i) Iron
 - ii) Silver
 - iii) Lead
 - iv) Tin
 - v) Copper
3. The following salts produce efflorescence in brickwork. What are the chemical formulae?
 - i) Calcium chloride
 - ii) Calcium sulphate
 - iii) Magnesium chloride
4. a) Explain the difference between organic and inorganic acids.
b) State three properties of acids.
5. a) State three properties of a base.
b) Give the chemical formula of the base used in houses to unblock the drains.
c) What happens when an acid attacks marble?
d) Complete the following reaction:

Marble + dilute sulphuric acid $\rightarrow$ + water + ...

6. Complete the following reactions:
 - i) Sodium + dilute hydrochloric acid $\rightarrow$ + hydrogen gas
 - ii) Sodium + dilute sulphuric acid $\rightarrow$ + hydrogen gas
 - iii) Iron + dilute hydrochloric acid $\rightarrow$ Ferrous chloride + ...
 - iv) Iron + ... $\rightarrow$ Ferrous sulphate + hydrogen gas
 - v) Aluminium + ... $\rightarrow$ Aluminium chloride + hydrogen gas
 - vi) Sulphuric acid + sodium hydroxide $\rightarrow$ + water

References/Further reading

1. Fullick, A. and McDuell, B. (2008). *Edexcel AS Chemistry*. Harlow: Pearson Educational.
2. Fullick, P. (2006). *AQA Science - GCSE Chemistry*. Cheltenham: Nelson Thornes.

5

Effects of chemicals and atmosphere on materials

Learning outcomes:

- 1) Explain oxidation and its effects on metals.
- 2) Describe electrolysis and electrolytic corrosion.
- 3) Explain the applications of electrolysis.

5.1 Introduction

Metals fulfil an important role in the construction of buildings. Aluminium, steel, lead and copper have a range of uses in the construction of buildings and other structures. Some of the uses are:

Aluminium: doors, windows, cladding and roof construction

Steel: doors, windows, structural steel sections such as universal beams, universal columns etc. and reinforcement for reinforced concrete.

Lead: roof construction

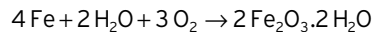
Copper: pipes for central heating and water supply, and roofing

When exposed to the atmosphere these metals are affected by air, water and impurities in the air, and the phenomenon is known as corrosion. There are two ways in which the corrosion of metals can occur: oxidation and electrolytic corrosion.

5.2 Oxidation

Oxidation is the action of oxygen and water on metals resulting in the formation of a new substance. An example of this effect that we come across quite often is the corrosion of iron. This phenomenon is also known as **rusting** and is due to the oxidation of iron forming a new substance.

Iron + water + oxygen → hydrated iron oxide



The rust (hydrated iron oxide) formed is reddish-brown in colour and porous. The rust allows more air and water to pass through and attack the metal underneath. Iron/steel is extracted from iron ores that are oxides of iron. When iron/steel components are exposed to the atmosphere, the metal reacts with air and moisture to revert back to the parent material, i.e. the iron ore. A thin layer of rust can be useful sometimes; for example, a very small amount of rust on reinforcement steel will improve its bond with fresh concrete.

Both air and water are required for the rust to form. In the absence of either or both, rusting of iron will not occur. This can be demonstrated by performing a simple experiment, as explained in Section 5.2.1. Iron/steel is used in manufacturing several building components, therefore it is necessary to provide a protective coating so that the rusting can be checked. A detailed discussion on the protection of steel is given in Section 5.4.2.

5.2.1 Experiment: To show that oxygen (or air) and water are necessary for the rusting of iron

Apparatus and materials: glass tubes, tap water, boiled water, iron nails and calcium chloride crystals.

Method: Three or four nails are put in the test tubes and exposed to three types of environment (see Figure 5.1):

- a) tap water
- b) water that has been boiled for a few minutes
- c) dry air

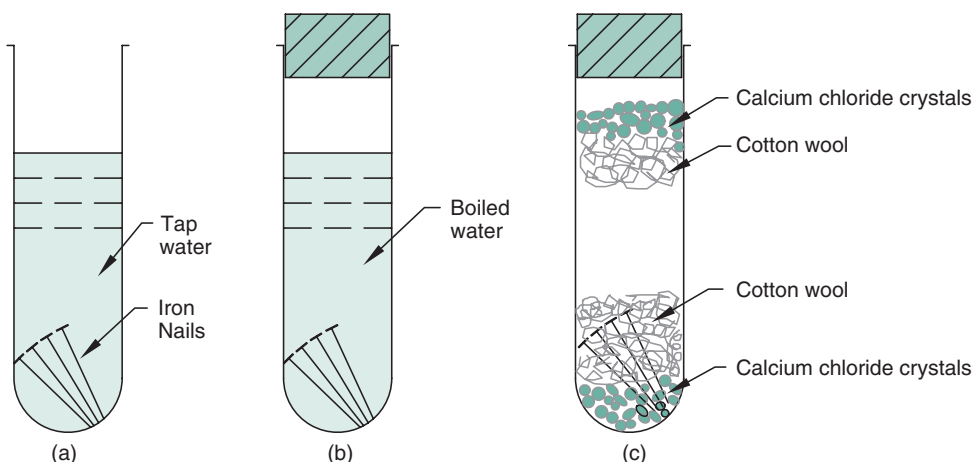


Figure 5.1 Oxidation (rusting) of iron nails: (a) water and air; (b) boiled water; (c) dry air.

Table 5.1 Effect of atmosphere on some metals

Metal	Effect of the atmosphere
Aluminium	Aluminium is covered with a film of aluminium oxide which prevents further corrosion of the metal.
Copper	Copper is covered with a protective green coating which is carbonate/sulphate of copper.
Zinc	A film of basic zinc carbonate is formed which protects the metal from further corrosion.
Lead	The surface of freshly cut lead is bright in appearance, but on exposure to the atmosphere it becomes dull. This is due to the formation of basic lead carbonate which prevents further corrosion.

On checking the nails after a few days, it will be noticed that:

- The iron nails in the tap water are rusted as they are exposed to water and air. Ordinary water contains some dissolved oxygen.
- The iron nails in the water that has been boiled and cooled are not rusted. When ordinary water is boiled for some time, most of the dissolved air is removed. For rusting, both air and water are required.
- The nails in dry air are not rusted. Calcium chloride crystals absorb moisture from the air making it dry.

If the nails are partially submerged in water, the intensity of rusting will be far greater as moisture and air are both easily available.

This experiment proves that for the oxidation of iron both air and water (moisture) are required. In the absence of either or both, oxidation will not take place.

The corrosive action of the atmosphere is not just limited to steel, other metals are also affected. However, the corrosive action is not drastic as the surface corrosion protects the metals from further deterioration. Table 5.1 summarises the effects of the atmosphere on a selection of metals.

These metals are also affected by acid rain. The effect, however, is insignificant as:

- The acid is very weak.
- The protective layer of carbonate/oxide prevents the acid from penetrating and causing reaction with the metal.

More information on acid rain is given in Section 5.6.

5.3 Electrolysis

It is important to study **electrolysis** before trying to understand electrolytic corrosion, which can deteriorate zinc, iron and some other metals.

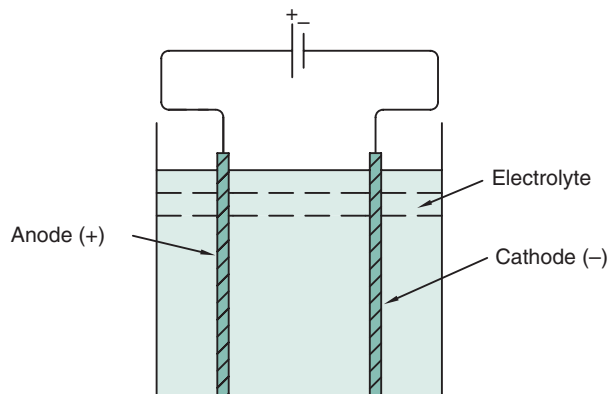


Figure 5.2

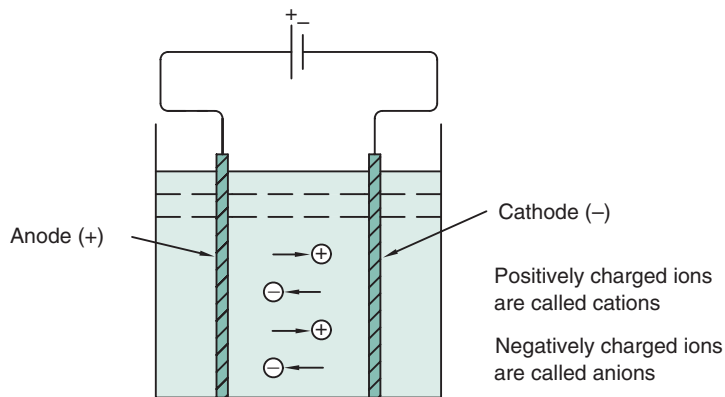


Figure 5.3

In Figure 5.2 the circuit shown consists of:

- A cell shown as
- Metal rods or plates known as **electrodes**. The negative electrode, which is connected to the negative terminal of the cell, is called the **cathode**. The electrode connected to the positive terminal of the cell is called the **anode**. The flow of current from the cell is considered to be from the positive terminal to the negative terminal.
- A liquid that allows the current to pass through. It is called an **electrolyte**, and is basically a solution in water of acids, alkalis or salts. Non-electrolytes such as pure water do not allow electricity to pass through.

If we take copper sulphate as the electrolyte, then there are two types of ions in the solution: positively charged copper ions and negatively charged sulphate ions. When current is passed through the electrodes, they become charged and, consequently, positively charged copper ions will be attracted towards the cathode which is negatively charged. Similarly, negatively charged sulphate ions are attracted towards the anode (Figure 5.3). The process of decomposition of an electrolyte is known as **electrolysis**.

Electrolysis can be used in many industrial processes such as electroplating, production of sodium hydroxide, extraction of aluminium from bauxite and purification of copper.

5.4 Electrolytic corrosion

As discussed in Section 5.3, the passage of electric current through an electrolyte can start a chemical action. Similarly, a chemical action can cause the flow of an electric current when two metals, placed in an electrolyte, are in contact. A situation similar to this may arise in buildings or other structures where two dissimilar metals have been used. In the presence of rainwater, which is slightly acidic and hence an electrolyte, an electric circuit is formed which results in the corrosion of one of the metals.

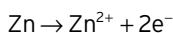
The rate at which a metal is dissolved (or corroded) depends on the relative position of the metal in the electrochemical series. Table 5.2 shows the electrode potential of a selection of metals.

Metals at the top of the table are more reactive (or easily corroded) whereas silver and gold are highly resistant to corrosion. Each metal when immersed in an electrolyte attains a potential which is shown in Table 5.2. If plates or rods of zinc and copper are immersed in an electrolyte and connected by a wire, the voltage will be approximately 1.1 volts.

$$\text{Voltage} = 0.34 - (-0.76) = 1.1 \text{ volts}$$

The phenomenon of electrolytic corrosion can be understood by studying the simple cell shown in Figure 5.4.

The zinc electrode can be amalgamated with mercury so that the acid does not attack zinc directly starting a reaction between the two. Zinc is more reactive than copper, therefore some of its atoms pass into solution before those of copper, leaving electrons behind. Each atom leaves two electrons on the zinc electrode:



Zinc becomes negatively charged because of the electrons left behind.

Table 5.2 The electrochemical series

Metal	Valency	Electrode Potential (volts)
Calcium	Ca^{2+}	-2.87
Magnesium	Mg^{2+}	-2.34
Aluminium	Al^{3+}	-1.66
Zinc	Zn^{2+}	-0.76
Iron	Fe^{2+}	-0.44
Tin	Sn^{2+}	-0.14
Lead	Pb^{2+}	-0.13
Copper	Cu^{2+}	+0.34
Silver	Ag^{2+}	+0.80
Gold	Au^{3+}	+1.50

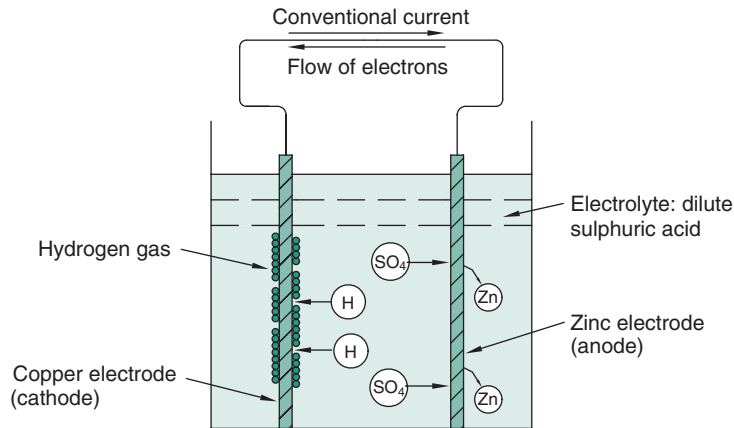
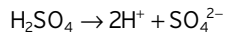


Figure 5.4 The simple cell.

Sulphuric acid ionises into hydrogen and sulphate ions when it is mixed with water



The sulphate ions are attracted towards zinc ions to form zinc sulphate (ZnSO_4). As sulphate ions are attracted by zinc ions, hydrogen ions move and deposit on the copper electrode. Electrons, which have been left on the zinc electrode, flow towards the copper electrode as shown in Figure 5.4. Hydrogen ions, deposited on the cathode, receive these electrons and result in the formation of hydrogen gas. As more zinc ions enter the solution from the zinc electrode, corrosion occurs. Corrosion will be severe if the size of the zinc electrode is very small as compared to the copper electrode. The flow of electrons through the wire is called an electric current.

When the cell was first discovered, scientists thought that the current flow was from the positive to the negative electrode. This convention is still used to show the flow of current.

In the simple cell, the anode is the negatively charged electrode, which is different from the statement in Section 5.3 that the anode is positively charged. This confusion can be avoided if we define an anode and a cathode as:

anode: the electrode where conventional current enters the cell.

cathode: the electrode where conventional current leaves the cell.

5.4.1 Examples of electrolytic corrosion

If the zinc coating is damaged, the simple cell is formed as the two metals are in contact in the presence of water (Figure 5.5). As zinc is more reactive than steel, it becomes the anode and starts to corrode. Zinc coating is called the sacrificial anode as it corrodes to protect the main metal, i.e. steel.

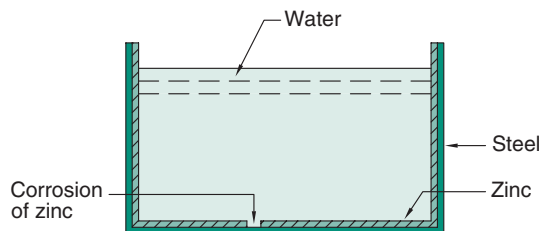


Figure 5.5

- a) Steel water tanks are provided with a coating of zinc, which protects steel from corrosion.
- b) In central heating systems that have steel radiators and copper pipes, steel becomes the anode as it is higher than copper in the electrochemical series. The joint between the radiator and the copper pipe may leak after a number of years. In more severe cases, pin holes may appear in the radiators.
- c) Mild steel consists of two grains: ferrite and pearlite. Ferrite is pure iron but pearlite is formed from alternate layers of ferrite and cementite, Fe_3C . Ferrite is known to be anodic to pearlite and starts to dissolve preferentially in the presence of water. There are also other reasons for the production of anodes and cathodes in steel, e.g. inclusion of some other grains in steel, surface imperfections etc.
- d) Lead is an extremely malleable metal and easily moulded into any shape. It is used as a roofing material to cover large, as well as small, areas. Correct fixing of leadwork is necessary to avoid premature failure. Lead sheets should be fixed by copper nails as galvanised iron nails will corrode due to electrolytic corrosion.

5.4.2 Protection of steel from corrosion

- a) **Galvanising:** The steel components or objects are coated with a thin layer of zinc or tin, either by electroplating or by dipping in the molten metal. Zinc and tin are not affected by oxidation. However, the performance of the protective layer is affected if it is scratched and there is a presence of water.
- b) **Surface treatments:** Components of steel such as window frames can be protected from corrosion by applying paint; other objects can be applied with bitumen or grease depending on where they are situated. The main disadvantage with this method is that the protective layer has to be renewed every few years.
- c) **Sacrificial anode:** A metal can be protected by attaching it to another metal that is higher in the galvanic series. As explained earlier, the metal that is higher in the electrochemical series will corrode to protect the other metal. Underground steel pipes are connected to a more electronegative metal such as zinc or magnesium. A simple cell is created which causes the corrosion of zinc/magnesium, protecting the steel pipe. This method is also known as 'galvanic cathodic protection'.
- d) **Impressed current cathodic protection:** For larger structures such as reinforced concrete, steel piles, gas pipelines etc., the galvanic anodes cannot provide enough

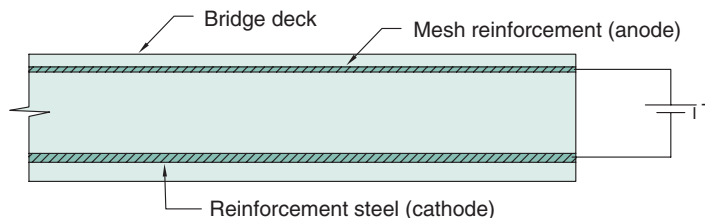


Figure 5.6 Impressed current cathodic protection.

current for complete protection. In these cases, impressed current cathodic protection (CP) may be used to protect the structure.

Steel reinforcement is used in concrete to resist the tensile stress. The reinforcement bars are protected from corrosion by the alkaline concrete environment. In winter, de-icing salts are used on concrete road surfaces and bridge decks which permeate the concrete gradually. The chloride ions from the de-icing salt neutralise the alkaline concrete environment and thus the reinforcement is exposed to corrosion. The corrosion of steel reinforcement can be prevented by impressed current CP which involves applying an electrical field to the concrete structure with the steel reinforcement being used as the cathode, as shown in Figure 5.6. The current will flow from the anode to the steel reinforcement, protecting the steel from corrosion.

A number of anode systems are available; titanium mesh with concrete overlay is used for horizontal applications such as bridge decks.

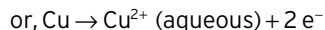
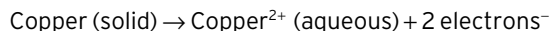
5.5 Applications of electrolysis

Electrolysis is used in several applications, some of which are given here:

5.5.1 Electroplating (Figure 5.7)

Electrolysis can be used to coat iron or other cheaper metals with thin layers of more expensive metals like silver and gold. If we want to coat an iron nail with copper, it is connected to the negative terminal of the battery, i.e. it is made a cathode. The positive terminal of the battery is connected to a plate or rod of copper. The electrolyte can be a salt of copper, for example, copper sulphate, copper nitrate etc.

When the current is switched on, the copper electrode dissolves to form copper ions:



The electrons flow from the copper electrode to the iron nail. At the cathode the copper ions in the electrolyte are turned into copper atoms and deposited as a thin layer on the nail.

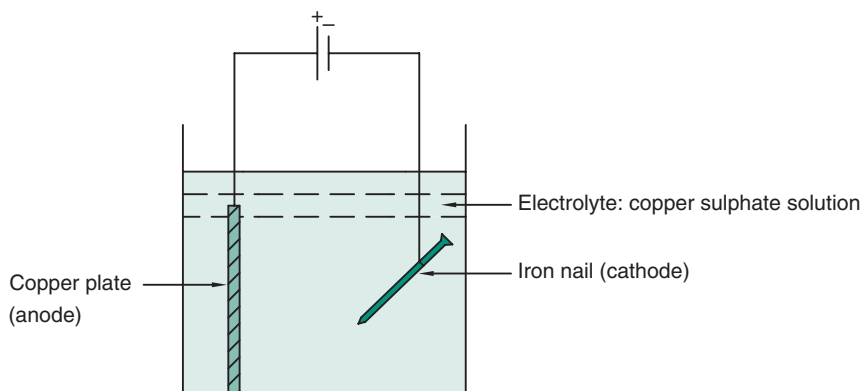


Figure 5.7 Electroplating.

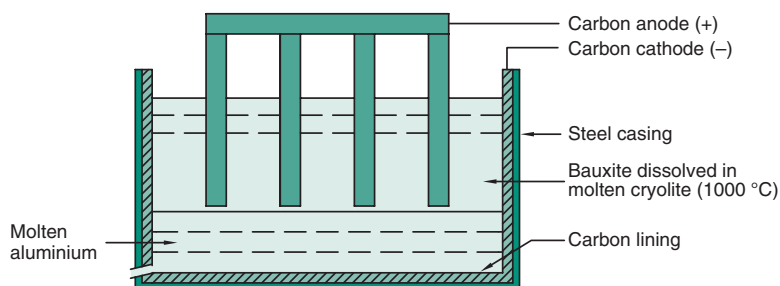


Figure 5.8 Electrolysis of bauxite.

5.5.2 Extraction of aluminium

Aluminium is extracted from its ore, bauxite, which is aluminium oxide ($\text{Al}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$). Aluminium oxide is very stable and is not easily reduced to aluminium. Extraction by electrolysis is not easy because the melting point of bauxite is very high (2050°C). The problem is solved by using molten cryolite (sodium hexafluoroaluminate, Na_3AlF_6) as the electrolyte in which bauxite dissolves at about 900°C .

Carbon is used as the anode as well as the cathode in the cell. As the current is passed, molten aluminium collects at the bottom of the cell from where it is tapped off, as shown in Figure 5.8.

5.6 Acid rain

Acid rain is a combination of very weak acids such as sulphuric acid and nitric acid. Most of the sulphur dioxide gas that is converted to acid comes from coal when it is burnt in industrial processes such as power generation at thermal power stations. Coal contains

up to about 5% sulphur, which is responsible for producing sulphur dioxide gas on burning:

Sulphur + oxygen (in air) → sulphur dioxide gas

In the presence of sunlight, sulphur dioxide, oxygen and water vapour combine to form sulphurous acid. This is further oxidised to form sulphuric acid which falls when it rains or snows.

In a similar way, the exhaust fumes of motor vehicles are converted to nitric acid when they react with water vapour. Rainwater also dissolves carbon dioxide gas (CO_2) from the air to form carbonic acid, H_2CO_3 . The pH value of acid rain is about 4.

Acid rain affects trees, and buildings built of marble. Dilute acids react with marble to produce hydrogen gas, salt and water. After prolonged attack, acid rain causes discoloration and disintegration of marble, as is happening in the case of the Taj Mahal, the white marble mausoleum built in 1622, in Agra (North India).

References/Further reading

1. Breithaupt, J. (2008). *AQA Physics A*. Cheltenham: Nelson Thornes.
2. Fullick, P. (2006). *AQA Science - GCSE Chemistry*. Cheltenham: Nelson Thornes.

6

Electricity

Learning outcomes:

- 1) Explain Ohm's law and solve numerical problems involving this law.
- 2) Solve problems involving resistors in series/parallel.
- 3) Explain the construction of a transformer and solve associated numerical problems.
- 4) Describe the distribution of electricity from the power plant to the consumer.

6.1 Introduction

When a plastic rod is rubbed with nylon or another synthetic fabric, it becomes electrically charged and will attract light objects like small pieces of paper. Similarly, when a glass rod is rubbed with silk it becomes electrically charged. On rubbing the glass rod with silk, some electrons from the glass are attached to the silk making the glass positively charged due to the loss of electrons. The charge on the glass rod (and the plastic rod) is called the static electric charge. Any two charged objects will exert a force on each other. Similar charges will produce a repulsive force while opposite charges produce an attractive force.

Electric current is the flow of electric charge through a conductor. Both the static charge and the electric current are formed because of the electrons.

6.2 Coulomb's law

In 1785, Coulomb, a French physicist, measured the force of attraction and repulsion between two stationary electrical charges and stated that the charges attract or repel each other with a force (F) that is directly proportional to the product of the two charges and inversely proportional to the square of the distance between them:

$$F \propto \frac{q_1 q_2}{r^2}$$

$$\text{or, } F = k \frac{q_1 q_2}{r^2}$$

where q_1 and q_2 are the electric charges and r is the distance between them. k is the constant of proportionality and is known as the electrostatic constant.

The value of k is $9 \times 10^9 \frac{\text{Nm}^2}{\text{C}^2}$

Therefore, $F = 9 \times 10^9 \frac{q_1 q_2}{r^2}$

If two charges placed at a distance of 1m are similar and equal, and repelled with a force of $9 \times 10^9 \text{N}$, the magnitude of each charge is 1 coulomb.

6.3 Electric current

The electric current is defined as the rate of flow of electric charge through a circuit.

Unit: The unit of current in SI units is the ampere (A).

The **ampere** is defined as the current if 1 coulomb of charge flows through a conductor in one second.

1 ampere (A) = 1 coulomb per second

An ammeter is used to measure the electric current through a conductor and must be connected in series with the conductor, as shown in Figure 6.1.

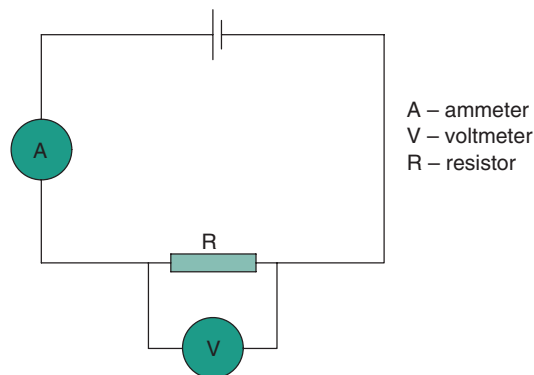


Figure 6.1

6.4 Potential difference

To understand potential difference (p.d.), consider a pipe that allows the flow of a liquid. The flow is only possible if the pipe is laid at a slope, i.e. the ends are at different heights. Similarly, current will flow through a conductor if its ends are maintained at different charges, or at different potentials.

Unit: The unit of potential difference is the **volt**.

A voltmeter is used to measure the potential difference between two points on a circuit. It is always connected in parallel, as shown in Figure 6.1.

6.5 Electromotive force (e.m.f.)

The maximum potential difference that a cell can produce in a circuit is called its **electromotive force** or e.m.f. This includes the potential difference required to drive the current through the cell itself. The e.m.f. of a cell depends only on the materials used in its manufacture. As mentioned in Section 6.4, electric current flows in a circuit/conductor if its ends are at different potentials. The e.m.f. may be considered to be the external force necessary to make the current flow in a circuit. It is defined as the work done (in joules) in moving a unit charge from one end of the circuit to the other.

6.6 Ohm's law

Ohm's law is the most fundamental law of electricity and was formulated by Georg Ohm in 1826. He conducted experiments using several types of wires and found that the current (I) flowing through each depended on the potential difference (V) applied across its ends. The law states that the current flowing through a metal conductor is directly proportional to the p.d. applied across its ends provided that the temperature and other physical conditions remain constant.

$$V \propto I$$

$$V = I.R$$

R is the constant of proportionality known as the **resistance** of the conductor. It is the resistance offered by the conductor to the flow of charge. Its value depends on the material, dimensions and the temperature of the conductor.

The above formula can also be written as:

$$R = \frac{V}{I} \quad \text{and} \quad I = \frac{V}{R}$$

Unit: Resistance is measured in ohms (Ω).

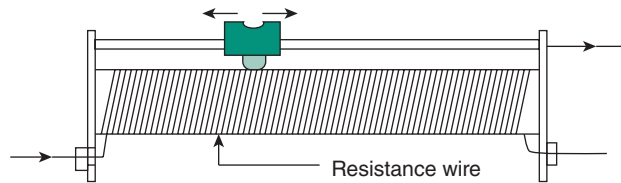


Figure 6.2 Rheostat.

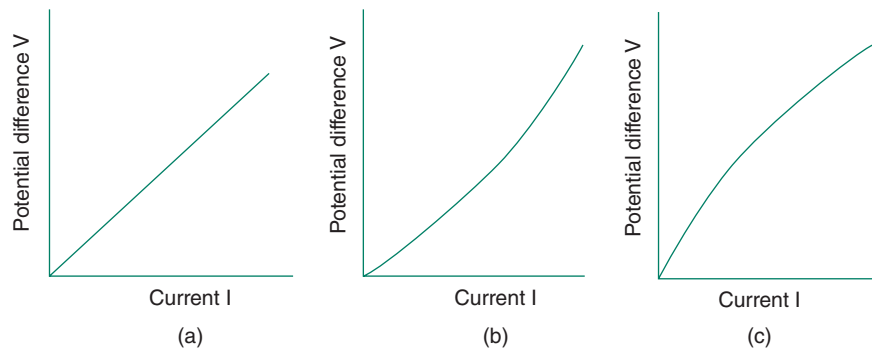


Figure 6.3

The resistance of a conductor is one **ohm** if a current of one ampere flows through it on applying a p.d. of one volt.

Devices specially made to provide resistance in electrical circuits are known as **resistors**. They reduce the flow of current in a simple circuit. Figure 6.2 shows a variable resistor known as a rheostat which is used for varying the current flowing in a circuit. Moving the position of the sliding contact changes the length of the coiled wire and hence its resistance.

The resistance of most metals increases with temperature. However, some materials like silicon become better conductors (resistance decreases) as they get warmer. Figure 6.3 shows three relationships between potential difference and current for metals/materials used in electrical circuits:

- Figure 6.3a shows that the current in a metal wire is proportional to the p.d. at a constant temperature.
- Figure 6.3b shows that, as the temperature rises, the current does not remain proportional to the p.d. In most metals, an increase in p.d. causes a smaller increase in the current, or, in other words, the resistance increases.
- Figure 6.3c shows that in silicon an increase in the p.d. causes a greater increase in the current, hence the resistance decreases.

Example 6.1

Calculate:

- the current I in the circuit of Figure 6.4a
- the voltmeter reading in Figure 6.4b
- the value of the resistor in the circuit of Figure 6.4c

Solution:

$$\text{a) } I = \frac{V}{R} = \frac{10}{40} = 0.25 \text{ A}$$

$$\text{b) } V = I R = 4 \times 8 = 32 \text{ V}$$

This is equal to the voltage read by the voltmeter

$$\text{c) } R = \frac{V}{I} = \frac{4}{0.5} = 8 \Omega$$

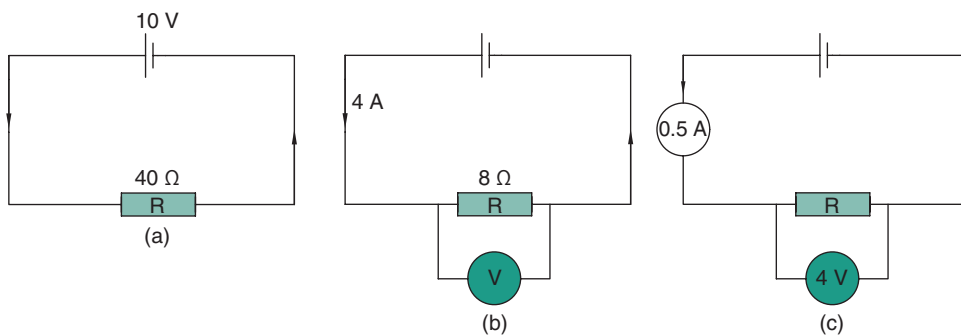


Figure 6.4

6.7 Electrical resistivity and conductivity

The resistance of a conductor is directly proportional to its length (L) and inversely proportional to its cross-sectional area (A).

$$\text{Resistance, } R \propto \frac{L}{A}$$

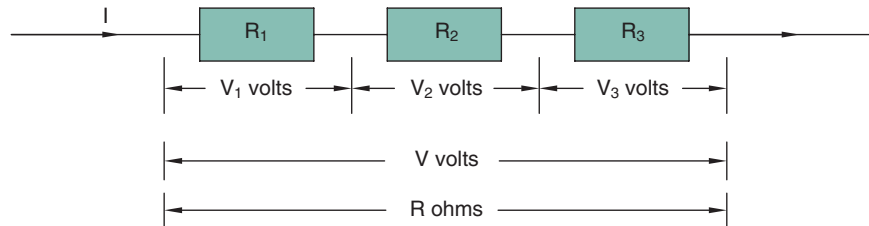
$$R = \rho \frac{L}{A} \quad \text{or, } \rho = \frac{AR}{L}$$

ρ , the constant of proportionality, is known as the electrical resistivity.

Metals and their alloys have low resistivity and are known as good conductors of electricity. Wood, rubber, glass etc. have high resistivity and are called bad conductors of

Table 6.1 Electrical resistivity of some metals/materials

Material	Electrical resistivity at 0°C Unit: Ωm
Carbon	3.5×10^{-5}
Silver	1.6×10^{-8}
Copper	1.7×10^{-8}
Aluminium	2.7×10^{-8}
Iron	10.0×10^{-8}
Wood	$10^8\text{--}10^{11}$
Glass	$10^{10}\text{--}10^{14}$

**Figure 6.5** Resistors in series.

electricity, or good insulators. Materials having resistivity in-between those of conductors and insulators are called semi-conductors. Table 6.1 gives the values of electrical resistivity of a selection of materials.

6.8 Resistors in series/parallel

6.8.1 Resistors in series

Figure 6.5 shows three resistors R_1 , R_2 and R_3 connected in series. If a battery is connected across the circuit, the same current, I , passes through each resistor.

V_1 , V_2 and V_3 are the potential differences across resistors R_1 , R_2 and R_3 respectively.

$$V_1 = I R_1 \quad V_2 = I R_2 \quad V_3 = I R_3$$

In a series circuit, the sum of individual voltages across individual resistors is equal to the total applied voltage,

$$\begin{aligned} \text{or, } V &= V_1 + V_2 + V_3 \\ &= I R_1 + I R_2 + I R_3 \\ &= I (R_1 + R_2 + R_3) \end{aligned}$$

(1)

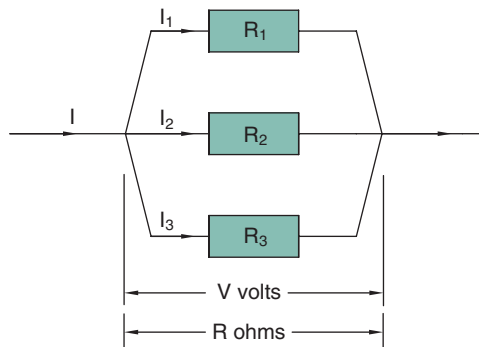


Figure 6.6 Resistors in parallel.

If R is the total resistance, then $V = IR$ (2)

From equations 1 and 2, $R = R_1 + R_2 + R_3$

The following conclusions can be made for resistors in series:

1. The total resistance of a circuit is equal to the sum of the individual resistances and the internal resistance of the battery.
2. The current in all resistors is the same.
3. The p.d. across a resistor depends on its resistance.

6.8.2 Resistors in parallel

Resistors placed side by side in a circuit are said to be in parallel (Figure 6.6). The potential difference across each resistor is equal to the applied potential difference. If I_1 , I_2 and I_3 are the values of current through resistors R_1 , R_2 and R_3 respectively, the total current I is given by:

$$I = I_1 + I_2 + I_3$$

The potential difference across each resistor is the same, i.e. V . Therefore:

$$V = I_1 R_1 = I_2 R_2 = I_3 R_3$$

$$\text{or, } I_1 = \frac{V}{R_1}; \quad I_2 = \frac{V}{R_2}; \quad I_3 = \frac{V}{R_3}$$

$$\begin{aligned} I &= \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3} \\ &= V \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right) \end{aligned}$$

$$\frac{I}{V} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \quad \left(\frac{I}{V} = \frac{1}{R} \right)$$

where R is the total resistance of the circuit.

The following conclusions can be made for resistors in parallel:

1. The reciprocal of the total resistance of a circuit is equal to the sum of the reciprocals of the individual resistances.
2. The p.d. is the same in all resistors.
3. The current in each resistor depends on its resistance.

Example 6.2

A current of 2 A flows through two resistances of $6\ \Omega$ and $4\ \Omega$ connected in series. Find the p.d. across each resistance and the supply voltage.

Solution:

Figure 6.7 shows the circuit in which a current of 2 A flows.

$$R_1 = 6\ \Omega, \text{ and } R_2 = 4\ \Omega$$

$$\text{Total resistance } R = R_1 + R_2 = 6 + 4 = 10\ \Omega$$

$$\begin{aligned} \text{Potential difference across } 6\ \Omega \text{ resistor, } V_1 &= I R_1 \\ &= 2.0 \times 6 = \mathbf{12.0\ V} \end{aligned}$$

$$\begin{aligned} \text{Potential difference across } 4\ \Omega \text{ resistor, } V_2 &= I R_2 \\ &= 2.0 \times 4 = \mathbf{8.0\ V} \end{aligned}$$

$$\begin{aligned} \text{Supply voltage, } V &= I R \\ &= 2.0 \times 10 = \mathbf{20.0\ V} \end{aligned}$$

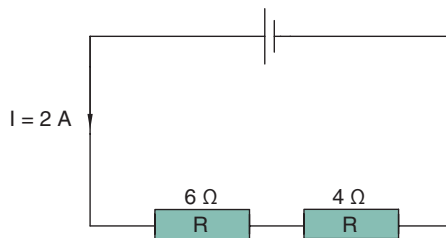


Figure 6.7

Example 6.3

Figure 6.8 shows two resistors connected in parallel, in a circuit. Find:

- the total resistance of the circuit
- the current in the circuit
- the current in the $8\ \Omega$ resistor

Solution:

- a) Total resistance, R , can be represented as:

$$\begin{aligned}\frac{1}{R} &= \frac{1}{R_1} + \frac{1}{R_2} \\ &= \frac{1}{4} + \frac{1}{8} \\ \frac{1}{R} &= \frac{3}{8}\end{aligned}$$

After transposition, $3R = 1 \times 8$ or, $R = \frac{8}{3} = \mathbf{2.67\ \Omega}$

- b) Current in the circuit,

$$\begin{aligned}I &= \frac{V}{R} \\ &= \frac{12}{2.67} = \mathbf{4.49\ A}\end{aligned}$$

- c) Current in the $8\ \Omega$ resistor $= \frac{V}{R}$
 $= \frac{12}{8} = \mathbf{1.5\ A}$

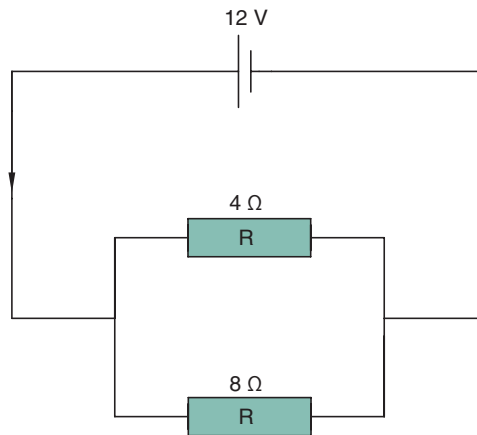


Figure 6.8

6.9 Transformers

Transformers are used to increase or decrease the voltage so that some electrical devices can work using the mains supply of 230 V. For example, the voltage is reduced from 230 V for use with calculators, laptop computers, power tools and other devices. There are two types of transformers:

- a) Step-up transformers: to increase the voltage
- b) Step-down transformers: to decrease the voltage

A transformer consists of two coils (or windings) of copper wire, the primary and the secondary coil, wound around a soft iron core (Figure 6.9). The primary coil is supplied with alternating voltage from a.c. supply, which creates a magnetic field around the coil. The magnetic field is continuously changing due to the nature of the a.c. supply. The changing magnetic field passes through the secondary coil and induces alternating voltage in it. This process, which is an example of electromagnetic induction without using a permanent magnet, is known as **mutual induction**. Only varying voltage can cause mutual induction which means that only a.c. supply can be used as the primary input.

Figure 6.10a shows that in a step-up transformer the number of turns in the primary coil is fewer than the number of turns in the secondary coil. In a step-down transformer (Figure 6.10b) the arrangement of coils is reversed. The voltage induced in the secondary coil depends on:

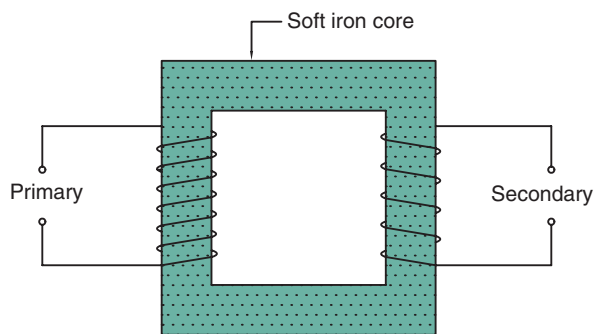


Figure 6.9 Transformer.

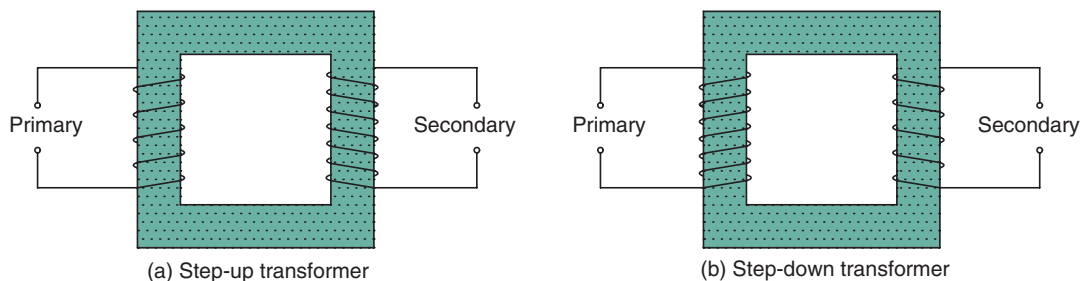


Figure 6.10 Step-up and step-down transformers.

- a) Number of turns in the primary coil
- b) Number of turns in the secondary coil
- c) Voltage in the primary coil

These factors can be combined in the form of a formula:

$$\frac{\text{Primary voltage (V}_p\text{)}}{\text{Secondary voltage (V}_s\text{)}} = \frac{\text{Number of turns in the primary coil (N}_p\text{)}}{\text{Number of turns in the secondary coil (N}_s\text{)}}$$

$$\text{or, } \frac{V_p}{V_s} = \frac{N_p}{N_s}$$

The materials used for the windings (copper) and the core (soft iron) are so selected that the resistance offered by the windings to the current is low to avoid heating of the coil and thus wastage of energy. Soft iron is magnetised easily on passing the current, and, similarly, is demagnetised quickly when the current flow is stopped. The core is constructed of laminated layers of insulated soft iron to stop the flow of current between the layers and thus keep the losses, due to heating effect, to a minimum. An efficiently designed core would ensure that all the electrical energy given to the primary coil is passed on to the secondary coil.

Power input in primary = Power output from secondary

$$V_p \times I_p = V_s \times I_s \quad (\text{power} = V \times I)$$

where I_p and I_s are the currents in the primary, and the secondary, coil respectively.

Transformers are used in the transmission of electrical energy from the power station to the consumer. They are initially used to step up the voltage, and then to step it down gradually.

Example 6.4

A transformer steps down the main supply of 230 V to 9 V to operate a calculator.

- a) If the secondary has 80 turns, calculate how many turns are on the primary.
 - b) Calculate the current in the primary if the current in the calculator is 2 A.
- Assume that the transformer is 100% efficient.

Solution:

$$\begin{aligned} \text{a) } \frac{V_p}{V_s} &= \frac{N_p}{N_s} \\ \frac{230}{9} &= \frac{N_p}{80} \end{aligned}$$

$$N_p \text{ (number of primary turns)} = \frac{230 \times 80}{9} = \mathbf{2044.4 \text{ or } 2045}$$

$$\begin{aligned} \text{b) } V_p \times I_p &= V_s \times I_s \\ 230 \times I_p &= 9 \times 2 \end{aligned}$$

$$I_p \text{ (current in the primary coil)} = \frac{9 \times 2}{230} = \mathbf{0.078 \text{ A}}$$

Table 6.2

Renewable resources	Non-renewable resources
Geothermal	Coal
Hydroelectricity	Natural Gas
Solar	Nuclear Fuels (uranium and plutonium)
Tides	Oil
Waves	
Wind	

6.10 Power generation

Electrical energy is produced from several resources, which can be grouped into two broad types: renewable and non-renewable, as shown in Table 6.2.

There are advantages and disadvantages of both types of resources; however, the disadvantages of non-renewable resources are more serious. The fossil fuels (coal, oil and natural gas) will eventually run out as their deposits are limited. To stop the fossil fuels running out so quickly, we need to conserve energy and use more renewable resources. Whilst most resources require turbines and generators for producing electricity, a wind turbine has its own generator.

A majority of the power stations use a source of energy (coal, water etc.), turbines and generators. In the case of fossil fuels and nuclear energy, steam is produced in boilers, which is used to drive the turbines. In **hydroelectric** power stations water is stored by building a concrete, or an earth, dam. Water is allowed to fall through large-diameter pipes onto the turbines. The impact of water has enough energy to drive the turbines. A similar arrangement is used to generate electricity from tidal barrages.

Wind turbines built in exposed places are used to produce electricity directly. The wind turns the blades of the turbine, which turns the generator that is provided inside each turbine.

There are three ways in which **solar energy** can be harnessed: solar cells (or photo-voltaic cells); solar panels; and solar furnaces. Solar cells generate electric current directly from sunlight. Solar panels contain water pipes under a black surface. Heat is absorbed from the sun by the black surface, which heats the water in the pipes. A solar furnace consists of a large array of curved mirrors, which focus the sunlight onto one spot. This produces a very high temperature, which is used to produce steam from water. Steam is used to drive turbines as in the other power stations.

The governments and people of most nations now realise that we need renewable resources of energy as the reserves of coal and crude oil may only last for a few decades more. The governments of some countries are very serious about the energy issue and are investing large amounts of money in solar power and other renewable resources. Abu Dhabi (United Arab Emirates) has developed a new town, called Masdar City, where electricity is produced from solar power rather than from fossil fuels. Algeria has already developed a 150 MW CSP (concentrated solar power) plant with plans for exporting up to 6 GW of solar power to southern Europe by 2020.

6.11 Power distribution

In Britain electricity is generated at a voltage of 11–25 kV and then stepped up to 275 kV or 400 kV by transformers. The power is then transmitted all over the country through the national grid. UK's **national grid** is a network of pylons and cables and is used to take electrical energy from the power stations and supply it to homes, factories, offices and other buildings/structures. Figure 6.11 shows the distribution of electricity from power plant to homes, offices and factories. The voltage is stepped down to 11 kV in stages at sub-stations for large industrial sites and to 400 V for general distribution. Connection between any two phase wires provides 400 V supply, suitable for heavy machinery. Connection between a phase wire and the neutral produces a potential of 230 V. Dwelling houses receive single-phase supply from one phase wire and the neutral. Buildings receiving 400 V supply have all the three phase wires.

Electricity is generated from coal, water and other resources at a power station. As electricity is distributed over large parts of the country by high-tension overhead power lines, it is important to reduce the energy loss due to heating effects. This can be achieved by supplying electricity at a high voltage, as shown in Example 6.5.

The voltage produced in alternating current (AC) is constantly changing, as shown in Figure 6.12. The maximum, average and RMS (root mean square) values are different from one another as shown by the relationships:

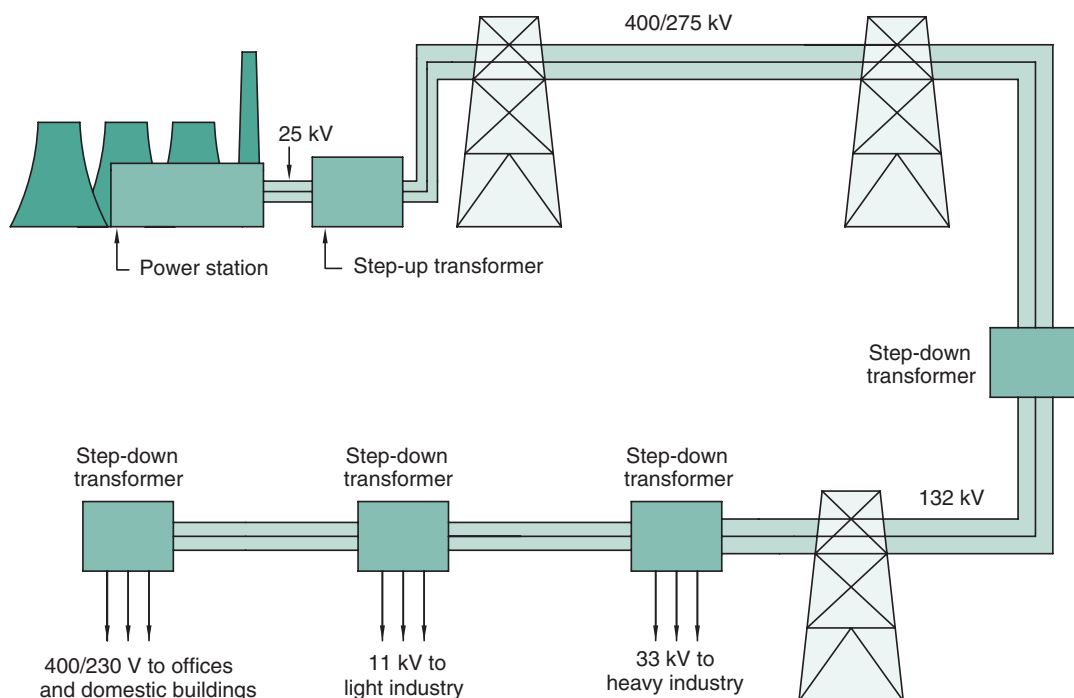


Figure 6.11 Distribution of electricity.

$$\begin{aligned}\text{Average voltage} &= 0.637 \times \text{maximum voltage} \\ &= 0.637 \times 325.3 = 207.2 \text{ V}\end{aligned}$$

$$\text{RMS voltage} = 0.7071 \times 325.3 = \mathbf{230 \text{ V}}$$

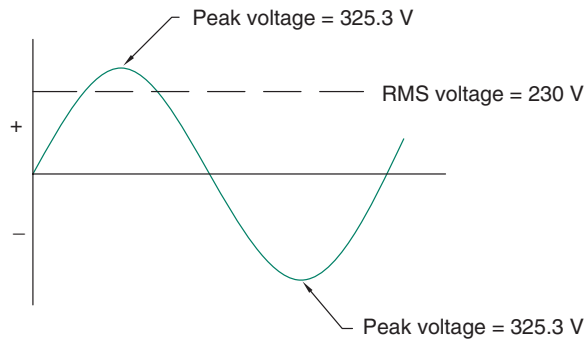


Figure 6.12 Alternating current.

Example 6.5

Find the power wasted as heat in cables when 15 kW is transmitted through a cable of resistance 0.5Ω at:

- a) 230 V b) 275 000 V

Solution:

$$\begin{aligned}\text{a) Current} &= \frac{\text{Power}}{\text{Voltage}} = \frac{15\,000}{230} \\ &= 65.2 \text{ A}\end{aligned}$$

$$\begin{aligned}\text{The power lost in the cable} &= I^2 R \\ &= 65.2^2 \times 0.5 = \mathbf{2125.52 \text{ W}}\end{aligned}$$

$$\text{b) Current} = \frac{15\,000}{275\,000} = 0.05454 \text{ A}$$

$$\begin{aligned}\text{The power lost in the cable} &= I^2 R \\ &= 0.05454^2 \times 0.5 = \mathbf{0.0015 \text{ W}}\end{aligned}$$

The above calculations show that at a voltage of 275 000 V the power loss is negligible.

6.12 Supply to small buildings

An underground electricity supply cable containing one phase wire and one neutral wire is supplied by the electricity board. The service cable is terminated at a sealed chamber which contains a 100 amp fuse and a neutral link. A connection is made to the meter from

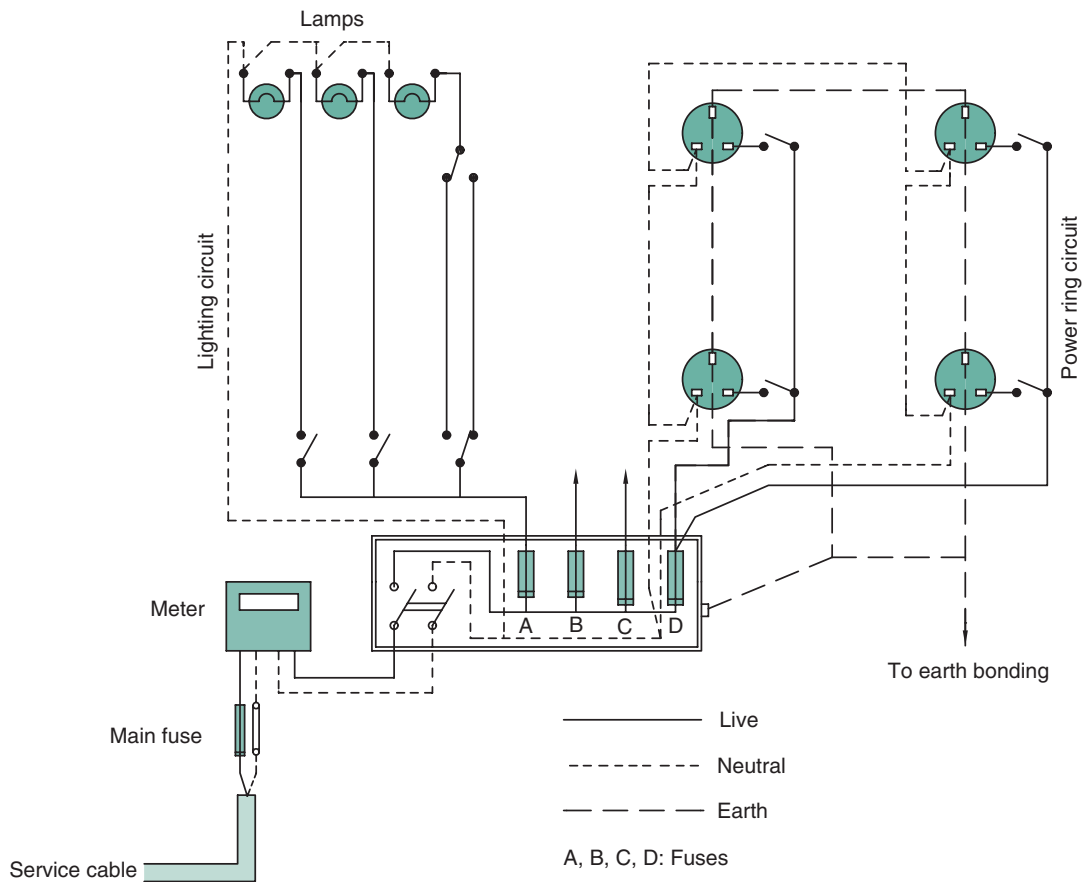


Figure 6.13 Domestic electric installation.

which cables are connected to the consumer's unit. Each circuit is protected by a miniature circuit breaker, also called a fuse, as shown in Figure 6.13. The lighting circuit and the ring circuit are also shown in Figure 6.13. The ring circuit is used to supply electricity to the power sockets. The lighting circuit is protected by a 6 amp fuse whereas the ring circuit is protected by a 32 amp fuse. There are also fuses for an immersion heater, electric shower and a cooker.

Exercise 6.1

1. A current of 10 A flows through a resistance of 40Ω . What is the p.d. across this resistance?
2. Two resistances of 4Ω and 8Ω are connected in series. Find the p.d. across each resistance and the supply voltage, if a current of 4 A flows through the circuit.

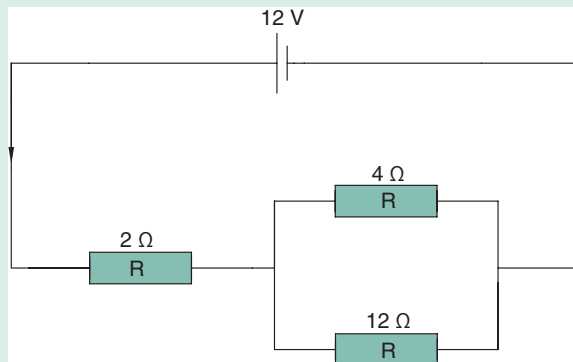


Figure 6.14

3. Three resistances of 4Ω , 6Ω and 12Ω are connected in parallel. Find the total resistance of the circuit.
4. Two resistances of 4Ω and 12Ω are connected in parallel across a 12 V supply. Calculate:
 - a) the total resistance of the circuit
 - b) the current in the circuit
 - c) the current through each resistance
5. Figure 6.14 shows a 12 V battery of internal resistance 1.0Ω connected to resistors A, B and C. Find:
 - a) the total resistance of the circuit
 - b) the current in each resistor
6. A transformer steps down the main supply of 230 V to 110 V to operate a hammer drill.
 - a) If the primary has 115 turns, calculate how many turns are on the secondary.
 - b) Calculate the current in the primary if the current in the hammer drill is 10 A. Assume that the transformer is 100% efficient.

References/Further reading

1. Breithaupt, J. (2008). *AQA Physics A*. Cheltenham: Nelson Thornes.

7

Introduction to construction technology

Learning outcomes:

- 1) Explain the difference between substructure and superstructure.
- 2) Discuss a range of foundations for low-rise buildings.
- 3) Explain the functions of the external envelope and describe the main building elements.

7.1 Introduction

In this chapter the basic terminology used in building construction and some of the main elements of buildings will be explained. These terms and simple construction processes will be used in other chapters while discussing the effects of heat, sound, forces and light.

Buildings may be constructed in several forms and it is not possible to explain every type of construction here. However, the main forms of construction such as cellular construction, framed construction and portal frames will be discussed in this chapter.

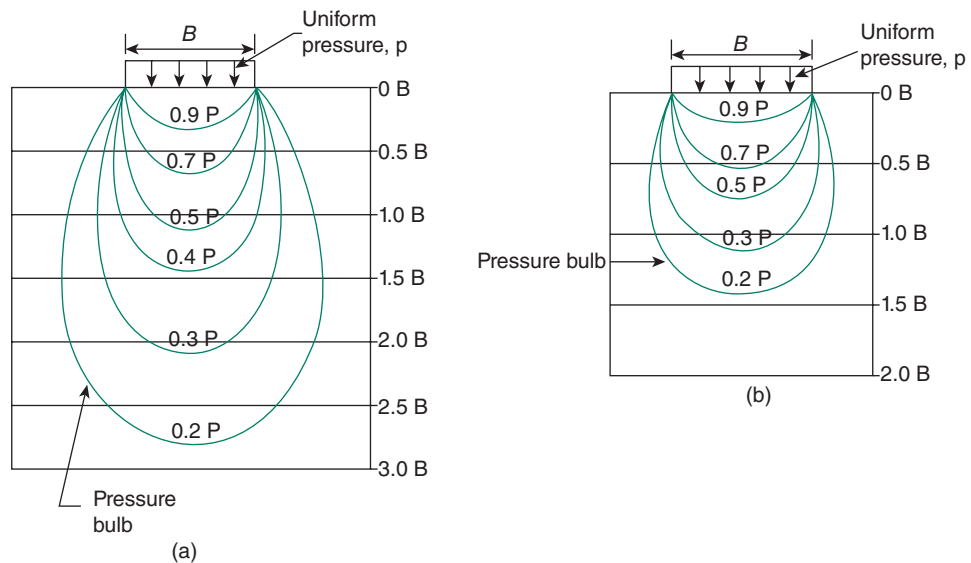
7.2 Substructure and superstructure

A majority of buildings consist of two main parts: the substructure and the superstructure. The **substructure** is usually considered as the part which is below ground level (G.L.) and consists of foundations, walls and floors that provide support for the superstructure. The **superstructure** is defined as the part of the building that is above the substructure.

It is necessary to excavate trenches until stable soil strata are reached and the foundation of a building is constructed. In its simple form, the foundation is a strip of concrete (minimum thickness = 150 mm) that supports the walls of a building. From the foundation the loading is distributed onto the soil strata, also known as the natural foundation. There are many types of subsoil, each having some ability to carry the building load. This ability is known as the **bearing capacity** of the soil and is defined as the safe load that a unit area of ground will carry. The amount of force exerted by a building on the ground per unit area

Table 7.1 Typical values of bearing capacity

Subsoil type	Bearing capacity (kN/m ²)
Soft clay	80
Firm clay	120
Fine sand, loose and dry	100
Hard clay	400
Compact gravel and sand	500
Rocks	600-10000

**Figure 7.1** Vertical stress under foundations: (a) under a strip foundation; (b) under a pad foundation.

is known as the **bearing pressure**, and for the stability of the building it should not exceed the bearing capacity. Table 7.1 gives the values of bearing capacity for some soils/rocks.

7.2.1 Soil investigation

Before a building is built, it is important to carry out a soil investigation to find the nature and thickness of the subsoil strata. The results of the subsoil investigation are used for many purposes, one of which is to design the building foundation in a safe and economical manner. During soil investigation, disturbed and undisturbed soil samples are taken to determine the properties of the subsoil and the thickness of the soil strata. Undisturbed samples of soils, taken from boreholes and trial pits, are also used to determine the strength of the soils that will support the structure.

The depth, to which the soil investigation should be carried out, depends on the type of the foundation. Boussinesq's equation is used to determine vertical stresses under continuous, rectangular and circular foundations. Figure 7.1 shows the magnitude of vertical pressure, in terms of the bearing pressure, p , at various points. For example, the

vertical pressure at any point along the '0.3p line' is equal to 30 per cent of the applied contact pressure. These lines of equal pressure are bulb-shaped and hence are called **pressure bulbs**. The most commonly used pressure bulb, for deciding the maximum depth of soil investigation, is the one for 0.2p because practically any stress less than 0.2p is of little consequence. For a typical strip foundation (width (B) = 0.6m), to be provided at a depth of 1.0m below the ground level, the soil investigation should be done to a depth of $1.0 + 2.8 B$, or 2.7 m below G.L.

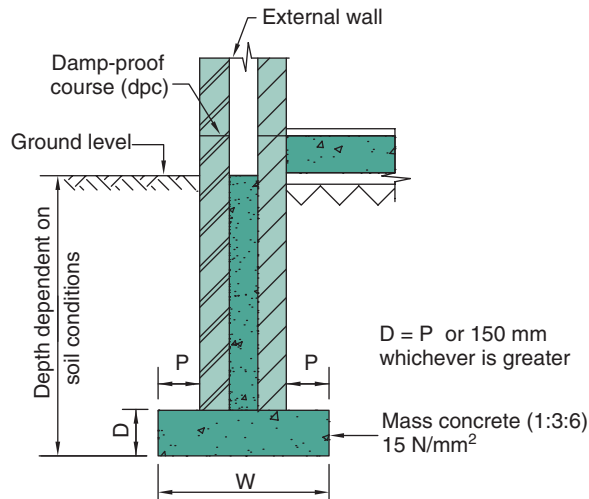
7.3 Foundations

The function of a foundation is to transmit the total load from a building to the ground safely and without causing any settlement or movement of any part of the building. The foundation of a building should also ensure the safety of the adjoining structures. The foundations of domestic buildings are constructed of concrete because fresh concrete is semi-liquid and would take the shape of the excavation. The most common types of foundations for low-rise buildings (height up to 9.0m) are strip, deep-strip or trench-fill, wide-strip, raft and pad foundations.

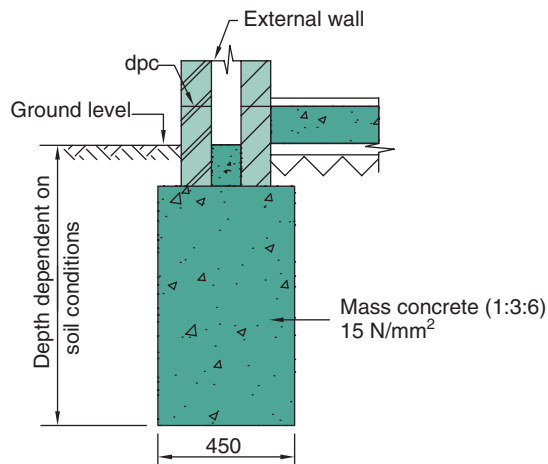
- a) Strip foundation (Figure 7.2): A strip foundation consists of a strip of concrete having uniform width and thickness supporting the full length of all load-bearing walls. Approved document A to the Building Regulations gives suitable minimum widths of strip foundations for various loadings and types of subsoil. The thickness of concrete should be equal to its projection from the wall, but in no case less than 150mm. A variation of a strip foundation is that of the deep-strip or trench-fill foundation. More concrete is used in a deep-strip foundation but the amount of brickwork and labour are greatly reduced.
- b) Raft foundation (Figure 7.3): A raft foundation may be used when the bearing capacity of the soil is very low. It covers the whole area of the building and consists of a reinforced concrete slab with extra thickening under load-bearing walls.
- c) Pad foundation (Figure 7.4): A pad foundation is basically a slab of concrete that supports a column. As the columns carry heavy loading, pad foundations are invariably reinforced with steel bars. The size of a pad foundation depends on the column load and the bearing capacity of the subsoil on which it rests.

7.3.1 Settlement

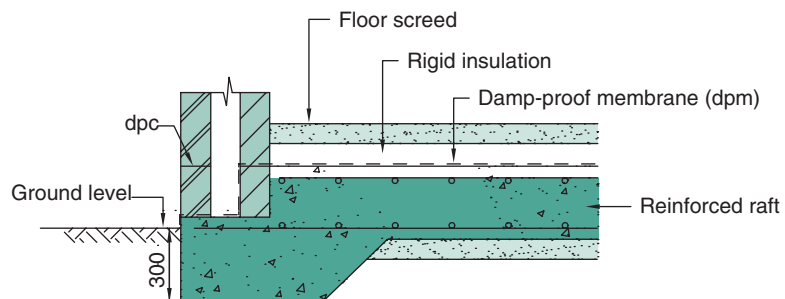
The **settlement** of a structure, which may be caused by several factors, is a result of the compression of the soil strata supporting that structure. Due to the construction of a new building, the stress in the soil supporting the foundation increases. This in turn causes the soil particles to come closer, increasing the contact area between them. The increased inter-particle contact area is responsible for supporting the increased load due to the new construction. As the soil particles come together the water that is present in the voids, called pore water, is drained out. This process is called the **consolidation of soils**. In sandy soils the drainage of the pore water is fast, hence the settlement is over in a short period of time. In clay soils, the drainage of the pore water takes a long time, hence the consolidation process is usually slow.



(a) Traditional strip



(b) Deep strip

Figure 7.2 Strip foundations.**Figure 7.3** Reinforced concrete raft foundation.

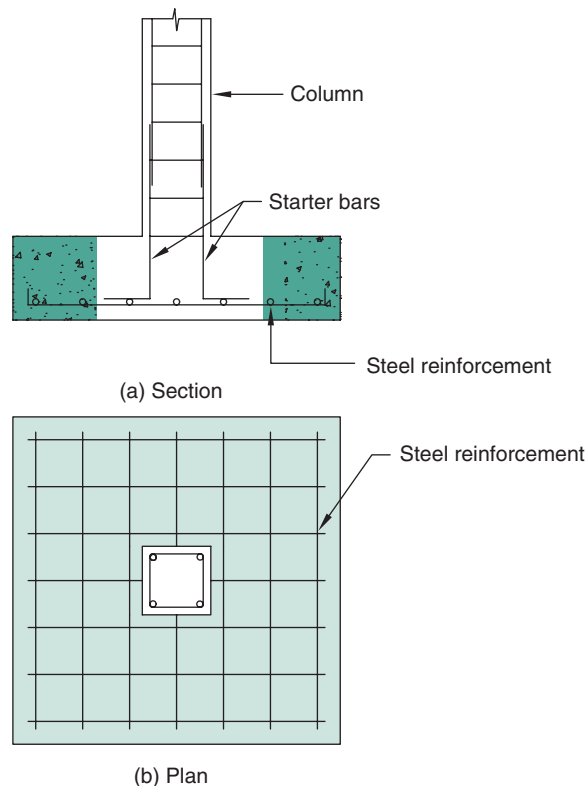


Figure 7.4 Pad foundation.

7.4 Forms of construction

Buildings are provided so that we can perform a range of activities. Houses, shops, schools/colleges, cinema halls, temples, churches, airports etc. are built to cater for the needs of humans. Various forms of construction are available to construct these and other types of buildings; some of these forms of construction are:

- Cellular construction (Figure 7.5): This form of construction consists of load-bearing external and internal walls. The walls spread the loading on strip, or other suitable, foundations which in turn disperse it to the subsoils. Buildings constructed using this form are rigid and stable.
- Cross-wall construction (Figure 7.6): This form of construction consists of a series of parallel walls, built at right angles to the front elevation, which carry the floor and roof loads. The floors are built rigidly into the walls to make the walls stable by providing lateral restraint.
- Framed or skeletal construction: A series of vertical and horizontal structural members set at right angles, as shown in Figure 7.7, provide support to the roof, floors and walls. The beams support the floors and transfer their load to the columns.

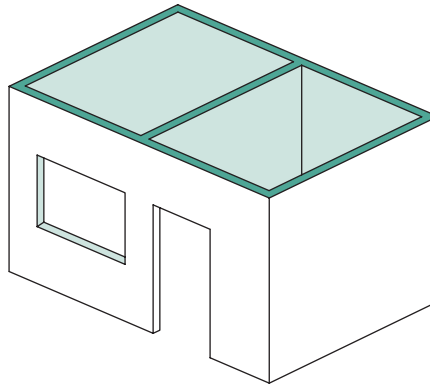


Figure 7.5 Cellular construction.

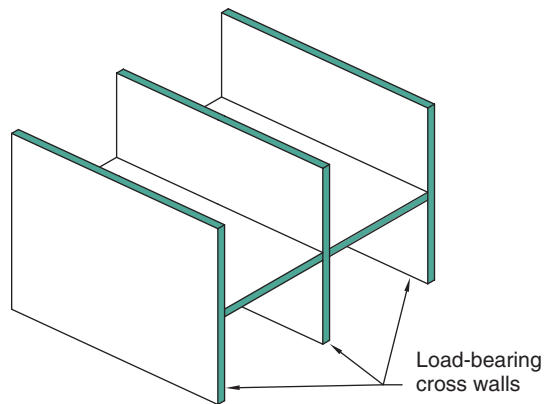


Figure 7.6 Cross-wall construction.

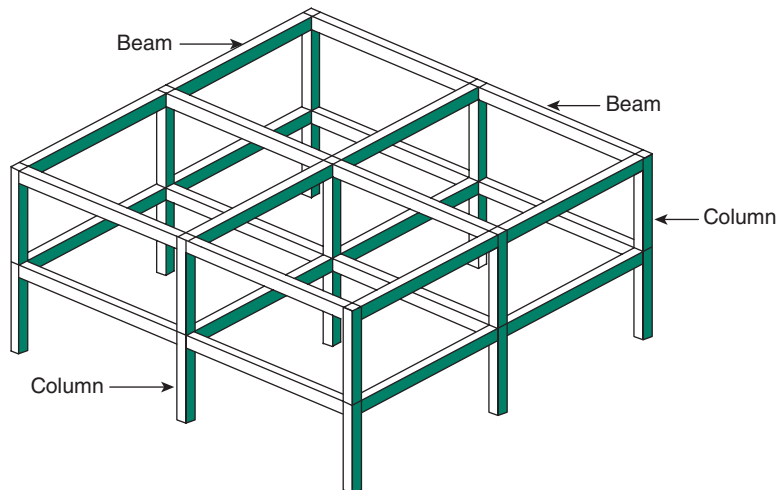


Figure 7.7 Framed construction.

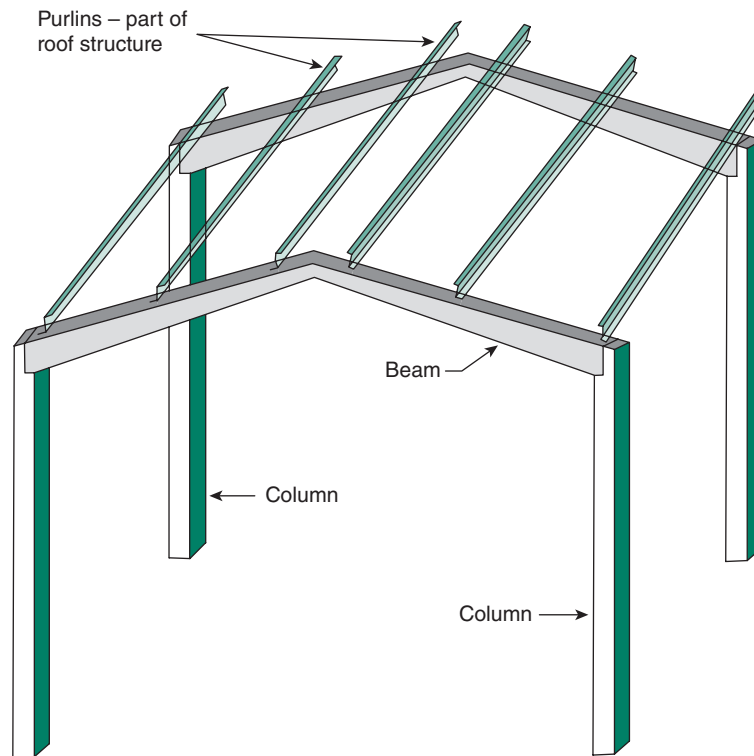


Figure 7.8 Portal frames.

The columns transfer the entire load of the building to the foundations. Most multi-storey buildings are constructed using either reinforced concrete (R.C.) or structural steel frames.

- d) Portal frames: Portal frames consist of two uprights rigidly jointed by a horizontal, sloping, or curved, third member. Each frame requires lateral support, which is provided by bracing from other similar frames, as shown in Figure 7.8.

7.5 The external envelope

All human beings require a shelter for protection from the elements, an enclosed space and to provide a suitable internal environment for working, rest, recreation and other activities. The shelter can be called the 'external envelope' and consists of roof, walls, doors and windows. One of the main requirements of the external envelope is that it should provide a strong and stable structure. The materials used in its construction should be strong enough to carry:

- a) Self-weight of the envelope
- b) Loading from people and furniture

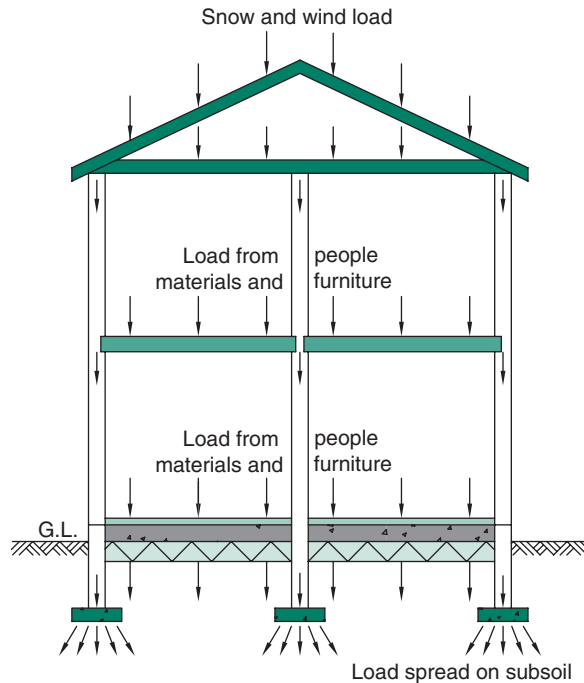


Figure 7.9 Transfer of load from superstructure to substructure.

- c) Loads transferred from the floors
- d) Loading due to wind, snow and rain

Figure 7.9 shows how the forces are transferred from roof, walls, floors etc. to the building foundations, and then from the foundations onto the subsoil. Brief details of the main building elements are given in the following sections.

7.5.1 Ground floors

A ground floor may be constructed as either a solid floor or a suspended floor. A solid ground floor (see Figure 7.3) rests on the ground whereas a suspended floor rests on walls. A suspended timber ground floor is not much different from upper-floor construction except that insulation is necessary to have a low U-value.

7.5.2 Cavity walls

Cavity walls provide better thermal insulation and resistance to moisture penetration as compared to solid brick walls. A cavity wall is constructed by building two walls, or leaves, tied by galvanised steel, or plastic, wall ties (Figure 7.10). The cavity between the outer brick leaf and inner aerated concrete block leaf is filled with insulation material to conform to the current Building Regulations on thermal insulation.

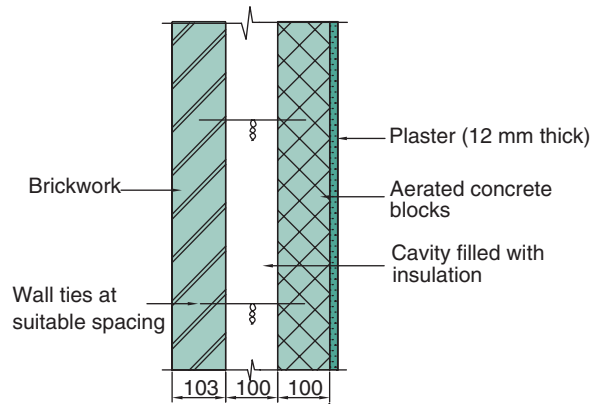


Figure 7.10 Cavity wall.

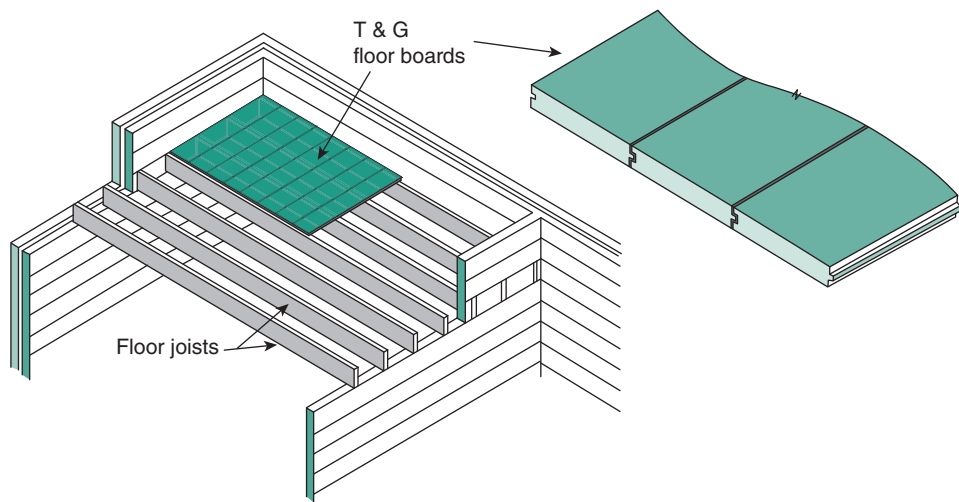


Figure 7.11 Suspended timber upper floor.

7.5.3 Suspended timber upper floors

The upper-floor construction consists of timber joists and floor boards or chipboard flooring as shown in Figure 7.11. The width of the joists is usually 50 mm, but their depth depends on the room span. The thickness of the floor boards or chipboard flooring depends on the spacing between the joists. The joists are supported either directly on the walls or on joist hangers. Plasterboard is fixed to the underside of the joists to provide the ceiling finish for the lower floor.

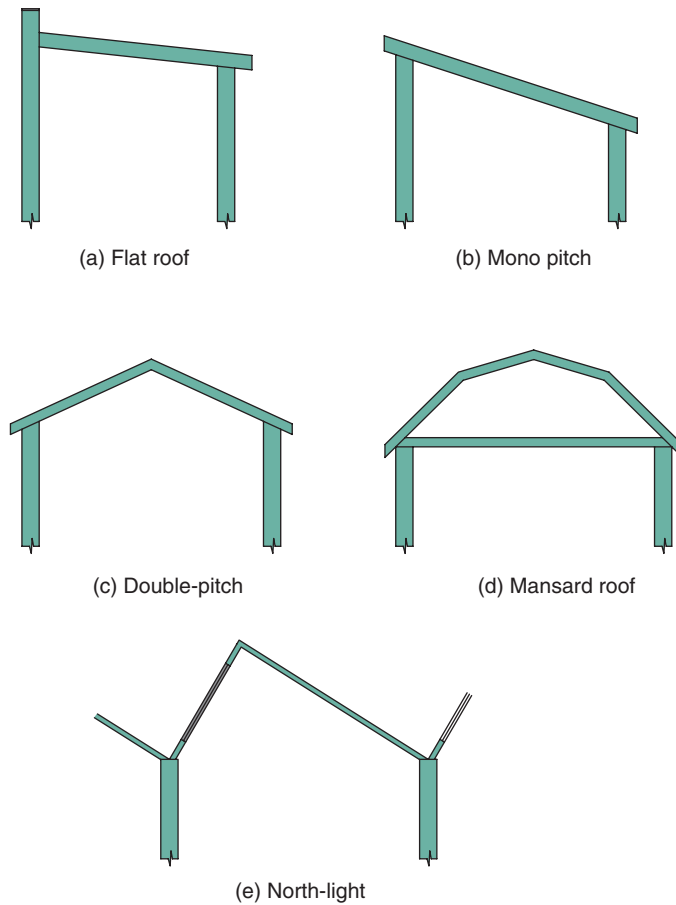


Figure 7.12 Roof shapes.

7.5.4 Roofs

The main function of a building roof is to keep out the rain, snow, wind and sun, and to drain away the rainwater. Roofs may be classified by considering their shape, span and structural design. Two of these are explained below:

- a) Shape (Figure 7.12): Some of the main roof shapes are: flat, pitched (mono-pitch, double-pitch, mansard, north-light etc.) and curved (barrel-vault, dome, cross-vault, hyperbolic-paraboloid etc.).
- b) Structural form (Figure 7.13): This method of classification depends on how the roof coverings are supported. Some of the roof forms considering the structural aspect are: couple roof, close-couple roof, collar roof, purlin roof, trussed-rafter roof, portal frames etc.

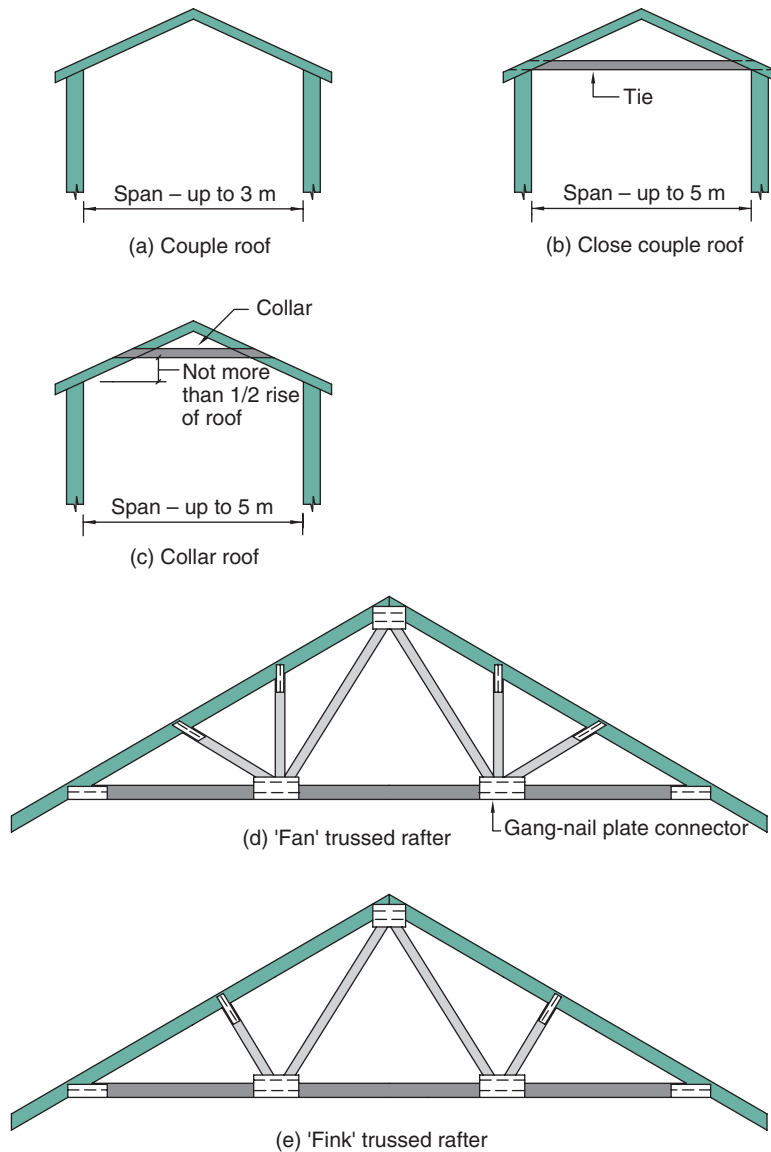


Figure 7.13 Structural forms of roofs.

When the span of a roof exceeds 5.0 m, the rafters may sag under the weight of the roof coverings. Longitudinal beams called **purlins** are provided to support the rafters, and hence the roof construction is known as a **purlin roof**.

Trussed rafters, used in modern houses, are made by joining the timber sections with gang-nail plates. Trussed rafters are made in factories and are much easier to make as compared to the traditional roof. Two common shapes are the fink type, and the fan type, trussed rafters, as illustrated in Figure 7.13.

References/Further reading

1. Chudley, R. and Greeno, R. (2008). *Building Construction Handbook*. Oxford: Butterworth-Heinemann.
2. Cooke, R. (2007). *Building in the 21st Century*. Oxford: Blackwell Publishing.

8

Thermal energy 1

Learning outcomes:

- 1) Define temperature and heat.
- 2) Explain states of matter, latent heat and sensible heat.
- 3) Explain expansion and contraction of materials and solve numerical problems.
- 4) Explain the process of heat transfer and its practical applications.

8.1 Introduction

There are many forms of energy, thermal energy being one of them. Without thermal energy life on this planet would not be possible. We use heat daily in our homes for cooking, space heating and hot water. Many industrial processes also use heat energy, for example, the generation of electricity in thermal power stations.

Heat affects buildings and other structures in many ways, and to understand these processes and problems a study of the nature and effects of heat is imperative. In this chapter the transmission of heat, expansion and contraction of materials, and thermal insulation of building elements will be discussed. But first it is necessary to define and discuss temperature, its measurement, and units of heat.

8.2 Temperature

The term, temperature, is used to express the degree of hotness of a substance. It is measured by using a device called a thermometer. Of the different types of thermometers that are available, the mercury thermometer is the most widely used. This is basically a glass tube with one end closed and the other made to form a bulb, which acts as a mercury

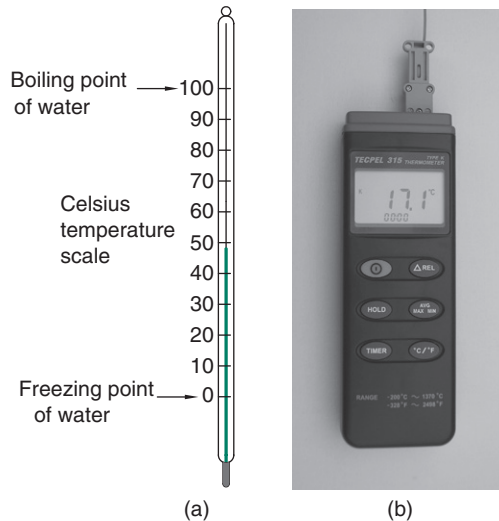


Figure 8.1 Mercury and electronic thermometers.

reservoir. The stem is marked into graduations called degrees, as shown in Figure 8.1. The figure also shows a digital thermometer which consists of a sensor known as a thermistor. Owing to a change in temperature the resistance of the sensor changes; this is measured by the circuit in the device and converted into a temperature.

8.2.1 Temperature scales

- a) **The Celsius scale:** The temperature of pure melting ice is zero-degree Celsius (written as 0°C) and the temperature of steam from boiling water is 100°C . Between 0°C and 100°C , the scale is divided into 100 equal divisions, each one being called a degree.
- b) **The thermodynamic temperature scale:** Charles Law states that the volume of a fixed mass of gas at constant pressure is proportional to its temperature. If the temperature of the gas is lowered, the volume reduces as well. The temperature at which the volume will become zero is called the **absolute zero temperature**. This is the lowest temperature that can be attained theoretically, but impossible practically, as the volume of a gas can never become zero. Using the absolute zero as the zero temperature, the thermodynamic temperature scale was devised. The scale is divided into units called kelvins denoted as K rather than $^{\circ}\text{K}$. The size of one **kelvin** is the same as that of a degree Celsius.

$$0\text{ K} = -273^{\circ}\text{C (approx.)}$$

$$273\text{ K} = 0^{\circ}\text{C}$$

$$373\text{ K} = 100^{\circ}\text{C}$$

8.3 Units of heat

The quantity of heat required to raise the temperature of 1 gram of water through 1°C is called the **calorie**. In the S I system the unit of heat energy is the **joule** (J) which is defined as the work done when a force of 1 Newton acts through a distance of 1 metre.

Power is defined as the rate of transfer of energy:

$$\text{Power} = \frac{\text{energy transferred}}{\text{time taken}}$$

The SI unit of power is the watt (W) and is equal to the transfer of one joule of energy per second (s):

$$1\text{W} = 1\text{J/s}$$

$$1\text{kilowatt (kW)} = 1000\text{ W}$$

$$1\text{megawatt} = 1000000\text{ W (or } 10^6\text{ W)}$$

8.4 States of matter

Anything that occupies space, i.e. has volume, and has mass, is called matter. Typical examples are: air, water, metals, wood, plaster, glass etc. There are three forms in which matter can occur: solid, liquid and gas. These forms are known as the states of matter. Water is one of the substances that we use daily, and the three states in which it exists are:

Solid - ice

Liquid - water

Gas - water vapour and steam

The properties of solids, liquids and gases depend on the forces between their molecules. The molecules of a solid are held together by strong forces of attraction. The movement of molecules past one another is not possible, therefore the shape, volume and mass of a solid remain the same.

The molecules of a liquid are quite close, but the forces holding them together are not very strong. The molecules can move past one another, enabling a liquid to take the shape of the container in which it is stored; however, its volume remains constant.

A gas has definite mass, but the shape and volume can change, as the molecules of a gas are far apart. Compressing a gas or changing its shape and volume are quite easy.

8.4.1 Changes in the physical state

In a physical change, the state may alter from solid to liquid or from liquid to gas and vice versa, but the basic structure of the substance remains unchanged. This is quite different

from a chemical change where the new material formed is different from the original substance. A chemical change is irreversible whereas a physical change is reversible. Ice changes into water on heating, but when the temperature of water is lowered below 0°C , ice is formed, showing that this is a reversible change. The rusting of iron due to oxidation is a chemical change, as a new substance is formed, the properties of which are totally different from the parent material.

8.4.2 Experiment: The physical states of water

Apparatus and materials: Beaker, retort stand and clamp, thermometer, Bunsen burner, tripod and gauze, clock and ice.

Procedure:

- 1) Take some ice cubes and put them in the beaker.
- 2) Set up the apparatus as shown in Figure 8.2, and note the temperature; this should be below 0°C .
- 3) Start heating the ice and record the temperature of the ice at regular intervals. The data may be recorded in a tabular form.
- 4) Continue to observe and note the temperature at regular intervals. The temperature will stay at 0°C for some time while the ice is melting.
- 5) After all the ice has melted, the temperature of the water will start to rise until the water begins to boil. The temperature of boiling water, if it is pure, should be 100°C . If there are impurities in the water, the boiling temperature may be slightly higher.
- 6) The temperature will stay at 100°C as the water boils and evaporation takes place. The experiment may be terminated after a few minutes.

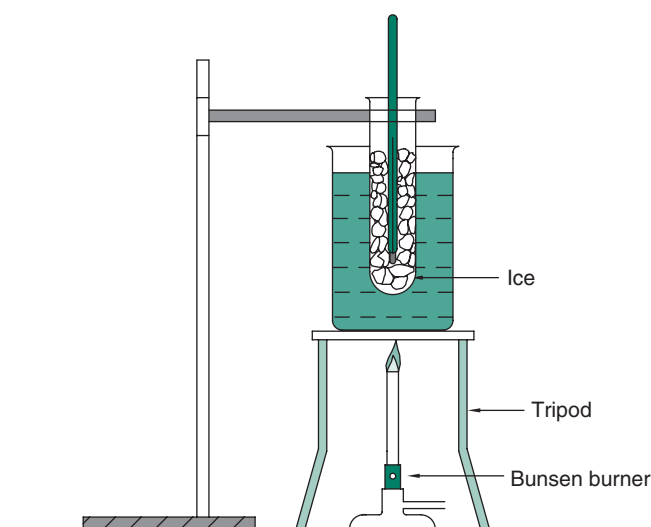


Figure 8.2

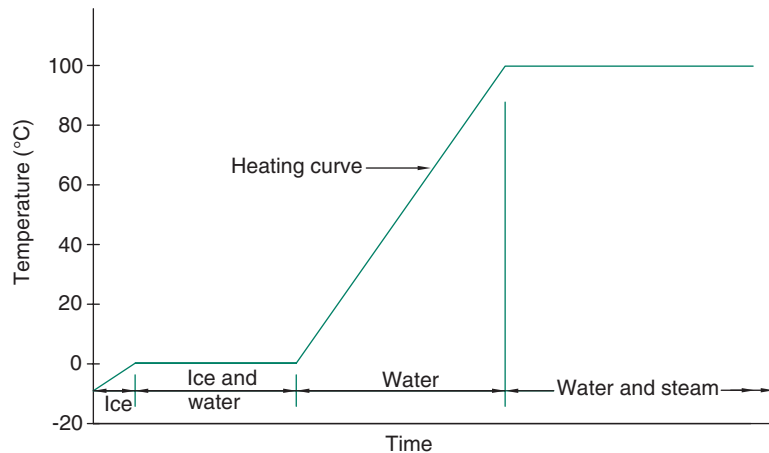


Figure 8.3 Heating curve for ice.

Results and discussion:

The data is plotted as temperature versus time, as shown in Figure 8.3; the graph is called the heating curve of ice. Ice is solid, and to change ice into water, heat energy is required. The temperature rises to 0°C as the ice starts to melt and remains unchanged until all the ice has melted. This is shown as the 'ice and water' stage in Figure 8.3.

The amount of heat required to change ice into water, the temperature remaining unchanged at 0°C, is known as the **latent heat** of ice. The latent heat of ice is 330 kJ/kg, which means that 330 kJ of heat energy are required to convert 1 kg of ice into water at 0°C.

The temperature at which a substance begins to melt is known as its melting point; the melting point of ice is 0°C. Further heating raises the temperature of the water (liquid state) steadily, as shown in the 'water' stage in Figure 8.3. Heat used in this way is called **sensible heat**. If the water is pure, it will begin to boil at 100°C. The temperature remains unchanged as water is being converted into steam and vapour (the 'water and steam' stage). The reason for this is that heat is required to change boiling water into steam. This is called the latent heat of steam. Its value is 2250 kJ/kg, or, in other words, 2250 kJ of heat energy are required to convert 1 kg of boiling water into steam.

8.5 Expansion and contraction of solids

Buildings and civil-engineering structures are affected by the expansion and contraction of materials as the surrounding temperature increases or decreases. Thermal expansion and contraction create stresses in buildings and other structures. Appropriate provisions are made in these structures so that the expansion or contraction takes place

without creating any stress in the materials. Typical examples are the expansion and contraction joints in bridge decks and concrete roads. A detailed discussion is given in Section 8.5.3.

Thermal expansion or **thermal movement** is of three types: linear, superficial and cubical. Only the linear expansion is explained here in detail.

8.5.1 Linear expansion

If a bar of steel, or another metal, of length l is heated to raise its temperature from t_1 to t_2 , there will be an increase in the length of the bar. The increase in length, Δl , is proportional to:

- i) Original length, l
- ii) Increase in temperature, Δt ($\Delta t = t_2 - t_1$)

Combining the two above, $\Delta l \propto l \Delta t$ ($\propto$ is the sign of proportionality)

$$\text{or, } \Delta l = \alpha l \Delta t$$

$$\text{therefore } \alpha = \frac{\Delta l}{l \Delta t}$$

where α , the constant of proportionality, is known as the **coefficient of linear expansion**

The coefficient of linear expansion of a material is defined as the change in length per unit length per unit change in temperature.

Unit: per °C or, mm/m °C.

Table 8.1 gives the values of the coefficients of linear expansion of a range of common materials.

Table 8.1 Coefficients of linear expansion

Material	α (per °C) (or per K)
Aluminium	0.000023 or (23×10^{-6})
Brass	0.000019 or (19×10^{-6})
Bricks	0.000007 or (7×10^{-6})
Concrete	0.000011 or (11×10^{-6})
Copper	0.000017 or (17×10^{-6})
Glass	0.0000085 or (8.5×10^{-6})
Invar	0.000001 or (1×10^{-6})
PVC	0.00007 or (7×10^{-5})
Steel	0.000012 or (12×10^{-6})

Example 8.1

A 2.0 m length of copper pipe is heated from 20 °C to 60 °C. Calculate the thermal movement if the coefficient of linear expansion of copper is 0.000017 per °C.

Solution:

Original length (l) = 2 m = 2000 mm

Change in temperature (Δt) = 60 – 20 = 40 °C

$\alpha = 0.000017$

$$\alpha = \frac{\Delta l}{l \Delta t}$$

$$\begin{aligned} \text{Change in length or thermal movement, } \Delta l &= \alpha l \Delta t \\ &= 0.000017 \times 2000 \times 40 \\ &= \mathbf{1.36 \text{ mm}} \end{aligned}$$

8.5.2 Experiment: Determination of coefficient of linear expansion

Apparatus: Expansion apparatus as shown in Figure 8.4, metre rule, micrometer, Bunsen burner, tripod and gauze, thermometer (0–110 °C) and sample.

Procedure:

1. The metals that can be used in this experiment are usually steel, aluminium, copper and brass, and are available as 500 mm (approx.) long tubes. Take the appropriate tube, enclose it in the insulation sleeve and pass the ends through metal blocks A, B and C.
2. Set up the apparatus as shown in Figure 8.4.
3. Measure the distance between the reference marks on blocks A and B; this is the original length of the tube (l).
4. Measure the distance between the blocks B and C (d_1) with a micrometer. Tighten the screws on blocks A and C.
5. Note down the room temperature (t_1 °C).
6. Light the burner and allow the steam to pass through the tube for 5 minutes when the water boils.
7. Measure the distance between blocks B and C again (d_2). The difference between distances d_2 and d_1 gives the expansion of the tube.
8. Repeat the procedure with the other metal tubes, if required. Table 8.2 may be used to record the test data.

$$\begin{aligned} \text{Coefficient of linear expansion of steel} &= \frac{\Delta l}{l \times \Delta t} \\ &= \frac{0.45}{502 \times 80} = \mathbf{0.000011 \text{ or } 11 \times 10^{-6} \text{ per } ^\circ\text{C}} \end{aligned}$$

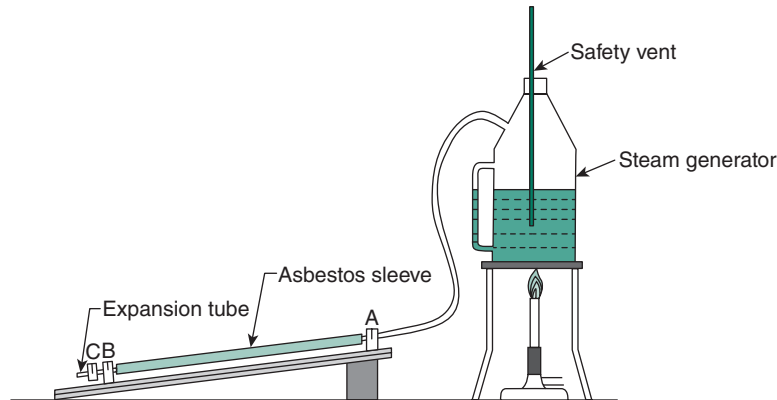


Figure 8.4 Determination of linear expansion.

Table 8.2

Metal	Distance A-B (l) mm	Distance B-C (d_1) mm	Distance B-C (d_2) mm	Expansion ($d_2 - d_1$)	Initial Temperature (t_1)	Final Temperature (t_2)	Temp. Diff. ($^{\circ}\text{C}$) ($t_2 - t_1$)
Steel	502	9.0	9.45	0.45	20	100	$100 - 20 = 80$

8.5.3 Practical examples of expansion and contraction

The expansion and contraction joints in concrete roads are shown in Figure 8.5. Concrete shrinks when it changes from semi-liquid to solid state and gains strength. If this factor is not taken care of, the concrete will crack haphazardly. By providing contraction joints, the cracking takes place only at predetermined places, i.e. at the contraction joints. To induce cracking at a predetermined place, the depth of the slab is reduced by incorporating fillets. Steel dowel bars are provided to strengthen the road slab and to maintain continuity.

In the UK, expansion joints in concrete roads are provided only if the construction takes place between 21 October and 21 April. Half the length of each dowel bar is coated with a debonding agent like bitumen, so that the concrete road is able to move as it expands. If the dowel bars are not debonded, concrete will grip them making it difficult for the concrete to expand in a safe and satisfactory manner. The debonded sides of the dowel bars also carry compressible plugs, which absorb the movement of the concrete road.

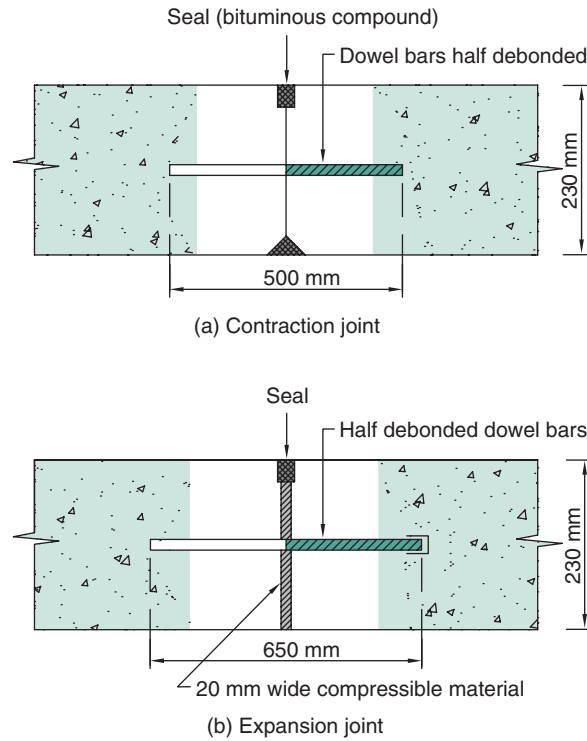


Figure 8.5 Joints in concrete roads.

In steel and concrete bridges provision is made for one end to move in the event of expansion or contraction. In steel beams the end is provided with rollers or rockers so that the bridge can expand or contract as the ambient temperature increases/decreases. In short-span concrete bridges, polytetrafluoroethylene (PTFE – a smooth plastic) bearings are provided to allow the bridge to expand or contract (see Figure 8.6).

Expansion joints are also provided in long brick walls; brick walls exceeding 15 m in length require expansion joints.

PVCu expands or contracts significantly due to changes in temperature. The use of this material in manufacturing doors, windows, conservatories and other components has become widespread in the UK. When old timber or metal windows are replaced by double-glazed PVCu windows, an all-around gap of 5 mm is provided to accommodate the expansion.

When strips of the same length, but of different metals, are heated through the same temperature, their expansions are not equal. For example, the expansion of brass is twenty times more than that of Invar. A strip made from these two substances, called a bimetallic strip, bends when it is heated. Owing to the higher coefficient of linear expansion of brass, the strip bends with the brass on the outside. This property is used to make a thermostat, which is a device used in boilers, heating systems, ovens etc. to control temperature. Figure 8.7 shows the principle of a thermostat that uses a bimetallic strip

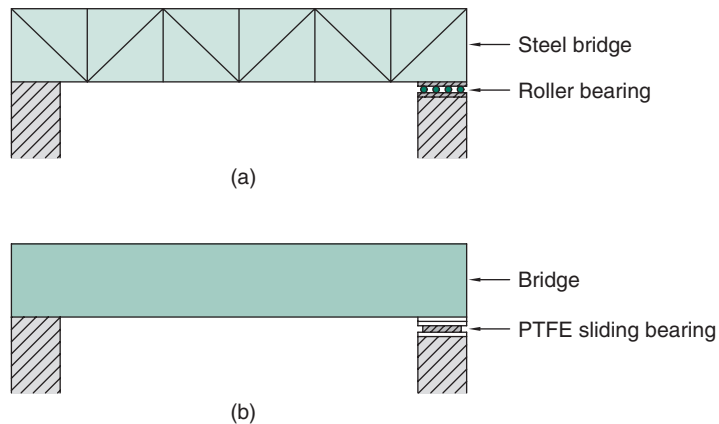


Figure 8.6 Bridge bearings.

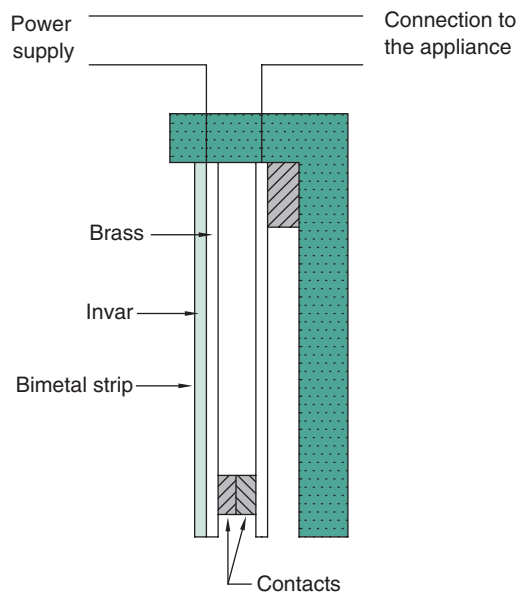


Figure 8.7 Thermostat.

that can be used to control room temperature. When the two contacts touch, the current flows through the circuit and the heater is turned on. When the room temperature rises, the bimetallic strip expands and bends with the brass on the outside. The electrical contacts separate and the circuit to the heater is broken, thus switching off the heater. When the air temperature drops, the bimetallic strip straightens and the heater is switched on again as the electrical contacts touch. The thermostat may be set at different temperatures by turning the control knob.

8.6 Heat transfer

Heat transfer from one substance to another, or from one point to another in a substance, may take place due to conduction, convection or radiation.

8.6.1 Conduction

If one end of a metal rod is put in a flame, the other end will become hot after some time. The process by which heat energy travels from one end of the rod to the other, without the molecules changing their positions, is known as conduction. Metals such as copper, silver, steel and aluminium allow the heat to pass through easily and quickly, and are called **good conductors** of heat. Non-metals and other substances like plastic, timber, cork, air and water are called bad conductors or **good insulators** as they do not conduct heat very well. Bad conductors have several applications in science and engineering, which are discussed in Chapter 9.

It is often necessary to compare the ability of various materials to conduct heat and the property, which is often used for this purpose, is called the **thermal conductivity** or λ -value (also known as k-value).

The thermal conductivity of a material is defined as a measure of the rate at which heat is conducted through it under specified conditions. The conditions are that the material should have a thickness of 1m, surface area of 1m^2 and temperature difference of 1°C maintained between the opposite sides.

Consider a material of thickness d metres heated at one side, as shown in Figure 8.8. Heat comes out of the opposite side, assuming that the heat loss from the other sides is prevented. The amount of heat, Q joules, which flows from side 2 to side 1 is:

- Directly proportional to the surface area (A) of side 2, as the greater the surface area, the higher the flow of heat.
- Directly proportional to the temperature difference, θ , between side 2 and side 1 ($\theta = \theta_2 - \theta_1$), as more heat will flow if the temperature difference between the two sides is large.
- Directly proportional to the time (t) for which the heat flows.
- Inversely proportional to the thickness (d) of the material. If the material is very thick, only a small amount of heat will flow through it and vice versa.

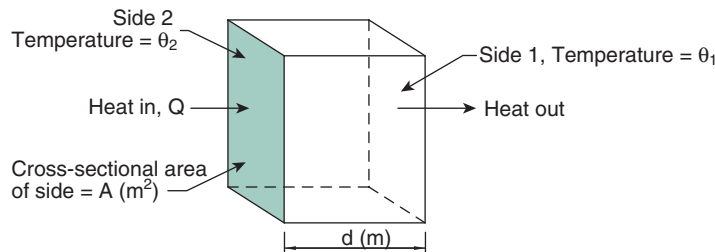


Figure 8.8

The amount of heat transferred will also depend on the nature of the material. Good conductors allow more heat to pass through as compared to bad conductors. Combining all the above factors, the amount of heat (Q), flowing through the material, is proportional to:

$$\frac{tA(\theta_2 - \theta_1)}{d}$$

$$\text{or, } Q \propto \frac{tA(\theta_2 - \theta_1)}{d}$$

$$\frac{Q}{t} \propto \frac{A(\theta_2 - \theta_1)}{d}$$

In order to form an equation, the sign of proportionality is removed and a constant introduced. The constant used here is ' λ ' (or ' k '):

$$\frac{Q}{t} = \frac{\lambda A(\theta_2 - \theta_1)}{d}$$

$$\text{therefore } \lambda \text{ (or } k) = \frac{Qd}{tA(\theta_2 - \theta_1)}$$

' λ ' in the above equation is known as the thermal conductivity of the material. A good conductor of heat will have a higher value of thermal conductivity than that for a bad conductor. Thermal conductivity values for a selection of materials are given in Table 8.3.

Table 8.3 Thermal conductivity of some building materials

Material	Thermal conductivity (λ) W/m K
Aluminium	164
Brickwork (external)	0.84
Concrete - dense	1.5
Concrete - lightweight	0.57
Aerated concrete blocks	0.11
Insulation - expanded polystyrene board	0.033
- eco-wool	0.042
- glass fibre	0.04
- mineral wool batts	0.038
Plaster - dense	0.46
Plaster - lightweight	0.16
Plasterboard	0.16
Steel	43
Glass	1.02

Unit: To work out the unit of thermal conductivity, the symbols in the above equation are replaced with appropriate units:

Quantity of heat, Q : joules (J)

Thickness of the material, d : metres (m)

Time during which heat flows, t : seconds (s)

Surface area of the material, A : m^2

Temperature difference, $\theta_2 - \theta_1$: $^{\circ}\text{C}$ or K

$$\begin{aligned}\lambda &= \frac{Qd}{tA(\theta_2 - \theta_1)} \text{ becomes } \lambda = \frac{\text{Jm}}{\text{sm}^2^{\circ}\text{C}} \\ &= \frac{\text{Wm}}{\text{m}^2^{\circ}\text{C}} \quad \left(W = \frac{\text{J}}{\text{s}} \right) \\ &= \frac{\text{W}}{\text{m}^{\circ}\text{C}} \quad (\text{watts per metre per degree Celsius})\end{aligned}$$

If kelvin is used instead of $^{\circ}\text{C}$, the unit will be $\frac{\text{W}}{\text{mK}}$

8.6.2 Experiment: To compare the thermal conductivity of metals

Apparatus: As shown in Figure 8.9, wax, Bunsen burner, beaker, tripod and gauze.

Procedure:

- 1) Set up the apparatus as shown in Figure 8.9. The apparatus consists of a container and rods of steel, copper, aluminium, plastic and wood.
- 2) Apply a coating of molten wax over all the rods.
- 3) Boil some water in the beaker and pour the boiling water into the apparatus.
- 4) Start observing the rods, and note the distance to which the wax has melted on various rods.

The distance to which the wax has melted is the highest in the case of the copper rod, meaning that the thermal conductivity of copper is higher than that of the other materials.

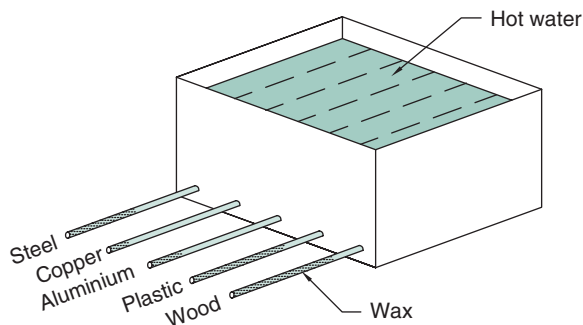


Figure 8.9 Comparison of thermal conductivities.

8.6.3 Convection

When water is heated in a vessel, it becomes hot after a few minutes. Although water is not a good conductor of heat, heat energy is still transferred from one point of the liquid to another. As water is heated, its particles at the bottom of the vessel become hot and expand as a result. Owing to expansion, the hot particles become lighter and rise. Their place is taken by cold particles from the upper section as they are slightly heavier than the hot particles. As the heating of the vessel is continued, water will begin to boil after some time.

As water, like many other liquids, is a bad conductor of heat, heat is not transferred by conduction. Instead, heat is transferred from one part of the liquid to another by the movement of its molecules. This process is called **convection**.

8.6.4 Practical examples of convection

Like water, air is also a bad conductor of heat. Still, heating of air in a room by a radiator or a heater can be done without any difficulty. The radiator or heater heats the surrounding air which, as a result, becomes lighter and rises. Its place is taken by cooler air which is heavier; the upward movement of warm air and the downward movement of cooler air are called the convection currents. Figure 8.10 illustrates this process.

Figure 8.11 shows a domestic gravity hot water system. The boiler heats the water in the pipework. Hot water rises as it becomes less dense and lighter, and cold water descends to take its place. These convection currents will heat all the water in the cylinder.

8.6.5 Radiation

The processes of conduction and convection need the presence of a substance for conveying heat from one point to another. **Radiation** is a process in which heat energy travels from one place to another without requiring a medium. Heat energy from the sun is received by us due to radiation as there is no medium (air) beyond the earth's

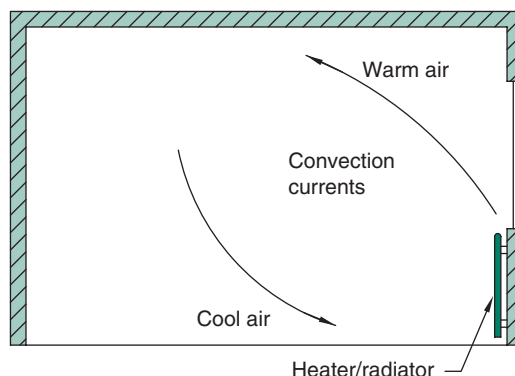


Figure 8.10 Transfer of heat by convection.

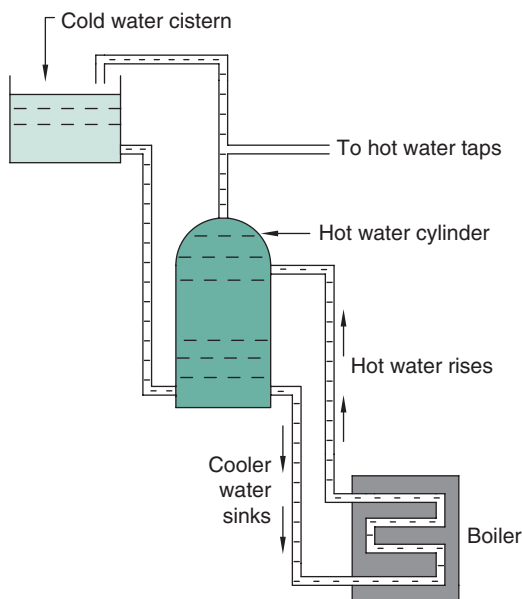


Figure 8.11 Convection currents in hot water system.

atmosphere. The radiant heat, given off by the sun and other hot objects, consists of infra-red rays having a wavelength between 750 nm (nanometres) and 0.001 mm.

A good radiator of heat is a good absorber as well, e.g. matt black objects. Shiny silver surfaces are bad radiators and absorbers, but good reflectors. This property is used in reflecting solar heat from flat felt roofing by either covering it with light-coloured stone chippings or painting it with a light-coloured paint.

Exercise 8.1

- Convert the following temperatures into kelvin:
a) 10°C b) 30°C c) -50°C
- Convert the following temperatures into $^{\circ}\text{C}$:
a) 295 K b) 315 K c) 343 K
- A 500 mm long aluminium tube was tested to determine the coefficient of linear expansion of aluminium. The following data were obtained from the test:
Initial temperature of the tube = 20°C
Final temperature of the tube = 100°C
Expansion of the tube = 0.91 mm
Calculate the coefficient of linear expansion of aluminium.
- A 5.0 m length of steel tube is heated from 10°C to 40°C . Calculate the thermal movement if the coefficient of linear expansion of steel is 12.0×10^{-6} per $^{\circ}\text{C}$.

References/Further reading

1. Chudley, R. and Greeno, R. (2008). *Building Construction Handbook*. Oxford: Butterworth-Heinemann.
2. CIBSE Guide A (2006). *Environmental Design*. London: Chartered Institution of Building Services Engineers.

9

Thermal energy and humidity

Learning outcomes:

- 1) Compare the thermal insulation values of different materials.
- 2) Explain thermal resistance and the coefficient of thermal transmittance.
- 3) Calculate the U-values of building elements.
- 4) Explain surface and interstitial condensation, and carry out calculations to determine the possibility of interstitial condensation in cavity walls.

9.1 Introduction

The basic concepts of heat transfer have been explained in Chapter 8. This chapter deals with one of the important aspects of our daily life, i.e. heat energy and its conservation. Heat energy is produced mainly from natural gas and electricity. Electricity is generated from several natural resources but only wind power, wave power and solar energy are renewable and do not create any pollution. They might have some impact on the environment, but the use of coal, water (hydro-electric projects) and nuclear fission/fusion can be more harmful to the environment. It is therefore important to conserve heat energy and reduce the demand for natural gas and electricity, which in turn will reduce the harm done to the environment.

In domestic buildings, offices, shops etc., heat loss in winter occurs due to the difference between the internal and the external air temperatures. The temperature inside a building is maintained at about 20 °C, but the external temperature fluctuates and could be sub-zero for several days/weeks. If a building is uninsulated and has single-glazed windows, then a large amount of heat is lost through its fabric (walls, roof, windows, floor and doors).

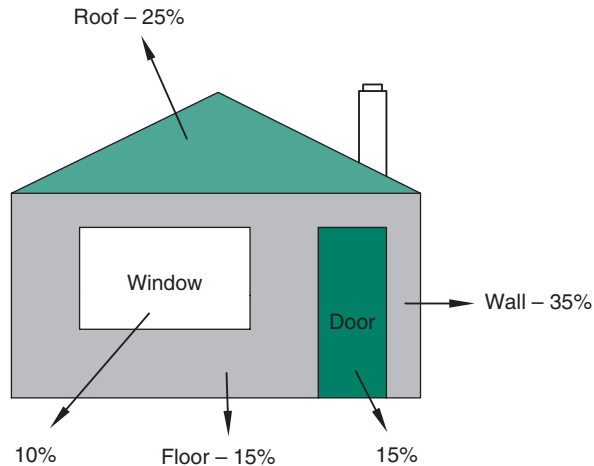


Figure 9.1 Typical heat loss for an uninsulated single-glazed house.

9.2 Thermal insulation

Figure 9.1 shows the typical values of heat loss from an uninsulated house. About 70% of the heat loss occurs through the roof, walls and windows, which can be reduced by insulating the loft and the external walls, and by replacing the old timber/metal windows with PVCu double-glazed windows.

In new buildings, heat energy can be conserved by providing ground-floor insulation in addition to the above measures.

There are several insulation materials that can be used in a building, the most common being:

Flexible: mineral wool and glass fibre quilts/batts;

Loose: expanded polystyrene granules, vermiculite and mineral wool;

Rigid: aerated concrete blocks, lightweight concrete and expanded polystyrene slabs.

Recently, eco-wool, which is made from recycled plastic bottles, has become popular, as its fibres do not cause any skin irritation or breathing problems.

Other insulating materials are wood, asbestos, sawdust and cork. Air, although not a material, is a very good insulator as its thermal conductivity is only 0.024 W/m K . For conservation of heat, we need to use materials that resist the flow of heat, i.e. have very low values of thermal conductivity. Table 9.1 shows the values of thermal conductivity for a range of construction materials.

There are several criteria that an insulating material has to meet. A good insulating material should be resistant to moisture and fungi, and should have adequate fire resistance. It should be available in different sizes and be harmless to humans and the environment. An experiment to compare the insulation values of different materials can be performed in the laboratory, as described in the next section.

Table 9.1 Thermal conductivity of some building materials

Material	Thermal conductivity (λ) W/m K
Aluminium	164
Brickwork (external)	0.84
Concrete - dense	1.5
Concrete - lightweight	0.57
Aerated concrete blocks	0.11
Copper	386
Glass	1.02
Insulation - cork board	0.04
- expanded polystyrene board	0.033
- eco-wool	0.042
- glass fibre	0.04
- mineral wool batt	0.038
- woodwool slabs	0.09
Marble	2.0 to 2.9
Plaster - dense	0.46
Plaster - lightweight	0.16
Plasterboard	0.16
Steel	43
Timber/timber products	
- softwoods (fir, pine)	0.12
- hardwoods	0.16 to 0.23
- plywood	0.12

9.2.1 Experiment: To compare the thermal insulation values of expanded polystyrene, vermiculite, mineral wool, glass fibre and cork

Apparatus:

Five beakers, five mercury thermometers, five test tubes with corks to hold thermometers, a large beaker, Bunsen burner, tripod and gauze, five stop-clocks and materials as mentioned.

Procedure:

1. Arrange the apparatus and the materials as shown in Figure 9.2. Boil some water in the large beaker and pour sufficient quantities into all the test tubes.
2. After about 5 minutes empty the test tubes and refill them with boiling water and replace the corks containing the thermometers.
3. Start to record the temperature of each tube, making sure that all five temperatures are the same.
4. Read the thermometers every minute initially, increasing the interval between readings gradually.
5. The experiment may be terminated after about 20 minutes. Table 9.2 may be used for recording the data.

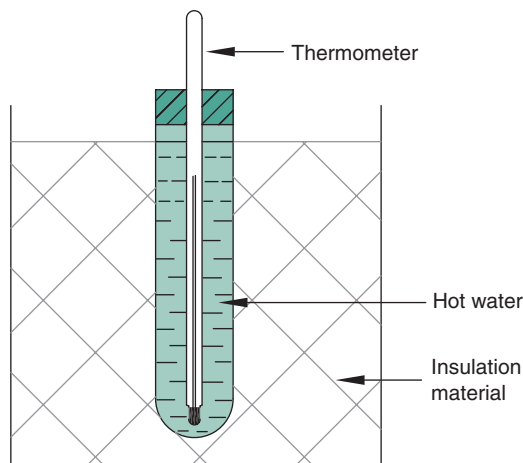


Figure 9.2

Table 9.2

Time (minutes)	Temperature (°C)				
	Expanded polystyrene	Vermiculite	Mineral wool	Glass fibre	Cork
0					
1					
2					
.....					

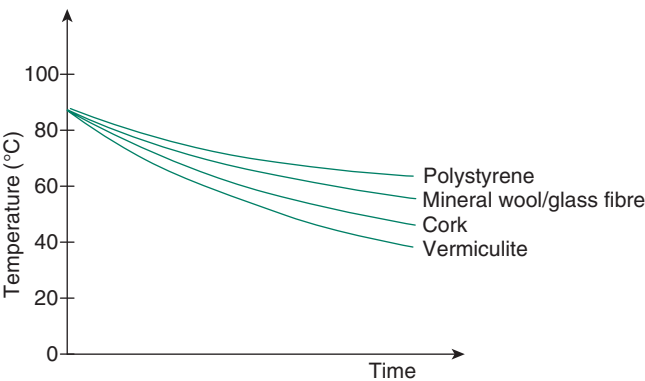


Figure 9.3

Results:

The temperatures of all the materials are plotted against time on the same graph, as shown in Figure 9.3. The graphs are called the cooling curves. The material that shows the lowest rate of cooling, i.e. the lowest drop in temperature, is the best insulator.

9.3 Heat transmission

9.3.1 Thermal conductivity

Thermal conductivity of a material (also known as the **λ -value** or **k -value**) is a measure of whether it will allow heat to pass through easily or offer resistance. The coefficient of thermal conductivity of a material, λ , is the amount of heat flowing (joules) per second across the opposite sides of a material 1m thick, and of cross-sectional area 1m², the sides being maintained at a temperature difference of 1K.

$$\lambda = \frac{W \times m}{m^2 \times T} \quad (\text{see Chapter 8, Section 8.6.1})$$

Unit: W/m K or W m⁻¹ K⁻¹.

9.3.2 Thermal resistivity (r)

Thermal resistivity is the reciprocal of thermal conductivity. A high value of thermal resistivity will indicate that the material offers a high resistance to the passage of heat, and hence is a good insulator. Like thermal conductivity, thermal resistivity is also based on unit measurements of a material, i.e. 1m thickness and 1m² cross-sectional area.

$$r = \frac{1}{\lambda}$$

Unit: m K/W or, m K W⁻¹.

9.3.3 Thermal resistance (R)

Thermal resistivity of a material is based on 1m thickness, but most building materials are available in different sizes and can be used to produce components of various thicknesses. Thermal resistance, therefore, is based on the actual thickness (d) of a material.

$$R = rd$$

$$\text{or, } R = \frac{d}{\lambda} \quad \left(r = \frac{1}{\lambda} \right)$$

Unit: m²K/W or, m²K W⁻¹.

Depending on the constructional details of a component, its total thermal resistance may be made up of the material resistance, the surface resistances and the airspace resistance:

- a) **Material resistance:** Each material offers some resistance to the transmission of heat. Good conductors like copper have low resistance whereas bad conductors like expanded polystyrene have high resistance to the transmission of heat. The material resistance is directly proportional to the thickness and inversely proportional to the thermal conductivity:

$$\text{Material resistance} = \frac{d}{\lambda}, \text{ where } d \text{ is the thickness of the material in metres.}$$

- b) **Surface resistance:** Air inside and outside a building is always moving due to temperature variations, ventilation and other effects. The surfaces of all building materials have some irregularities, which trap air, therefore, stationary layers of air are formed in close contact with the surfaces - internal as well as external. These stationary layers of air act like insulating layers due to the low thermal conductivity of air ($\lambda_{\text{air}} = 0.024 \text{ W/m K}$).

The air movement inside a building is far less than the air movement outside a building, therefore, the internal surface resistance is greater than the external surface resistance. Typical values are given in Table 9.3.

- c) **Airspace resistance:** Inside an airspace, e.g. in a double-glazed window or a cavity wall, heat may be transmitted by conduction, convection or radiation, or any combina-

Table 9.3 Standard thermal resistances

Type of resistance	Building element	Surface emissivity	Heat flow	Thermal resistance ($\text{m}^2 \text{ K/W}$)
Inside surface	Walls	High	Horizontal	0.12
		Low		0.30
	Roofs (flat or pitched)	High	Upward	0.10
		Low		0.22
	Floors/ceilings	High	Downward	0.15
Outside surface	Walls	Low	Horizontal	0.56
		High		0.06
	Roofs (flat or pitched)	High	Upward	0.05
		Low		0.05
	5 mm wide	High	Horizontal/Upward	0.11
Airsaces (unventilated)	20 mm or more	High	Horizontal/Upward	0.18

tion of the three. The thermal resistance of airspace is due to the low thermal conductivity of air. The airspace resistance depends on the width of the cavity and whether it is ventilated or unventilated, as shown in Table 9.3.

The total thermal resistance of an element depends on its construction. If there is no airspace in the element, then the total thermal resistance is the sum of the surface resistances and the material resistances. For example, in a solid brick wall, plastered on one side, the total thermal resistance (R_{total}) is given by:

$$R_{\text{total}} = R_{\text{si}} + R_{\text{plaster}} + R_{\text{brickwork}} + R_{\text{so}}$$

In an element that incorporates airspace, e.g. a double-glazed window, the total thermal resistance is given by:

$$R_{\text{total}} = R_{\text{si}} + R_{\text{glass}} + R_{\text{airspace}} + R_{\text{glass}} + R_{\text{so}}$$

where R_{si} is the resistance of the inside surface
 R_{so} is the resistance of the outside surface
 R_{glass} is the material resistance
 R_{airspace} is the airspace resistance

9.4 Thermal transmittance

Thermal transmittance, or the **U-value**, indicates the amount of heat energy that will flow per second through one square metre of a building element when the temperature difference between the inside and outside surfaces is one kelvin.

The current Building Regulations specify the following U-values for dwelling houses. These values have come down gradually by about 40% over the last two decades. The lower the U-value of an element, the better it is in resisting the flow of heat. The U-values shown in Table 9.4, taken from the current Building Regulations, are the area-weighted average values.

The U-value of an element/component can be determined from the following relationship:

$$U = \frac{1}{R_{\text{total}}}$$

Table 9.4

Building element	U-value ($\text{W/m}^2 \text{ K}$)
External walls	0.35
Roofs	0.25
Floor	0.25

Example 9.1

Find the U-values of: a) single-glazed window; b) double-glazed window.

Given: Thickness of glass = 4 mm

Thermal conductivity of glass = 1.02 W/m K

Thermal resistance of surfaces: 0.12 (inside), 0.06 (outside) m² K/W (from Table 9.3)

Thermal resistance of 20 mm wide airspace = 0.18 m² K/W (from Table 9.3)

Solution:

The first step is to draw the cross-section of the window (Figure 9.4) and list the layers of construction, including the surfaces, in a tabular form. The total thermal resistance of the component is determined, and its reciprocal calculated to obtain the U-value.

a) Single-glazed window

Material/layer	Thermal conductivity, λ (W/m K)	Thickness, d (m)	Thermal resistance, R (m ² K/W)	U-value (W/m ² K)
Inside surface			0.12	$U = \frac{1}{R_{\text{total}}}$
Glass	1.02	0.004	$\frac{d}{\lambda} = 0.004/1.02$ = 0.0039	
Outside surface			0.06	
			$R_{\text{total}} = 0.1839$	$= \frac{1}{0.1839}$ = 5.44

b) Double-glazed window

Material/layer	Thermal conductivity, λ (W/m K)	Thickness, d (m)	Thermal resistance, R (m ² K/W)	U-value (W/m ² K)
Inside surface			0.12	$U = \frac{1}{R_{\text{total}}}$
Glass	1.02	0.004	$0.004/1.02 =$ 0.0039	
Cavity			0.18	
Glass	1.02	0.004	$0.004/1.02 =$ 0.0039	$= \frac{1}{0.3678}$ = 2.72
Outside surface			0.06	
			$R_{\text{total}} =$ 0.3678	

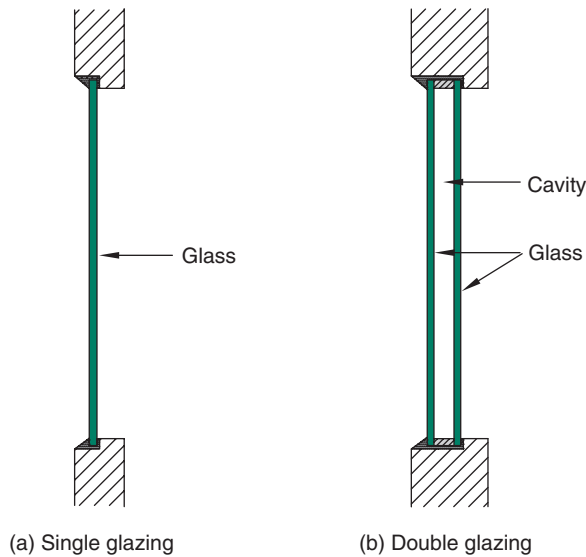


Figure 9.4

Example 9.2

- Calculate the U-value of a cavity wall with half-brick thick outer leaf, 100 mm wide cavity without insulation, 100 mm thick aerated concrete (Aer. Conc.) block inner leaf and 12 mm thick layer of lightweight plaster.
- Repeat the calculations if the cavity is provided with 100 mm thick mineral wool.

Thermal conductivities (W/m K):

Aer. Conc. blocks = 0.11; lightweight plaster = 0.16; bricks
= 0.84; mineral wool = 0.04

Surface resistances ($\text{m}^2 \text{ K/W}$): inside surface = 0.12; outside surface = 0.06

Airspace resistance = $0.18 \text{ m}^2 \text{ K/W}$

Solution:

Figure 9.5 shows the cross-section of the wall.

The question may be solved either electronically using a spreadsheet or by manual calculations. In this example, both methods are used:

Part (a) is solved by manual calculations and part (b) electronically.

In the spreadsheet, the formulae are entered in the first row, and replicated for the other rows.

a)

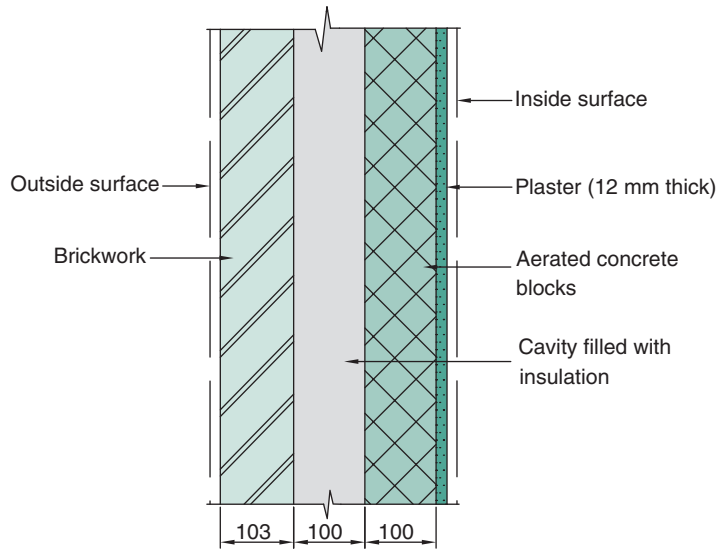
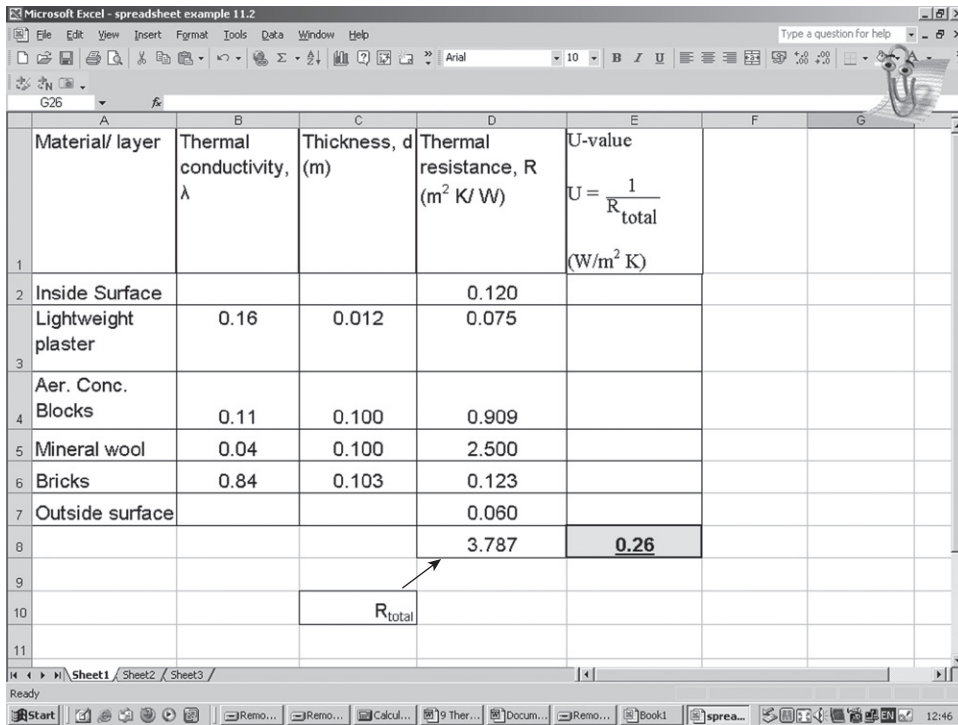


Figure 9.5 Cross-section of a cavity wall.

Material/ layer	Thermal conductivity, λ (W/m K)	Thickness, d (m)	Thermal resistance R (m ² K/W)	U-value (W/m ² K)
Inside surface	-	-	0.12	$U = \frac{1}{R_{\text{total}}}$
Lightweight plaster	0.16	0.012	$0.012/0.16 =$ 0.075	
Aer. Conc. blocks	0.11	0.100	$0.100/0.11 =$ 0.909	$= \frac{1}{1.467}$ = 0.68
Cavity	-	0.100	0.18	
Bricks	0.84	0.103	$0.103/0.84 =$ 0.123	
Outside surface	-	-	0.06	
			$R_{\text{total}} = 1.467$	

b)



	A	B	C	D	E	F	G
	Material/ layer	Thermal conductivity, λ	Thickness, d (m)	Thermal resistance, R ($\text{m}^2 \text{ K/ W}$)	U-value $U = \frac{1}{R_{\text{total}}}$ ($\text{W/m}^2 \text{ K}$)		
1							
2	Inside Surface			0.120			
3	Lightweight plaster	0.16	0.012	0.075			
4	Aer. Conc. Blocks	0.11	0.100	0.909			
5	Mineral wool	0.04	0.100	2.500			
6	Bricks	0.84	0.103	0.123			
7	Outside surface			0.060			
8				3.787	0.26		
9							
10			R_{total}				
11							

(The formulae used in this spreadsheet are shown in Appendix 1)

9.5 Heat loss from buildings

Heat is lost from buildings by conduction as well as convection. The former is also known as the heat loss through the fabric of the building, and the latter as the heat loss due to ventilation.

The **fabric heat loss** can be determined if we know the U-values of the building elements.

We know the unit of U-value is:

$$U = \text{W/m}^2 \text{ K}$$

Replacing m^2 and K with A (area of a component) and T (difference between the inside and outside temperatures) respectively, we have:

$$U = \frac{W}{A \times T}$$

After rearranging the terms, we have:

$$W (\text{rate of fabric heat loss}) = U \times A \times T$$

The **heat loss due to ventilation** occurs when the warm air of a room is replaced by fresh, but cooler, air from the outside. This change in air is necessary to replace the stale air with fresh air. This is usually achieved in two ways:

- a) Uncontrolled ventilation: Warm air escapes from the room when doors or windows are opened, or it escapes to the outside through gaps in the structure.
- b) Controlled ventilation: This is achieved by mechanical ventilation.

The fresh air needs to be heated for thermal comfort. The quantity of heat required to raise the temperature of 1m^3 of air by 1K (or 1°C) is known as the volumetric specific heat capacity of air. The volumetric specific heat capacity of air is $1212\text{J/m}^3\text{K}$. The heating requirement due to the fresh air coming into a room is incorporated into the calculations as the number of air changes per hour. So, if two air changes per hour are required for a room, it means that two volumes of air have to be heated from the external temperature to the internal temperature, every hour.

$$\text{Rate of heat loss due to ventilation} = \frac{c_v \times V \times N \times T}{3600}$$

where c_v is the volumetric specific heat capacity of air

V is the volume of the room (m^3)

N is the number of air changes per hour

T is the difference between the inside and outside air temperatures

The total rate of heat loss from a room is determined by adding the fabric heat loss and the ventilation heat loss.

$$\text{Total rate of heat loss} = \text{fabric heat loss} + \text{ventilation heat loss}$$

Example 9.3

- a) Calculate the total rate of heat loss from the building shown in Figure 9.6. A temperature of 20°C is to be maintained inside the building when the outside air temperature is 0°C . Allow 2 air changes per hour; the volumetric specific heat capacity of air is $1212\text{J/m}^3\text{K}$. The U -values ($\text{W/m}^2\text{K}$) are:

Walls = 0.35; floor = 0.25; roof = 0.25; doors = 2.2; windows = 1.9.

The ground temperature is 5°C .

Doors: Two - 0.84×2.0 m high

Windows: Six - 1.5×1.3 m high

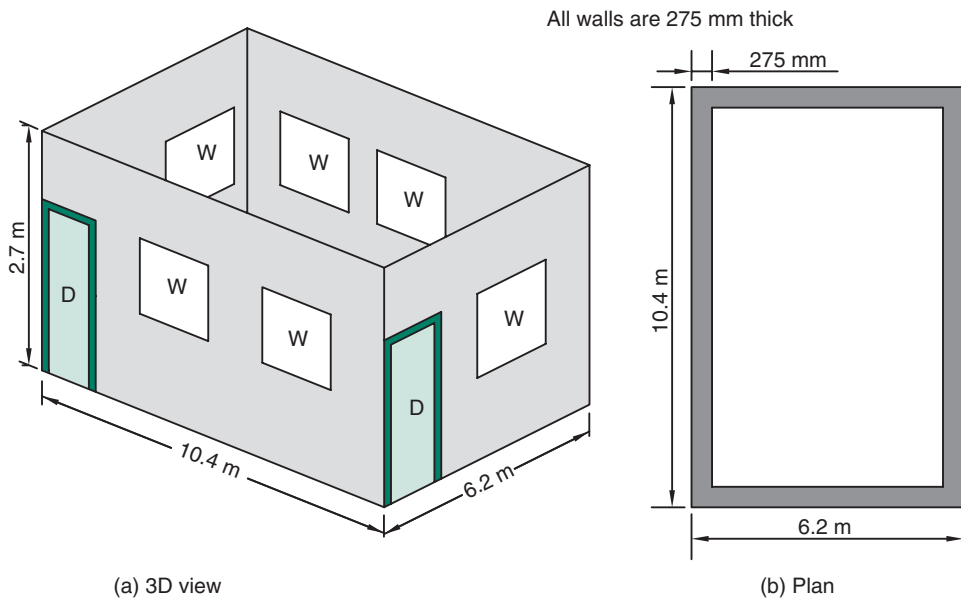


Figure 9.6

- b) Find the number of 900×600 mm high single convactor radiators required for the building.

Solution:

- a) The inside measurements should be used in this question:

$$\text{Walls: inside length} = 10.4 - 0.275 - 0.275 = 9.85 \text{ m}$$

$$\text{inside width} = 6.2 - 0.275 - 0.275 = 5.65 \text{ m}$$

$$\text{Wall area} = 2 \times 9.85 \times 2.7 + 2 \times 5.65 \times 2.7 = 83.7 \text{ m}^2$$

$$\text{Area of 2 doors} = 2 \times 0.84 \times 2.0 = 3.36 \text{ m}^2$$

$$\text{Area of 6 windows} = 6 \times 1.5 \times 1.3 = 11.7 \text{ m}^2$$

$$\begin{aligned} \text{Net wall area} &= \text{Gross wall area} - \text{area of doors and windows} \\ &= 83.7 - 3.36 - 11.7 = 68.64 \text{ m}^2 \end{aligned}$$

$$\text{Floor area} = \text{roof area} = 9.850 \times 5.650 = 55.65 \text{ m}^2$$

The rate of heat loss through the fabric of the building may be calculated by using the following table:

Element	U-value (W/m ² K)	Area, A (m ²)	Temperature difference, T (K)	Rate of heat loss = U × A × T (watts)
Walls	0.35	68.64	20 – 0 = 20	480.48
Doors	2.2	3.36	20 – 0 = 20	147.84
Windows	1.9	11.7	20 – 0 = 20	444.60
Floor	0.25	55.65	20 – 5 = 15	208.69
Roof	0.25	55.65	20 – 0 = 20	278.25
				Total = 1559.86

The rate of heat loss due to ventilation is given by the formula:

$$\text{Heat loss} = \frac{c_v \times N \times V \times T}{3600}$$

Number of air changes, N = 2 per hour

Volume of the building, V = 9.85 × 5.65 × 2.7 = 150.26 m³

Difference between the inside and outside temperatures, T = 20 K

$$\text{Heat loss due to ventilation} = \frac{1212 \times 2 \times 150.26 \times 20}{3600} = 2023.50 \text{ W}$$

Total rate of heat loss = 1559.86 + 2023.50 = **3583.36 W** or **3583.36 joules/sec.**

b) Total heat loss = 3583.36 W

Try 900 × 600 mm high single convector radiators.

Output of one radiator = 928 W (see information on radiators, Table 9.8)

Number of radiators required = 3583.36 ÷ 928 = 3.86

Provide four 900 × 600 mm high single convector radiators.

9.6 Temperature drop through materials

If the two parallel faces of a uniform material are kept at different temperatures, then by using appropriate instruments it would be found that the temperature dropped/increased uniformly through the material. Consider a cavity wall. If U is its U-value and T is the difference between the inside and outside temperatures, then

$$\text{Rate of heat loss} = U \times A \times T = U \times T \quad (\text{assuming surface area, } A = 1 \text{ m}^2)$$

The heat loss takes place through each layer of construction. Considering each layer separately, its U-value = $\frac{1}{R_{\text{layer}}}$, where R_{layer} is the thermal resistance.

Therefore, for each layer the temperature difference across its parallel faces (ΔT) can be determined from the equation:

$$U \times T = \frac{1}{R_{\text{layer}}} \times \Delta T$$

Transposing, $\Delta T = U \times T \times R_{\text{layer}}$

$$= \frac{1}{R_{\text{total}}} \times T \times R_{\text{layer}}$$

$$= \frac{R_{\text{layer}}}{R_{\text{total}}} \times T$$

where R_{total} is the total thermal resistance of a wall.

Example 9.4

Find the temperature drop across each layer of the cavity wall dealt with in Example 9.2b, and draw the structural temperature gradient. The inside and the outside temperatures are 20°C and 0°C respectively.

Solution:

Temperature difference, $T = 20 - 0 = 20^\circ\text{C}$

The calculations may be done in a tabular form, as shown:

Layer	Thickness, d (metres)	Thermal conductivity λ (W/m K)	Thermal resistance of layer (R_{layer}) ($\text{m}^2 \text{ K/ W}$)	Temperature drop across layer $\frac{R_{\text{layer}}}{R_{\text{total}}} \times T$	Boundary temperature ($^\circ\text{C}$)
Inside surface	-	-	0.12	$\frac{0.12}{3.787} \times 20 = 0.6$	20 $20 - 0.6 = 19.4$
Plaster	0.012	0.16	$0.012/0.16 = 0.075$	$\frac{0.075}{3.787} \times 20 = 0.4$	$19.4 - 0.4 = 19.0$
Blocks	0.100	0.11	$0.100/0.11 = 0.909$	$\frac{0.909}{3.787} \times 20 = 4.8$	$19.0 - 4.8 = 14.2$
Insulation	0.100	0.04	$0.100/0.04 = 2.5$	$\frac{2.5}{3.787} \times 20 = 13.2$	$14.2 - 13.2 = 1.0$
Bricks	0.103	0.84	$0.103/0.84 = 0.123$	$\frac{0.123}{3.787} \times 20 = 0.7$	$1.0 - 0.7 = 0.3$
Outside surface	-	-	0.06	$\frac{0.06}{3.787} \times 20 = 0.3$	$0.3 - 0.3 = 0$
			Total = 3.787		

The boundary temperatures are plotted to produce the structural temperature profile, as shown in Figure 9.7.

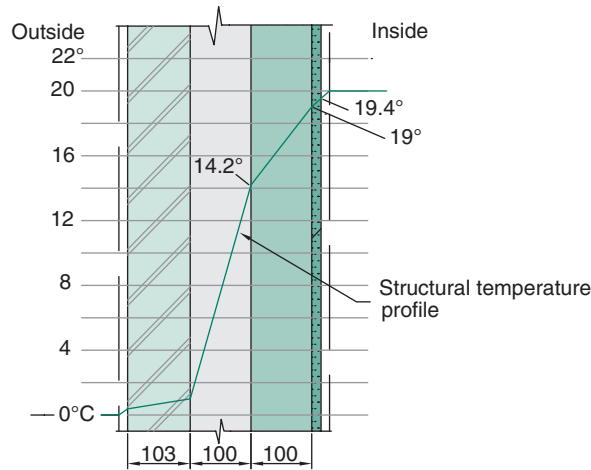


Figure 9.7 Structural temperature profile (or gradient).

9.7 Humidity

Three-quarters of the Earth's surface consists of water in the form of oceans, seas, lakes and rivers. Evaporation of water occurs continuously making the air humid and eventually leading to rain, snow, sleet etc. According to the kinetic theory, molecules of water are in constant random motion. Sometimes there are collisions between molecules, causing some to gain enough energy to escape from the water surface into the atmosphere. As the water molecule enters the atmosphere, it becomes water vapour (gas state), well below the boiling temperature of water.

Air inside a building always has some moisture in the form of water vapour, which results from cooking, washing and breathing by the occupants. The amount of water vapour in the air is known as the humidity, and depends on the air temperature. It is important to know how close the humidity of an air sample is to the saturation point. This is known as the relative humidity (R.H.), and is expressed as:

$$\text{R.H.} = \frac{\text{Mass of water vapour in the air}}{\text{Mass of water vapour in the air if it were saturated at the same temperature}} \times 100$$

The relative humidity inside buildings should be between 40% and 60% for human comfort. If it is above 60%, the occupants don't feel comfortable as the perspiration from their bodies evaporates very slowly. The human body produces heat energy from food to maintain the body temperature at 37°C. As the heat energy is produced continuously, there must be some process for the heat energy to escape so that the body temperature remains constant at 37°C. Much of this heat is carried away in water vapour resulting from breathing and sweating. When the ambient temperature is high and the air is humid, the evaporation of perspiration is very slow to keep the body comfortable.

9.7.1 Measurement of relative humidity

Several methods are available for measuring relative humidity. The instrument used for this purpose is known as a hygrometer. Many types of hygrometers are available, for example:

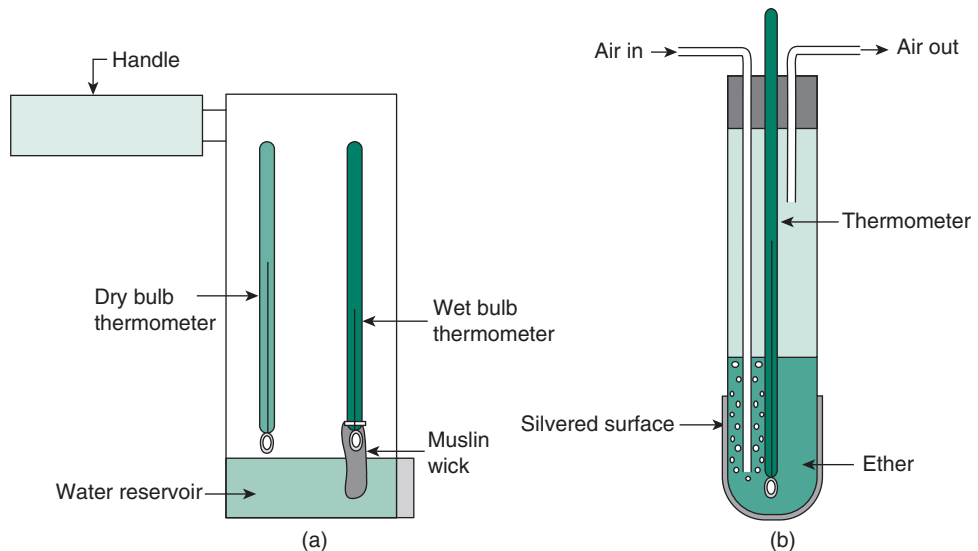


Figure 9.8 (a) Whirling hygrometer; (b) Regnault's hygrometer.

1. Wet and dry bulb hygrometer
2. Whirling hygrometer
3. The Regnault hygrometer
4. Paper or hair hygrometer
5. Electronic hygrometer

The **wet and dry bulb hygrometer** and the **whirling hygrometer** (Figure 9.8a) work on the same principle. The whirling hygrometer is rotated manually to speed up the evaporation of water. There are two mercury thermometers: the dry bulb thermometer and the wet bulb thermometer.

The dry bulb thermometer is exposed and used for recording the normal air temperature. The other thermometer is known as the wet bulb thermometer as its end, wrapped in muslin, dips into a water reservoir. As water evaporates from the muslin, it causes cooling and hence the temperature recorded by the wet bulb thermometer is lower than that recorded by the dry bulb thermometer. The readings from the two thermometers and Table 9.5 are used to find the relative humidity of the air.

The **Regnault hygrometer** consists of a glass tube, the lower end of which has a silvered surface. Other features of the apparatus are shown in Figure 9.8b. Air is blown through liquid ether, causing it to evaporate. As ether evaporates, the latent heat required for evaporation is extracted from the surroundings. The tube and the air surrounding it are cooled down. Eventually the air immediately around the bottom of the tube becomes saturated, and dew is formed on the silvered surface. The temperature is noted and the tube is allowed to warm up by stopping the passage of air. The temperature is noted again when the dew disappears. The average of the two temperatures is the dew point. The relative humidity is found by obtaining the saturated vapour pressures (SVP) from tables and substituting in the formula:

$$\text{Relative humidity} = \frac{\text{SVP of the water vapour at the dew point}}{\text{SVP of water vapour at the air temperature}} \times 100$$

Table 9.5 Relative humidity (%)

Dry bulb temperature reading (°C)	Difference between dry and wet bulb readings (°C)									
	1	2	3	4	5	6	7	8	9	10
10	87	74	62	50	38	27	16	5		
12	88	76	65	54	43	32	22	12	2	
14	89	78	67	57	47	37	27	18	9	1
16	89	79	69	59	50	41	32	24	15	7
18	90	80	71	62	53	45	36	28	21	13
20	91	81	73	64	56	48	40	32	25	18
22	91	82	74	66	58	50	43	36	29	23
24	91	83	75	68	60	53	46	39	33	27
26	92	84	76	69	62	55	49	42	36	31

Paper or hair hygrometers work on the principle that paper and hair increase in length when damp, and vice versa. This type of instrument is not very accurate as both paper and hair are not perfectly elastic, i.e. they are permanently stretched eventually.

Electronic hygrometers (Figure 9.9) can measure the humidity of air and give a digital read-out. As the humidity of the air changes, the sensor responds to it and results in the change of static charge stored in the capacitor. This is displayed as relative humidity.

**Figure 9.9** Electronic hygrometer.

Example 9.5

Use Table 9.5 to determine the relative humidity of air for the following data:

Wet bulb temperature = 14°C, Dry bulb temperature = 20°C

Solution:

Difference between dry bulb and wet bulb temperatures = $20 - 14 = 6^\circ\text{C}$

Refer to Table 9.5. The relative humidity that corresponds to the dry bulb temperature of 20°C and temperature difference of 6°C is the answer, i.e. **48%**.

9.8 Condensation

Condensation is said to have occurred if water vapour in the air changes its state to become water, i.e. changes from gas to liquid. Air inside a building always has some moisture in the form of water vapour. The capacity of air to hold moisture depends on its temperature.

Water vapour exerts pressure whether the air is unsaturated or saturated with moisture. When the air is saturated, the pressure exerted by water vapour is known as the saturated vapour pressure, measured in N/m² or pascals (Pa). Table 9.6 gives the values of the SVP against a range of temperatures. An important conclusion that can be drawn from Table 9.6 is that if a sample of air is saturated at a certain temperature, it can be made unsaturated by increasing its temperature, and vice versa. For example, if a sample of air is saturated at 14°C, the SVP will be 1598 Pa. If the temperature of that air sample is raised to 20°C, more water vapour will be required as the SVP at 20°C is 2337 Pa. In other words, the capacity of air to hold moisture increases as its temperature is raised, and vice versa.

The air inside a building is usually warm and unsaturated but the surfaces of window pane and external wall are cold, especially during winter. When warm air comes into contact with a cold surface, its temperature drops and its capacity to hold moisture decreases. As the external temperature continues to drop, the capacity of air to hold

Table 9.6 Saturated vapour pressure

Temperature	SVP (Pa)	Temperature	SVP (Pa)
0	610	16	1818
2	705	18	2063
4	813	20	2337
6	935	25	3166
8	1072	30	4242
10	1227	40	7375
12	1402	50	12340
14	1598		

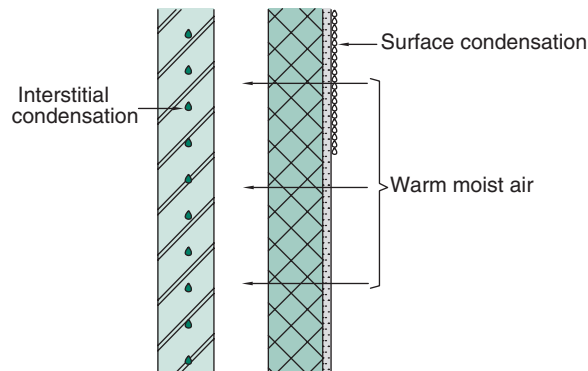


Figure 9.10 Condensation.

moisture keeps on decreasing, and eventually the air becomes saturated, with some moisture condensing and forming droplets of water on the cold surfaces.

The temperature at which water vapour starts to condense is called the **dew point**.

Unit: °C or K.

This may occur as condensation on the wall and window surfaces (surface condensation) and/or within the materials of construction (interstitial condensation), as shown in Figure 9.10. Surface condensation can cause the deterioration of paint, wood, plaster and wallpaper. Interstitial condensation reduces the effectiveness of aerated concrete blocks and insulation materials, like mineral wool, in a cavity wall. This is due to the higher thermal conductivity of water (0.57) as compared to those of lightweight concrete blocks and mineral wool. A detailed discussion on interstitial condensation is given in Section 9.8.3.

9.8.1 The psychrometric chart

The psychrometric chart (Figure 9.11) shows the graphical interaction between the relative humidity of air, its temperature and dew point. The x-axis shows the dry bulb temperature, which is considered to correspond to the air temperature. The curves showing relative humidity of 0%, 10%, 20% etc. start from the y-axis on the left and slope upward. The uppermost curve represents a relative humidity of 100%. The y-axis on the right represents the moisture content of air and the vapour pressure. The wet bulb temperature, which is associated with moist air, is represented by the diagonal lines.

9.8.2 Prevention of surface condensation

It has already been discussed in Section 9.8 that the capacity of air to hold moisture decreases as the air temperature is lowered. When the air temperature is equal to its dew point, the air becomes saturated and the excess moisture is deposited on cold surfaces such as the inside of external walls, and windows. Surface condensation may create several problems like mould growth, structural damage, deterioration of surface finishes

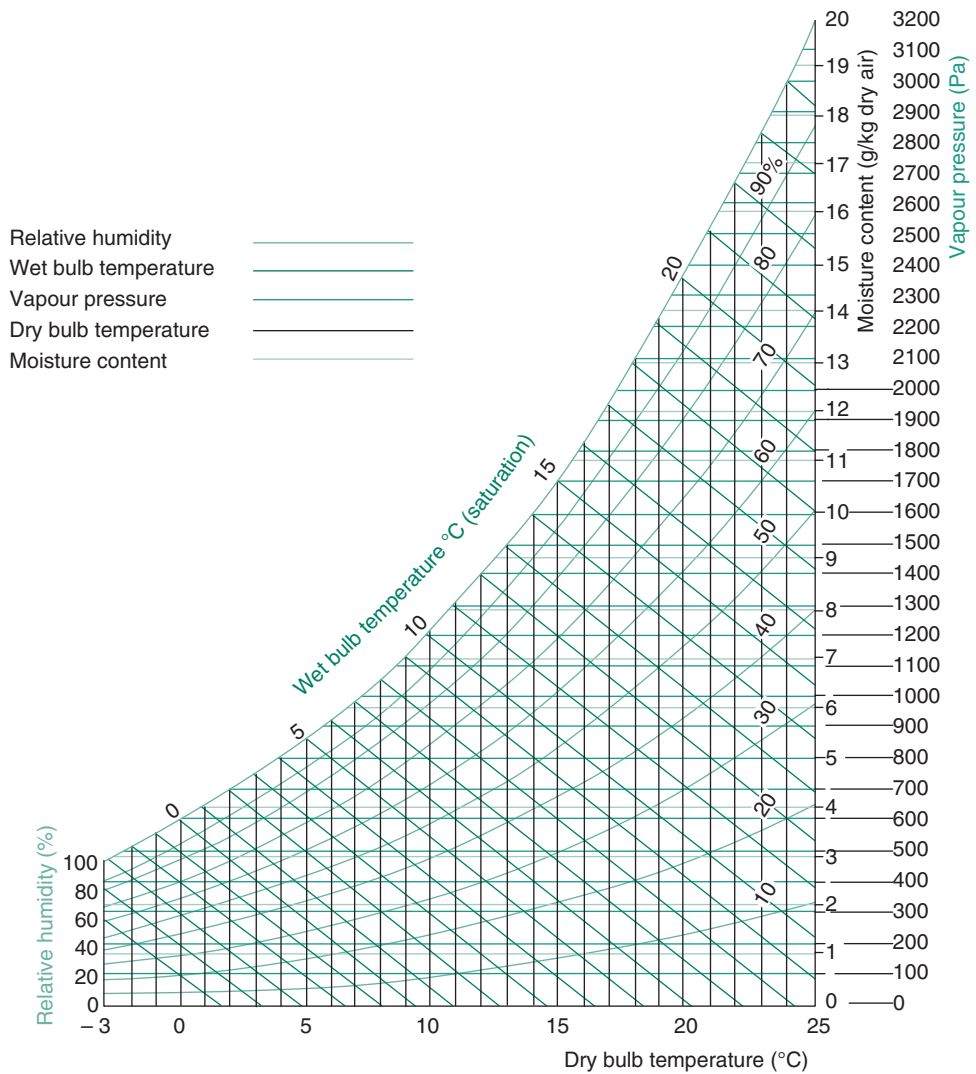


Figure 9.11 The psychrometric chart. (See colour insert.)

Example 9.6

The temperature of air in a building is 19°C and its relative humidity is 70%. Use the psychrometric chart and find:

- the moisture content of air and the vapour pressure
- the relative humidity of air if the temperature is raised to 23°C
- the temperature at which condensation will occur (dew point)

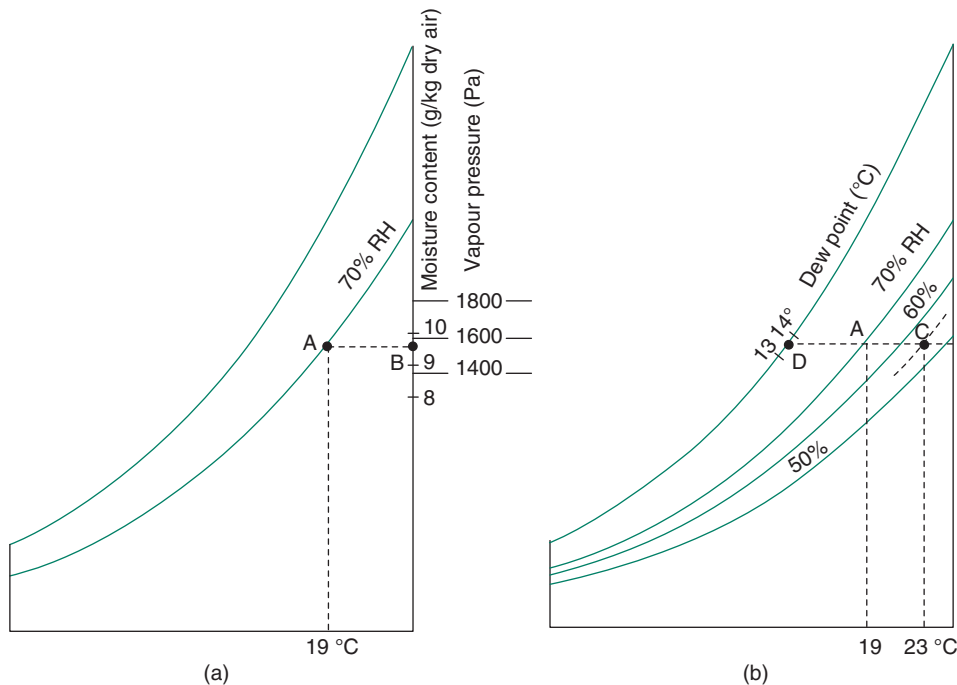


Figure 9.12 a. b.

Solution:

- a) On the psychrometric chart, the point where the vertical line from 19°C (x-axis) meets the 70% RH curve is located (point A). A horizontal line is drawn from point A, to meet the y-axis on the right at point B (Figure 9.12a). The values of the moisture content of the air and the vapour pressure are read off the vertical scales:

Moisture content = 9.7 g/kg

Vapour pressure = 1560 Pa

- b) From point A draw a horizontal line to meet the 23°C vertical line at point C (Figure 9.12b). The RH of the air at point C is 55% (approximately).
 c) From point A draw a horizontal line to meet the 100% RH curve at point D. The dew point is 13.6°C (Figure 9.12b).

and effect on occupants' health. These problems can be reduced by taking one or more of the following actions:

- a) **Temperature:** Warm air can hold more moisture than cold air, therefore, by providing adequate heating, the problem of condensation can be solved. For condensation-free surfaces, it is important to ensure that the air temperature is above its dew point.

- b) Ventilation: The temperature of outside air is usually lower than the inside air temperature, hence its moisture content is lower than that of inside air. By providing adequate ventilation, the moisture-laden air from a building is carried outside and fresh air, having much lower moisture, is allowed to flow inside a building.
- c) Insulation: By providing adequate insulation to the building elements, we can make sure that the inside surfaces do not cool down very quickly when the heating stops. Typical examples of where the inside surfaces can cool down very quickly are the uninsulated external solid brick wall and single-glazed windows. By replacing the single-glazed windows with PVCu double-glazed windows, the problem of condensation on the window glass can be reduced. The air inside the double-glazed units acts as an insulation. A similar effect can be achieved by providing adequate insulation to an uninsulated external solid brick wall.

9.8.3 Interstitial condensation

Most building materials, with the exception of metals, are permeable to water vapour. Bricks, blocks, plasterboard and other materials will allow some amount of vapour to pass through. If the temperature of a material falls below the dew point of water vapour, condensation will occur. Condensation occurring within a building element is called interstitial condensation.

The rate at which water vapour passes through a material depends on the difference between the inside and outside vapour pressures. The internal and external surfaces and highly porous materials have a negligible resistance to the flow of water vapour; other materials show some resistance, as shown in Table 9.7:

Table 9.7 Typical values of vapour resistivity/resistance

Material	Vapour resistivity (r_v) (MN s/g m)
Brickwork	25 to 100
Concrete	30 to 100
Expanded polystyrene	100 to 600
Mineral wool (insulation)	5
Plaster	60
Plasterboard	45 to 60
Plywood	1500 to 6000
Stone	150 to 450
Timber	45 to 75
Membrane	Vapour resistance (MN s/g)
Aluminium foil	4000
Gloss paint	7 to 40
Polyethylene sheet	110 to 120

The vapour resistance of a material (R_v), which measures its effectiveness in resisting the flow of water vapour, can be determined by multiplying its thickness (d) by its vapour resistivity (r_v):

$$R_v = r_v \times d$$

where d is the thickness in metres.

The overall resistance of a component to vapour flow may be obtained by adding the vapour resistances of all the constituent parts. The following sequence of calculations may be used to estimate the risk of interstitial condensation. In the first part, the temperatures across each layer of construction are calculated and, in the second part, the dew points are determined:

- i) Calculate the thermal resistance of each material used in the construction of the element and hence find the total thermal resistance.
- ii) Find the difference between the internal and external temperatures (T). Starting from the inside, calculate the temperature drop (T_{drop}) across each material/layer of construction:

$$\text{Temperature drop across a layer} = \frac{\text{Thermal resistance of the layer } (R_{\text{layer}})}{\text{Total thermal resistance } (R_{\text{total}})} \times T$$

$$\text{or } T_{\text{drop}} = \frac{R_{\text{Layer}}}{R_{\text{Total}}} \times T$$

where T is the difference between inside and outside temperatures.

- iii) Calculate the boundary temperatures.
- iv) Draw a cross-section of the element and plot the points showing temperature drop across the various materials of construction. Join the points by straight lines to produce the structural temperature profile. This completes the first part of the calculations.
- v) From the psychrometric chart, find the inside and outside vapour pressures, and the difference between them.
- vi) The water vapour flows from the high-pressure area towards the low-pressure area. Use the formula below to calculate the vapour pressure drop (P_{drop}) across each layer of construction:

$$\text{Vapour pressure drop across a layer} = \frac{\text{Vapour resistance of a layer } (R_v)}{\text{Total vapour resistance of element } (R_{v(\text{total})})} \times P$$

$$\text{or, } P_{\text{drop}} = \frac{R_v}{R_{v(\text{total})}} \times P$$

where P is the difference between inside and outside vapour pressures.

- vii) Calculate the vapour pressure at the boundary of each layer and find the dew points corresponding to these vapour pressures from the psychrometric chart.
- viii) Join all dew points by straight lines to obtain the dew point profile.
- ix) There is a risk of interstitial condensation if the structural temperature profile falls below the dew point profile.

The above procedure is followed in Example 9.7.

Example 9.7

A 300 mm thick (actual thickness is 303 mm) external wall is constructed of bricks, aerated concrete blocks, lightweight plaster and mineral wool. The inside air is at 22°C and 50% relative humidity; the outside air is at 0°C and 100% relative humidity. The properties of materials and their thickness are:

Material	Thickness (d)	λ-value	Vapour resistivity (r _v)
	mm	W/m K	MN s/g m
Plaster	12	0.18	60
Aer. Conc. blocks	100	0.11	50
Mineral wool	100	0.04	5
Bricks	103	0.84	50

Determine if there is a risk of interstitial condensation.

Solution:

Difference between the inside and outside temperatures (T) = 22 – 0 = 22 °C

Material or layer	Thickness, d (m)	Thermal conductivity, λ (W/m K)	Thermal resistance (m ² K/W)	Temperature drop (°C)	Boundary temperature (°C)
			$\frac{d}{\lambda}$	$\frac{R_{\text{Layer}}}{R_{\text{Total}}} \times T$	
Inside surface	-	-	0.12	$\frac{0.12}{3.779} \times 22 = 0.7$	22 22 – 0.7 = 21.3
Plaster	0.012	0.18	$d/\lambda = 0.012/0.18 = 0.067$	$\frac{0.067}{3.779} \times 22 = 0.4$	21.3 – 0.4 = 20.9
Aer. Conc. blocks	0.100	0.11	$= 0.100/0.11 = 0.909$	$\frac{0.909}{3.779} \times 22 = 5.3$	20.9 – 5.3 = 15.6
Mineral wool	0.100	0.04	$= 0.100/0.04 = 2.5$	$\frac{2.5}{3.779} \times 22 = 14.6$	15.6 – 14.6 = 1.0
Brickwork	0.103	0.84	$= 0.103/0.84 = 0.123$	$\frac{0.123}{3.779} \times 22 = 0.7$	1.0 – 0.7 = 0.3
Outside surface	-	-	0.06	$\frac{0.06}{3.779} \times 22 = 0.3$	0.3 – 0.3 = 0
			Total thermal resistance $R_{\text{total}} = 3.779$		

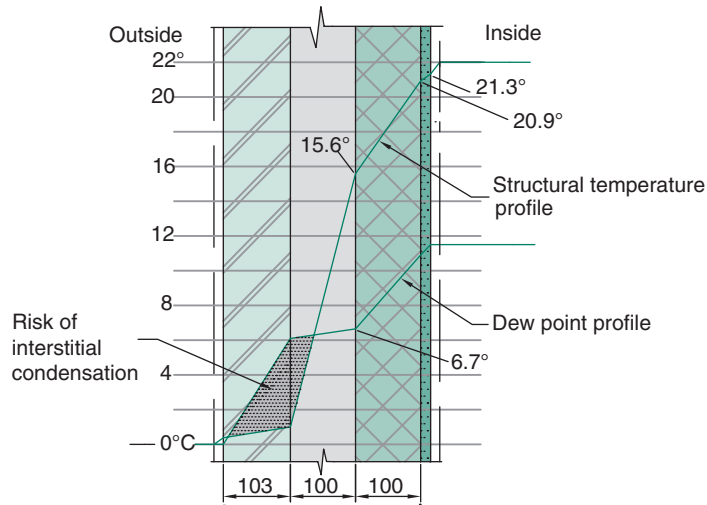


Figure 9.13

The cross-section of the wall is drawn to a suitable scale and the boundary temperatures are plotted (Figure 9.13). The points are joined by straight lines to produce the structural temperature profile. This completes the first part of the solution. In the second part, the vapour pressures at the boundary of materials are determined, which are then used to find the dew points from the psychrometric chart.

From the psychrometric chart:

Inside vapour pressure = 1340 Pa (air temperature = 22 °C; RH = 50 %)

Outside vapour pressure = 600 Pa (air temperature = 0 °C; RH = 100 %)

Vapour pressure difference, $P = 1340 - 600 = 740$ Pa

Material or layer	Thickness, d (m)	Vapour resistivity, r_v (MN s/g m)	Vapour resistance, R_v (MN s/g)	Vapour pressure drop across layer, P_{drop} (Pa)	Vapour pressure at boundary (Pa)	Dew point (°C)
			$r_v \times d$	$\frac{R_v}{R_{v(\text{total})}} \times P$		
Inside surface	-	-	-	-	1340	11.5
Plaster	0.012	60	0.72	$\frac{0.72}{11.37} \times 740 = 46.9$	$1340 - 46.9 = 1293.1$	10.9
Aer. Conc. blocks	0.100	50	5.0	$\frac{5.0}{11.37} \times 740 = 325.4$	$1293.1 - 325.4 = 967.7$	6.7
Mineral wool	0.100	5	0.5	$\frac{0.5}{11.37} \times 740 = 32.5$	$967.7 - 32.5 = 935.2$	6.1
Brickwork	0.103	50	5.15	$\frac{5.15}{11.37} \times 740 = 335.2$	$935.2 - 335.2 = 600$	0
Outside surface	-	-	-	-	600	0
			$R_{v(\text{total})} = 11.37$			

The dew points are plotted on the cross-section of the wall and joined by straight lines. If the structural temperature falls below the dew point, there is a risk of interstitial condensation. This is shown in Figure 9.13. In this example, the structural temperature falls below the dew point, hence there is a risk of interstitial condensation. The shaded portion, where the interstitial condensation could occur, exists in the whole length and height of the wall.

Example 9.8

Repeat Example 9.7 if the plaster is covered with vinyl wallpaper (vapour resistance = 10 MN s/g)

Solution:

The first part of the question remains unchanged.

In the second part, the dew points will change due to the wallpaper, as shown below:

Material or layer	Thickness, d (m)	Vapour resistivity, r_v	Vapour resistance	Vapour pressure drop across layer, P_{drop}	Vapour pressure at boundary (Pa)	Dew-point (°C)
Inside surface	-	-	-	-	1340	11.5
Vinyl wallpaper	-	-	10	$\frac{10.0}{21.37} \times 740 = 346.3$	$1340 - 346.3 = 993.7$	7.1
Plaster	0.012	60	0.72	$\frac{0.72}{21.37} \times 740 = 24.9$	$993.7 - 24.9 = 968.8$	7.0
Aer. Conc. blocks	0.100	50	5.0	$\frac{5.0}{21.37} \times 740 = 173.1$	$968.8 - 173.1 = 795.7$	4.0
Mineral wool	0.100	5	0.5	$\frac{0.5}{21.37} \times 740 = 17.3$	$795.7 - 17.3 = 778.4$	3.7
Brickwork	0.103	50	5.15	$\frac{5.15}{21.37} \times 740 = 178.4$	$778.4 - 178.4 = 600$	0
Outside surface	-	-	-	-	600	0
$R_{v(total)} = 21.37$						

The dew points are plotted on the cross-section of the wall and joined by straight lines, as shown in Figure 9.14. Although not significant, the vinyl wallpaper does reduce the effect of interstitial condensation.

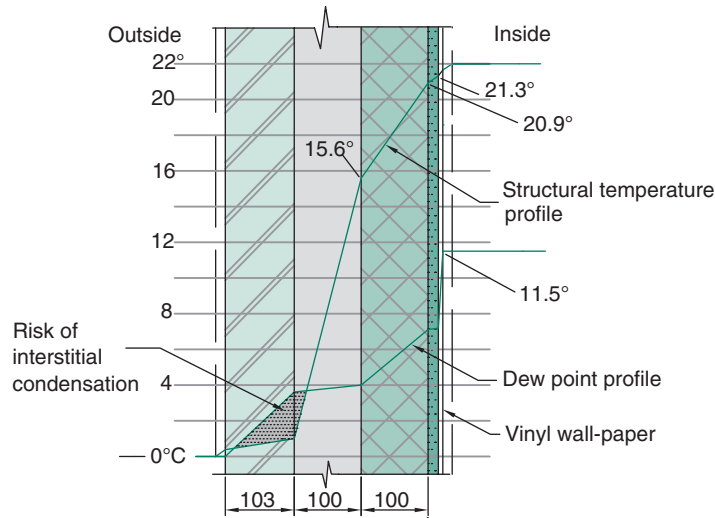


Figure 9.14

9.8.4 Prevention of interstitial condensation

Interstitial condensation can be avoided by keeping the humidity as low as possible. The minimum relative humidity of air, required for a comfortable condition, is 40%. This can be achieved by keeping a strict control on the sources of moisture so that the amount of water vapour passing through a wall or roof can be minimised. The flow of water vapour can be minimised by providing materials with low permeability, i.e. vapour barriers. These are of two types:

i) Membrane type

Examples of this type are aluminium foil-backed plasterboard, polythene sheet, asphalt-impregnated paper etc.

ii) Paint or liquid type

Examples of this type are aluminium paint and gloss paint.

The vapour barrier is always applied to the warm side of the element.

Exercise 9.1

- Find the U-values of a triple-glazed window, with two 20 mm wide air spaces.
Given: Thickness of glass = 4 mm
Thermal conductivity of glass = 1.02 W/m K
Thermal resistance of surfaces: 0.12 (inside); 0.06 (outside);
Thermal resistance of 20 mm wide airspace = 0.18 m² K/W
- Find the U-value of a 215 mm thick brick wall with 12 mm layer of dense plaster.
Thermal conductivities: Bricks = 0.84; plaster = 0.46 W/m K
Use the values of thermal resistances given in Question 1.
 - The U-value of the wall in Question 2a needs to be improved to 0.35 by using sheets of expanded polystyrene (EPS) and 9 mm thick plasterboard. Find the minimum thickness of EPS required to achieve the new U-value.
Thermal conductivities: EPS = 0.033; plasterboard = 0.16 W/m K
- Calculate the U-value of a cavity wall with half-brick thick (103 mm) outer leaf, 50 mm wide cavity, 100 mm thick aerated concrete block inner leaf and 12 mm thick layer of lightweight plaster.
Thermal conductivities: Aerated concrete blocks = 0.11; bricks = 0.84; lightweight plaster = 0.16 W/m K.
Thermal resistances of surfaces: 0.12 (inside); 0.06 (outside);
Thermal resistance of airspace = 0.18 m² K/W
 - Find the U-value of the wall if the cavity is completely filled with mineral wool insulation. Thermal conductivity of mineral wool is 0.04 W/m K.
- Calculate the total rate of heat loss from the building shown in Figure 9.6. A temperature of 22 °C is to be maintained inside the building when the outside air temperature is 0 °C. Allow 1 air change per hour; the volumetric specific heat capacity of air is 1212 J/m³ K. The U-values (W/m² K) are:
Walls = 0.35; floor = 0.25; roof = 0.25; doors = 2.2; windows = 1.9.
The ground temperature is 5 °C.
- The cavity wall of a dwelling house is constructed of bricks, aerated concrete blocks, lightweight plaster and mineral wool. The inside air is at 21 °C and 60% relative humidity. The outside air is at 0 °C and 100% relative humidity. The properties of materials and their thickness are:

Material	Thickness (d)	λ -value	Vapour resistivity (r_v)
	mm	W/m K	MN s/g m
Plaster	12	0.16	60
Aer. Conc. blocks	100	0.11	50
Mineral wool	50	0.04	5
Bricks	103	0.84	50

The cavity is 50 mm wide and filled with insulation. Determine if there is a risk of interstitial condensation.

Table 9.8 Heat output of compact radiators

Output based on a mean radiator water temperature of 70°C and a room temperature of 20°C							
Nominal height	Length mm	 Single convector		 Double panel plus		 Double convector	
		btu/h	watts	btu/h	watts	btu/h	watts
400 mm	500	1244	365	1066	521	2372	695
	600	1493	437	2132	625	2846	834
	700	1742	510	2487	729	3321	973
	800	1990	583	2842	833	3795	1112
	900	2239	656	3198	937	4270	1251
	1000	2488	729	3553	1041	4744	1390
	1100	2737	802	3908	1145	5218	1529
	1200	2986	875	4264	1249	5693	1668
	1400	3483	1021	4974	1457	6642	1946
	1600	3981	1166	5685	1666	7591	2224
500 mm	1800	4479	1312	6395	1874	8539	2502
	2000	4976	1458	...	...	9488	2780
	300	906	266	...	...	1702	499
	400	1208	354	...	...	2269	665
	500	1510	443	2114	620	2836	831
	600	1812	531	2537	743	3403	997
	700	2114	620	2960	867	3971	1163
	800	2416	708	3383	991	4538	1330
	900	2718	797	3806	1115	5105	1496
	1000	3021	885	4229	1239	5672	1662
600 mm	1100	3323	974	4652	1363	6240	1828
	1200	3625	1062	5074	1487	6807	1994
	1400	4229	1239	5920	1735	7941	2327
	1600	4833	1416	6766	1982	9076	2659
	1800	5437	1593	...	...	10210	2992
	2000	6041	1770	...	...	11345	3324
	300	1056	309	...	...	1960	574
	400	1408	412	...	...	2613	766
	500	1759	516	2432	713	3266	957
	600	2111	619	2918	855	3919	1148
	700	2463	722	3404	998	4573	1340
	800	2815	825	3891	1140	5226	1531
	900	3167	928	4377	1283	5879	1723
	1000	3519	1031	4864	1425	6532	1914
	1100	3871	1134	5350	1568	7186	2105
	1200	4223	1237	5836	1710	7839	2297
	1400	4926	1443	6809	1995	9145	2680
	1600	5630	1650	7782	2280	10452	3062
	1800	6334	1856	...	...	11758	3445
	2000	7038	2062	...	...	13065	3828

(Extract from Quinn Radiators)

References/Further reading

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10

Forces and structures 1

Learning outcomes:

- 1) Identify different types of forces (loading) that act on a structure.
- 2) Explain stress and strain in construction materials.
- 3) Define elasticity and explain the stress-strain relationship for ductile and brittle materials.
- 4) Solve problems based on stress, strain, elasticity and factor of safety.

10.1 Introduction

Buildings and civil engineering structures like roads, bridges, dams and tunnels are acted upon by forces which can basically be grouped into two categories: dead loading and imposed loading. These forces, if excessive, may be responsible for the failure of a structure. A building or a civil engineering structure is built to be strong, stable and durable to resist these forces. To achieve these requirements in an economical manner, it is necessary to use materials of appropriate quality and use a mathematical approach for preparing the structural design, which involves the determination of sizes and other attributes of the structural elements. However, before preparing the structural design, it is necessary to analyse the forces acting on a structure. This process is called structural analysis and involves calculating the resultant effect of all the forces which can later be used in the design calculations. For example, the structural analysis of a roof truss involves the calculation of forces in its members due to a combined effect of wind, snow and other loads acting on it. The structural analysis is utilised to determine the sizes of the truss members.

Engineers also deal with the forces acting on retaining walls, multi-storey buildings, bridges, dams and other structures. Each structure is exposed to different types of forces and, therefore, a different approach is required to analyse the forces in each case. A

detailed description of the nature of forces and their effects is given in the following sections.

10.2 Force

All structures are acted upon by a variety of forces. Some forces are small in magnitude causing no significant effect, whereas others can be large and must be considered in the design process. If a stationary body is acted upon by a force, then depending on the magnitude of the force it may or may not move. Similarly, a force applied to a moving body may do one or more of the following:

- a) Change its speed
- b) Change its direction
- c) Bring it to rest

Hence, **force** may be defined as that which changes, or tends to change, a body's state of rest or uniform motion in a straight line. A force can be represented in both magnitude and direction. The basic unit of force in the S.I. system is a Newton (N) which can be defined as the force required to produce an acceleration of 1 metre/sec^2 in a mass of 1 kg.

The direction of a force can be represented by an arrowhead, for example, a downward force may be represented as $\downarrow$ and an upward force as $\uparrow$.

Building elements are subjected to the following forces:

- a) Push or **compressive force**, which causes shortening of a material
- b) Pull or **tensile force**, which causes stretching of a material
- c) **Shear**, which causes part of the material to move horizontally or vertically against the rest

These forces are illustrated in Figure 10.1.

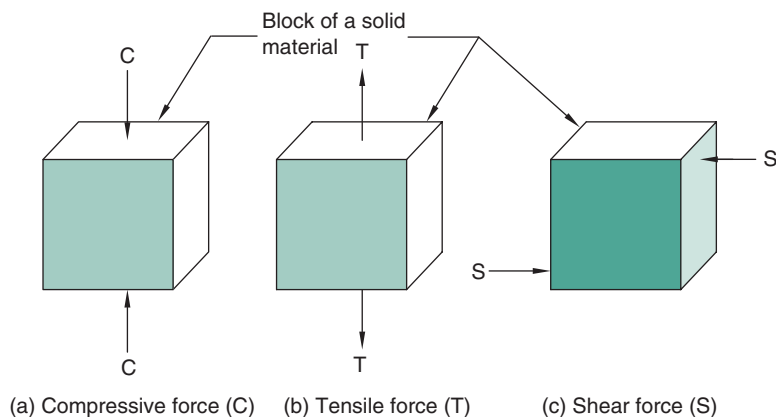


Figure 10.1 Types of force.

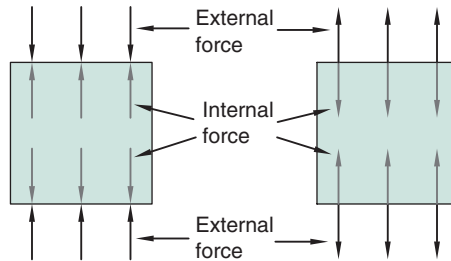


Figure 10.2 Internal and external forces.

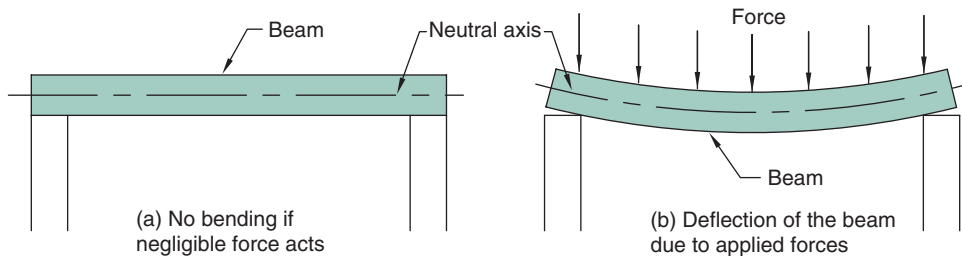


Figure 10.3 Deflection of a simply supported beam.

Some building elements may also be subjected to torsion, for example, edge beams in steel-framed or concrete-framed structures.

10.2.1 Internal and external forces

Consider two blocks of a material, as shown in Figure 10.2, one acted upon by a compressive force, and the other by a tensile force. These forces are called external forces. The blocks will resist the deforming action of external forces, as internal forces are set up within the material and act in an opposite direction.

10.3 Bending

The effects caused by direct compressive and tensile forces, as shown in Figure 10.1, can also occur in elements subjected to bending. Figure 10.3 illustrates that in a beam **deflection** (bending) takes place when forces act on it. It is quite evident from the deflected shape (Figure 10.3b) that the upper portion of the beam is shortened or compressed, and the lower portion stretched. In other words, we can say that the upper part is in compression, like the material shown in Figure 10.1a, and the lower part is in tension, like the material shown in Figure 10.1b. The centre line of the beam remains unchanged in length and that is why it is called the neutral axis. It is also evident from Figure 10.3 that compression occurs in the concave part of the beam, and tension in the convex part.

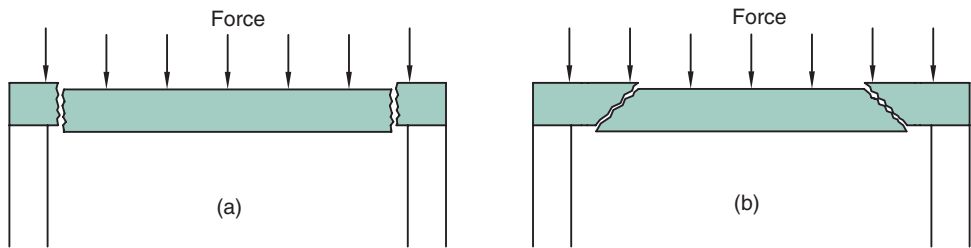


Figure 10.4 Failure of beams in shear.

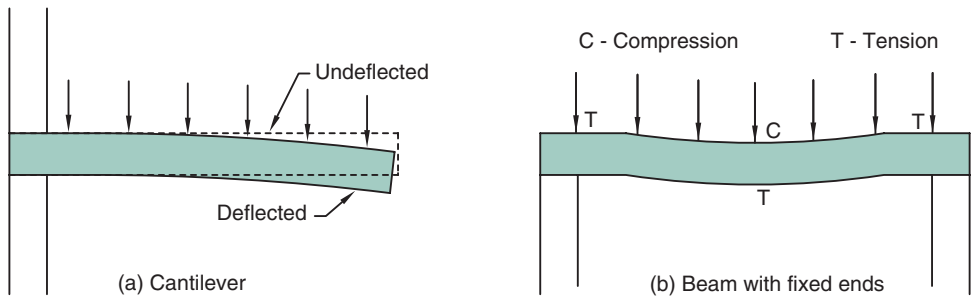


Figure 10.5 Deflection in cantilevers and beams with fixed ends.

The beam is also subjected to **shear**, which is due to the opposite directions of the reaction and the applied force. The maximum shear force, to which the beam is subjected, is near the supports (see also Chapter 11). In idealised situations shear failure is assumed to take place at a support (Figure 10.4a), but actually it depends on the material of the beam. For example, concrete is assumed to shear at 45° , as shown in Figure 10.4 b.

The beam shown in Figure 10.3 is a **simply supported** single-span beam, which means that the beam and its supports are not rigidly connected. A beam with one support is called a **cantilever**, which is shown in Figure 10.5a. The force acting on a cantilever causes tension in the upper half, and compression in the lower half.

In reinforced concrete (RC) framed buildings, the beams are considered to have **fixed ends**, i.e. the beams and the columns supporting them are constructed at the same time. The beam ends are not free to move when loading is applied as there are strong and rigid connections between the beams and the columns.

Figure 10.5 shows the deflected shapes of a cantilever, and of a beam with fixed ends.

10.3.1 Deflection

Some amount of deflection always occurs in beams and joists when a force (called a load in structural design) is applied on them. The amount of deflection depends on several factors, including:

- a) Magnitude of the load
- b) Size of the beam/joist
- c) Properties of the material concerned

The size of a beam may be adequate to save it from failure, but still a large deflection may be produced. This causes a practical difficulty in securing the finishes to the beams or joists.

The values of actual deflection (δ) of a simply supported beam subjected to a point load or to a uniformly distributed load are:

- i) For a point load (central), $\delta = \frac{Wl^3}{48EI}$
- ii) For a uniformly distributed load, $\delta = \frac{5Wl^3}{384EI}$

where E is the modulus of elasticity of the material

I is the moment of inertia of the beam

The actual deflection of a beam should not be more than 1/360 of the span.

10.4 Types of loading

A building is acted upon by many forces, which can be divided into two categories:

- a) Dead load, imposed load, wind load, and loading from other effects.
- b) Point load, uniformly distributed load and triangular load.

10.4.1 Dead load

The dead load of an element or a component is its self-weight, which depends on the density of the materials used and the dimensions of the component. Dead load is of a permanent nature, i.e. it always acts on a structure. For a two-storey dwelling house, the total dead load will consist of:

- a) Self-weight of the roof structure due to trussed rafters, roof tiles, battens and ceiling finish
- b) Self-weight of the first-floor construction
- c) Self-weight of the walls, from the top to foundation level
- d) Self-weight of the foundation

The calculation of the dead load of an element is very important as it forms a significant part of the design load.

10.4.2 Imposed load

Any load that is of a temporary nature is called imposed load (or live load). Many types of forces can be considered under this category, for example:

- a) Loading from people, furniture, goods etc. in dwelling houses, schools, colleges, hotels, warehouses etc.
- b) Loading from people, vehicles and trains etc. on bridges
- c) Snow load: this affects the roof structure of a building

Wind load is of a temporary nature as well, but, due to its complexity, it is dealt with separately.

10.4.3 Wind load

Wind exerts force on buildings, bridges and other objects that come in its way to obstruct the flow. The force depends on the design of the building, the wind speed and the geographical location. The roof tiles of dwelling houses are especially vulnerable to damage by wind forces.

10.4.4 Loading from other effects

There are some sources that can form a major part of the total load. Typical examples are: earth pressure in retaining walls, liquid pressure in liquid-retaining structures, and seismic load which can cause severe damage to buildings, depending on the intensity of the earthquake.

For simple structural designs, the dead load and the imposed load are added to find the design load. Figure 10.6 shows the dead and imposed loading acting on a low-rise building.

10.4.5 Point load (Figure 10.7a)

Force acting on a very small area is called a point load. For example, a person standing on a roof or on a floor is considered as a point load.

10.4.6 Uniformly distributed load (Figure 10.7b)

Forces distributed evenly over an area are considered as a uniformly distributed load (u.d.l.). The resultant force of a u.d.l. acts at the centre of the area on which the load acts.

10.4.7 Triangular load (Figure 10.7c)

The force acting on a retaining wall or a basement wall due to the retained soil (called earth pressure) is considered as a triangular load. The load is zero at the top and increases as the depth of the retained soil increases. The resultant force acts at a point that is at one-third of the height of the retained soil from the base of the wall.

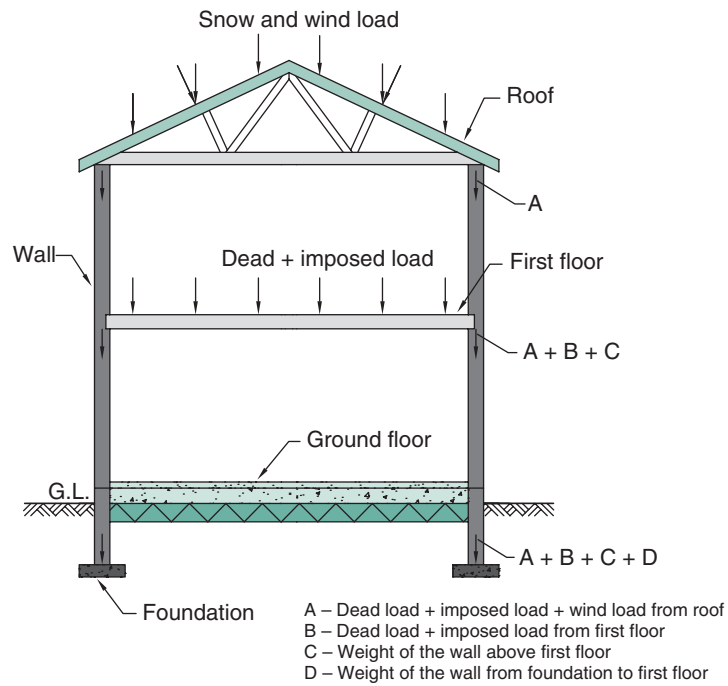


Figure 10.6

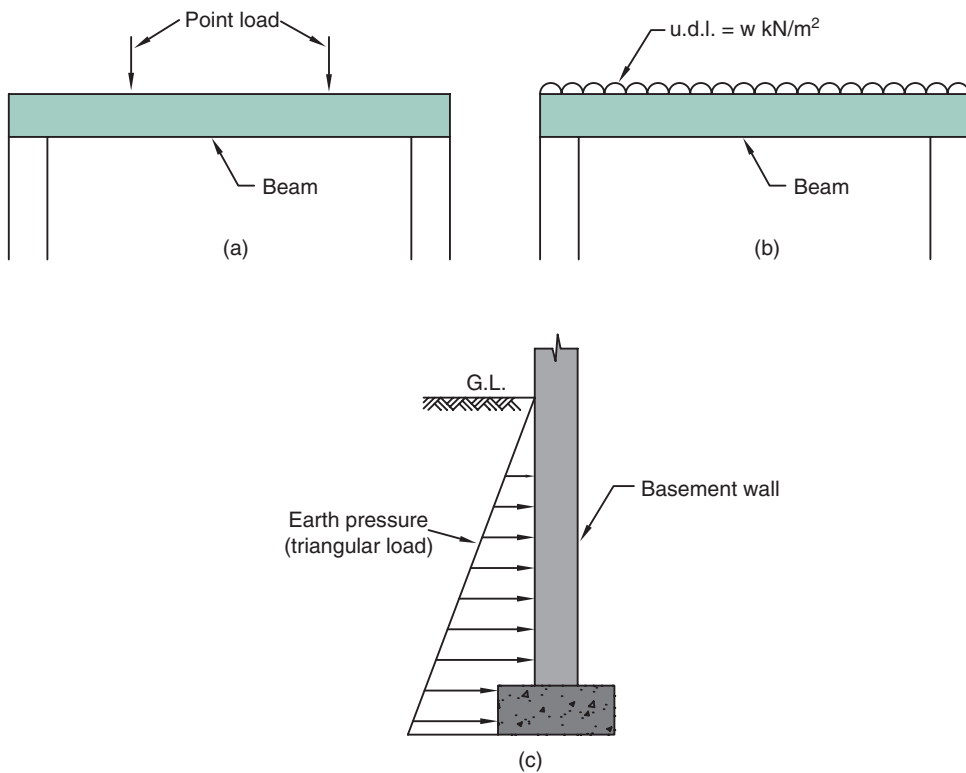


Figure 10.7 Types of loading.

Example 10.1

Find the dead load of a cavity wall measuring $8.0\text{ m} \times 5.2\text{ m}$ high. The densities of brickwork and blockwork are 2200 kg/m^3 and 600 kg/m^3 respectively. The cross-section of the wall is shown in Figure 10.8.

Solution:

To find the dead load, we need to find the volume of brickwork and blockwork first, and then use this relationship to find the mass:

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

$$\text{or, Mass} = \text{Density} \times \text{Volume}$$

$$\begin{aligned}\text{Volume of brickwork} &= \text{length} \times \text{height} \times \text{thickness} \\ &= 8.0 \times 5.2 \times 0.102 = 4.243\text{ m}^3\end{aligned}$$

$$\text{Volume of blockwork} = 8.0 \times 5.2 \times 0.100 = 4.160\text{ m}^3$$

$$\text{Mass of brickwork} = 2200 \times 4.243 = 9334.6\text{ kg}$$

$$\text{Mass of blockwork} = 600 \times 4.160 = 2496\text{ kg}$$

$$\text{Total mass of the wall} = 11830.6\text{ kg}$$

$$\begin{aligned}\text{Weight (or dead load) of the wall} &= \text{mass} \times g \\ &= 11830.6 \times 9.81 \\ &= 116058.2\text{ N or }116.058\text{ kN}\end{aligned}$$

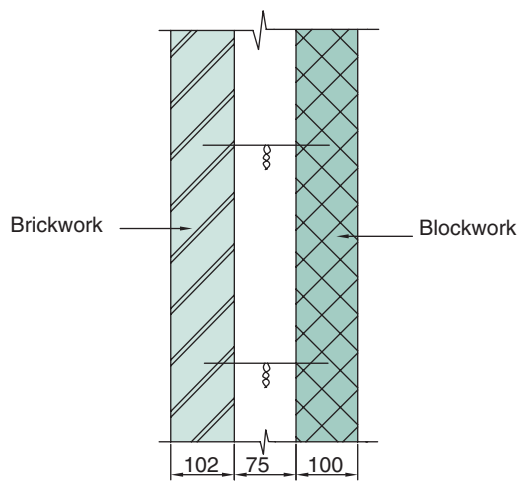


Figure 10.8 Section through a cavity wall.

Example 10.2

Figure 10.9a shows the details of a timber floor. If the densities of timber and plasterboard are 550 kg/m^3 and 950 kg/m^3 respectively, find the dead load of the floor per m^2 .

Solution:

Each joist supports the loading from an area enclosed by the dashed lines, shown as the shaded portion in Figure 10.9b. The width of this portion is 0.4 m , the same as the spacing between the joists.

Consider a $0.4 \text{ m} \times 1.0 \text{ m}$ section of the floor; the area of this section is 0.4 m^2

	Volume	Mass
Joist	Volume = length $\times$ width $\times$ depth $= 1.0 \times 0.050 \times 0.200 = 0.010 \text{ m}^3$	Mass = density $\times$ volume $= 550 \times 0.010 = 5.5 \text{ kg}$
Floor boards	Volume = $1.0 \times 0.4 \times 0.018$ $= 0.0072 \text{ m}^3$	Mass = 550×0.0072 $= 3.96 \text{ kg}$
Plasterboard	Volume = $1.0 \times 0.4 \times 0.012$ $= 0.0048 \text{ m}^3$	Mass = 950×0.0048 $= 4.56 \text{ kg}$

Total mass of floor for an area of $0.4 \text{ m}^2 = 5.5 + 3.96 + 4.56 = 14.02 \text{ kg}$

Mass of floor per $\text{m}^2 = 14.02 \times 1/0.4 = 35.05 \text{ kg}$

Dead load (or weight) per $\text{m}^2 = 35.05 \times 9.81$
 $= 343.84 \text{ N}$ or 0.344 kN

Note: If the room dimensions are known, then it will be more accurate to determine the number of joists and hence calculate their mass and weight per m^2 .

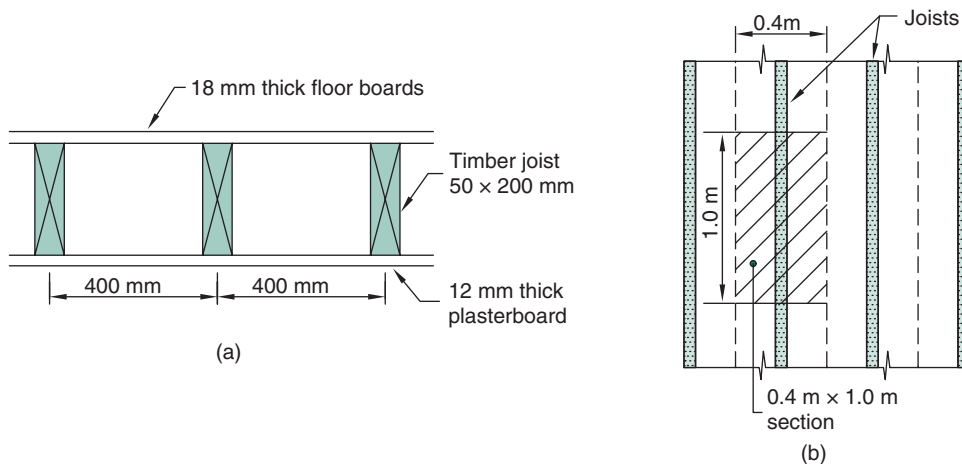


Figure 10.9 Timber floor.

10.5 Stress and strain

After finding the total force acting on a structure, it is necessary to find the stress and strain and check whether they are within permissible limits.

10.5.1 Stress

Stress is defined as the force per unit area. In many engineering problems the effect of force acting on an area can be determined only by calculating the stress produced.

$$\text{Stress} = \frac{\text{Force}}{\text{Area}}$$

The unit of force is Newton (N) or kiloNewtons (kN), and the units of area are mm^2 or m^2 . By definition, stress is the force (N or kN) per unit area (mm^2 or m^2), therefore, depending on which of these are being used, the units of stress are: N/mm^2 , N/m^2 , kN/mm^2 or kN/m^2 .

Depending on the type of the force, stress can be tensile, compressive or shear stress.

Example 10.3

A column measuring $0.4\text{ m} \times 0.4\text{ m} \times 4.0\text{ m}$ high supports a load of 500 kN. Find the stress at the top of the column in kN/m^2 and N/mm^2 .

Solution:

$$\text{Cross-sectional area of the column} = 0.4 \times 0.4 = 0.16 \text{ m}^2$$

$$\text{or, } 400 \text{ mm} \times 400 \text{ mm} = 160000 \text{ mm}^2$$

$$\begin{aligned} \text{Stress} &= \frac{500}{0.16} = 3125 \text{ kN/m}^2 \\ &= \frac{500 \times 1000 \text{ N}}{160000} = 3.125 \text{ N/mm}^2 \end{aligned}$$

10.5.2 Strain

A building material deforms when a significant amount of force is applied on it. A tensile force causes elongation of the material, and a compressive force causes shortening. As the volume of a material remains constant, the change in its length is accompanied by the change in cross-sectional area.

Strain (also called linear strain) is defined as the ratio of change in length of a material to its original length.

$$\text{Strain, } \epsilon^* = \frac{\text{Change in length (mm)}}{\text{Original length (mm)}}$$

* ϵ is the Greek letter called epsilon

Unit: Strain is specified as a number or percentage, as the change in length and the original length have the same units.

Some materials, like soils, do have a change in volume when forces act on them. The ratio of change in volume to the original volume is known as the volumetric strain.

$$\text{Volumetric strain, } \epsilon_v = \frac{\text{Change in volume}}{\text{Original volume}}$$

Example 10.4

A specimen of a metal, 75 mm long, was stretched with a force of 10 kN. The strain produced in the material was 10 %. Find the increase in the length of the specimen.

Solution:

$$\text{Strain (\%)} = \frac{\text{Change in length}}{\text{Original length}} \times 100$$

$$10 = \frac{\text{Change in length}}{75} \times 100$$

$$\text{After transposition, change in length} = \frac{10 \times 75}{100} = 7.5 \text{ mm}$$

Example 10.5

A specimen of steel, measuring 150 mm in length, was tested in compression under a load of 20 kN. The final length was 145 mm. Find the strain produced.

Solution:

$$\begin{aligned} \text{Strain} &= \frac{\text{Change in length}}{\text{Original length}} \\ &= \frac{150 - 145}{150} = 0.033 \end{aligned}$$

$$\text{As a percentage, strain} = 0.033 \times 100 = 3.33\%$$

10.6 Elasticity

Elasticity can be defined as that property of materials by virtue of which they regain their original shape and size when the deforming forces are removed.

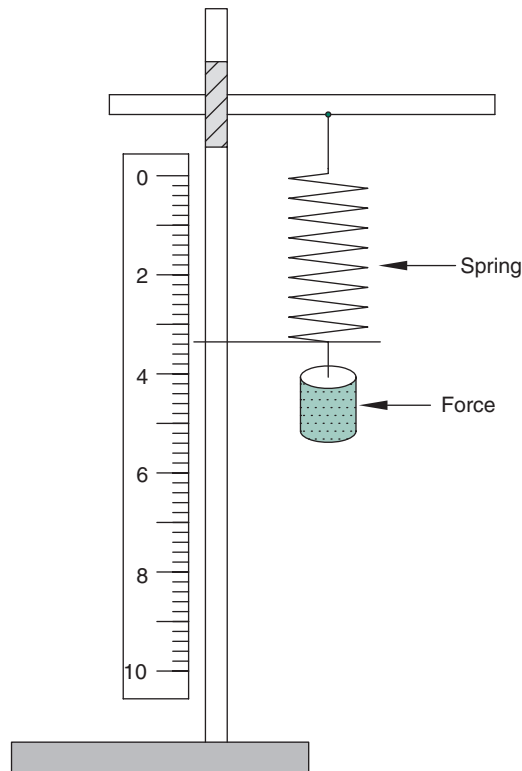


Figure 10.10 Proof of Hooke's law by loading a spring.

During the seventeenth century, Robert Hooke conducted experiments on metal wires and other types of samples and found that within the elastic range of a material the change in length was proportional to the force applied. This is known as Hooke's law and can be proven by performing tests on springs, metal wires, strips or solid cylindrical samples.

10.6.1 Experiment 1: Proof of Hooke's law

A spring is suspended from a fixed point so that only the lower end moves on applying a force. The spring is stretched by placing a mass of 0.250 kg at the lower end and its extension noted (see Figure 10.10). This process is repeated with a range of masses, e.g. 0.500 kg, 0.750 kg etc., and the corresponding extensions of the spring are recorded. The mass is converted into weight (force) by multiplying the mass in kilograms by 9.81 (10 is used in Table 10.1 for simplification). A graph is then plotted between force and extension as shown in Figure 10.11.

A line is drawn through all points and it is observed to be a straight line between the origin and point L. This shows that the extension produced in the spring is proportional to the force applied. The force that corresponds to point L is 12.5 kN. If the force is removed at any stage between the start and 12.5 kN, the spring will return to its original

Table 10.1

Force (N)	Extension (mm)
2.5	5.0
5.0	10.0
7.5	15.0
10.0	20.0
12.5	25.0
15.0	31.0
17.5	42.0

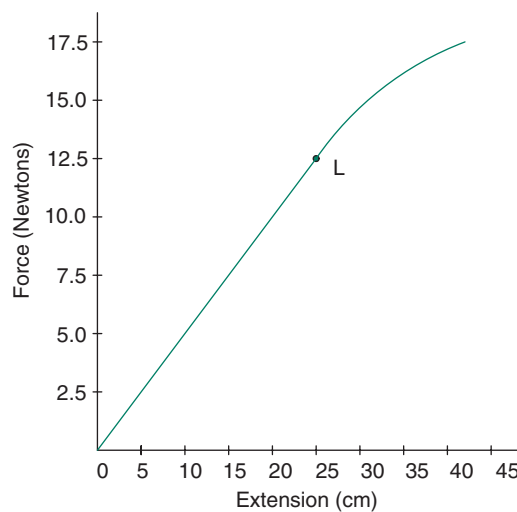


Figure 10.11

length. The spring behaves like an elastic material up to this point; hence it is called the elastic limit. If the spring is loaded beyond this point, the extension is no longer proportional to the force; the behaviour of the spring is called plastic behaviour. If the force is removed during the plastic stage, the spring does not return to its original length.

10.6.2 Experiment 2: Proof of Hooke's law

Hooke's law can also be proven by performing a tensile test on specially prepared metal, and non-metal, samples. The sample is secured in an apparatus known as a Hounsfield Tensometer and a tensile force is applied by turning the handle. The values of the force and the extension produced in the sample are taken at regular intervals until the sample snaps, and the results of the test are shown either as load versus extension, or as stress versus strain. Figure 10.12 illustrates the results of such a test. The graph shows that, as the tensile force is applied, elongation of the sample occurs. The elongation is directly proportional to the force applied as shown by the straight-line portion, and the point

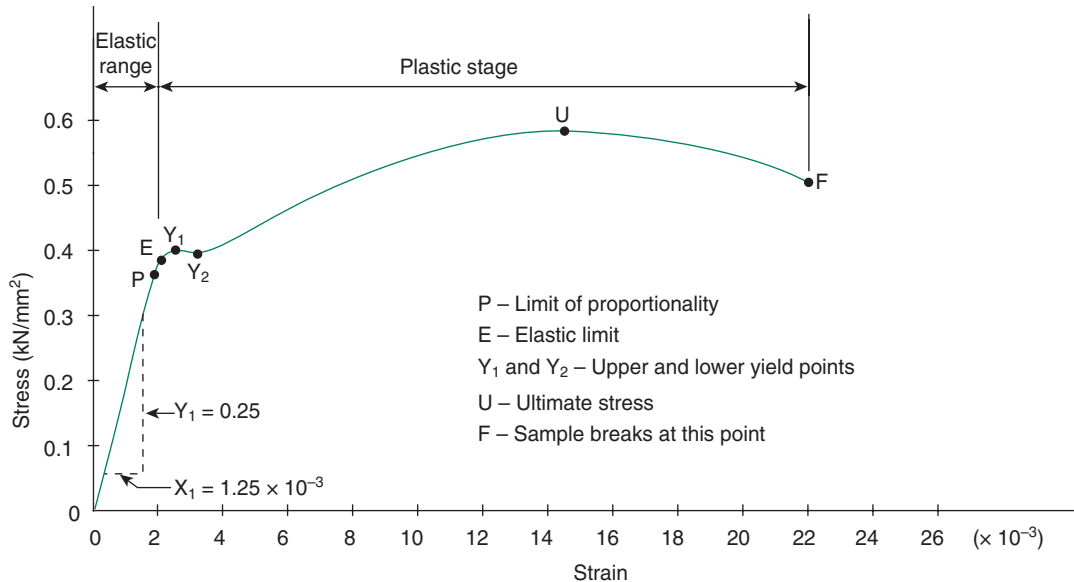


Figure 10.12 Stress-strain relationship for mild steel.

where this behaviour ceases is called the **limit of proportionality (P)**. The material obeys Hooke's law, i.e. behaves as an elastic material. The ratio of stress and strain within the elastic range is known as **Young's modulus** or **modulus of elasticity** and is denoted as E .

$$\text{Young's modulus, } E = \frac{\text{Stress}}{\text{Strain}}$$

As strain is expressed as a number, the unit of Young's modulus is kN/m^2 or kN/mm^2 .

After the limit of proportionality, the plot is no longer a straight line, but the material still behaves as an elastic material up to a point known as the **elastic limit (E)**. If the loading is removed, the sample will regain its shape and size. The elastic behaviour of the material ceases at the elastic limit and, on further loading, the sample shows plastic behaviour whereby the extension produced is not proportional to the loading. There is another effect produced by the plastic behaviour: the sample does not revert to its original shape and size when the load is removed. This permanent increase in the length of the sample is known as a permanent set.

On further increase in load, a point is reached where extension of the sample starts to increase without increment in the load. This point is known as the **upper yield point (Y₁)**. At this stage the material will flow (deform) even if the load is reduced slightly. After reaching the **lower yield point (Y₂)**, the material regains its resistance to the deforming force. To cause further deformation, the tensile force must be increased. The extension increases at a higher rate due to further increment in the force.

The highest point on the graph corresponds to the maximum load applied and is called the **ultimate stress (U)**. The length of the specimen starts to increase considerably now,

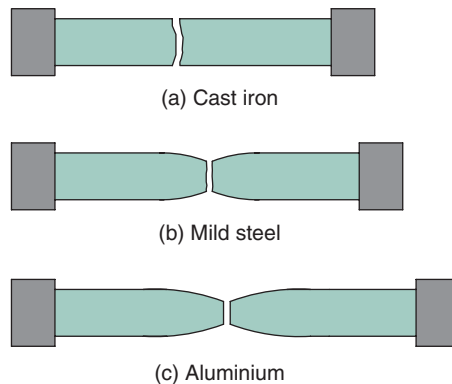


Figure 10.13 Shape of samples after failure.

with a reduction in the diameter of the sample at a random point. The sample eventually snaps (F) and the corresponding stress is known as the **breaking stress**. Figure 10.13 shows the test specimens of mild steel, aluminium and cast iron after failure. Cast iron, being a brittle material, does not show any elongation, but ductile materials like mild steel, aluminium and copper elongate due to the application of tensile force.

Some typical values of Young's modulus are:

Steel: 210 kN/mm^2 ; Aluminium: 70 kN/mm^2 ; Copper: 130 kN/mm^2 ; Timber: 10 kN/mm^2 (variable)

Example 10.6

A metal rod of 10 mm diameter had an initial length of 1.0 m. After a tensile force of 12 kN was applied to the rod, its length increased to 1.002 m. Calculate the Young's modulus of the metal.

Solution:

$$\begin{aligned}\text{Cross-sectional area of the rod} &= \pi r^2, \text{ where } r \text{ is the radius} \\ &= \pi(5)^2 = 78.54 \text{ mm}^2 \text{ (radius} = 10 \div 2 = 5 \text{ mm)}\end{aligned}$$

$$\text{Stress} = \frac{\text{Force}}{\text{Area}} = \frac{12}{78.54} = 0.1528 \text{ kN/mm}^2$$

$$\text{Strain} = \frac{\text{Change in length}}{\text{Original length}} = \frac{1.002 - 1.0}{1.0} = 0.002$$

$$\begin{aligned}\text{Young's modulus (E)} &= \frac{\text{Stress}}{\text{Strain}} \\ &= \frac{0.1528}{0.002} = 76.4 \text{ kN/mm}^2\end{aligned}$$

Example 10.7

Calculate the value of Young's modulus from the stress-strain graph of steel, as shown in Figure 10.12.

Solution:

A right-angled triangle of any size is drawn on the straight-line portion of the graph, as shown in Figure 10.12. The length of the vertical side (Y_1) and horizontal side (X_1) are determined and the following formula is used to calculate Young's modulus (E):

$$\begin{aligned} E &= \frac{\text{Stress}}{\text{Strain}} = \frac{Y_1}{X_1} \\ &= \frac{0.25}{1.25 \times 10^{-3}} \\ &= 200 \text{ kN/mm}^2 \end{aligned}$$

10.6.3 Factor of safety

Figure 10.12 shows that the maximum tensile stress resisted by a sample is known as the ultimate stress (or ultimate tensile strength), and is calculated as:

$$\text{Ultimate stress} = \frac{\text{maximum force carried}}{\text{original cross-sectional area of sample}}$$

In structural design it is important not to stress any material beyond its elastic limit, otherwise permanent deformation will occur. To ensure that the stress in a material does not exceed its elastic limit, the design calculations are based on a maximum allowable working stress:

$$\text{Maximum allowable working stress} = \frac{\text{ultimate tensile strength}}{\text{factor of safety}}$$

Example 10.8

A mild steel tie bar is to withstand a maximum tensile force of 100 kN. The ultimate tensile stress is 540000 kN/m^2 and the factor of safety is to be 3. If Young's modulus of steel is 210 kN/mm^2 , calculate:

- the diameter of the bar
- the extension of a 2.0 m long bar when subjected to a force of 100 kN

Solution:

$$\begin{aligned} \text{a) Maximum allowable working stress} &= \frac{\text{ultimate tensile strength}}{\text{factor of safety}} \\ &= \frac{540000}{3} = 180000 \text{ kN/m}^2 \end{aligned}$$

$$\begin{aligned} \text{Maximum allowable working stress} &= \frac{\text{maximum tensile force}}{\text{cross-sectional area of tie bar}} \\ 180000 &= \frac{100}{\pi r^2} \quad (r = \text{radius}) \end{aligned}$$

$$r^2 = \frac{100}{\pi \times 180000} = 0.000177$$

$$r = 0.0133 \text{ m}$$

$$\text{Diameter} = 2 \times r = 2 \times 0.0133 = 0.0266 \text{ m or } 26.6 \text{ mm}$$

$$\text{b) Strain} = \frac{\text{change in length}}{\text{original length}} = \frac{\Delta l}{2000} = 0.0005 \Delta l \quad (L = 2 \text{ m or } 2000 \text{ mm})$$

$$\text{Stress} = \frac{\text{force}}{\text{area}} = \frac{100}{\pi \times (0.0133)^2} = 179947.93 \text{ kN/m}^2 \text{ or } 0.18 \text{ kN/mm}^2$$

$$E = \frac{\text{Stress}}{\text{Strain}}$$

$$210 = \frac{0.18}{0.0005 \Delta l}$$

$$\Delta l = \frac{0.18}{0.0005 \times 210} = 1.71 \text{ mm}$$

Exercise 10.1

1. A sample of steel is subjected to a compressive force of 4 kN. Calculate the compressive stress in the sample if its cross-section is 10 mm × 10 mm.
2. A 3.0 m long wire is suspended vertically and a load is applied to the bottom of the wire. Find the strain in the wire if it is stretched by 4 mm.
3. A metal rod of 10 mm diameter had an initial length of 2.0 m. After a tensile force of 15 kN was applied to the rod, its length increased to 2.004 m. Calculate the Young's modulus of the metal.
4. In a tensile test on a metal, the values of stress and strain were calculated to be:

Stress (kN/mm ²)	Strain ($\times 10^{-3}$)
0	0
0.05	0.3
0.10	0.6
0.15	0.9
0.24	1.5
0.32	2.0
0.39	2.5

Plot a graph between stress and strain and calculate the value of Young's modulus.

5. A 2.5 m long metal bar measuring 15 mm $\times$ 10 mm in cross-section is stretched by a force of 15 kN. Find the extension produced if Young's modulus of the metal is 150 kN/mm².
6. A metal tie bar is to withstand a maximum tensile force of 100 kN. The ultimate tensile stress is 0.48 kN/mm² and the factor of safety is to be 2.5. If Young's modulus of the metal is 180 kN/mm², calculate:
 - a) the diameter of the bar
 - b) the extension of a 2.0 m long bar when subjected to a force of 100 kN

References/Further reading

1. Durka, F., Al Nageim, H., Morgan, W. and Williams, D. (2002). *Structural Mechanics*. Harlow: Prentice Hall.
2. Hulse, R. and Cain, J. (2003). *Structural Mechanics*. Basingstoke: Palgrave Macmillan.

11

Forces and structures 2

Learning outcomes:

- 1) Calculate bending moment and shear force in a beam subjected to point and/or uniformly distributed loading.
- 2) Draw bending moment and shear force diagrams.
- 3) Apply the law of triangle of forces to solve problems graphically.
- 4) Determine, graphically, the nature and magnitude of forces in the members of a roof truss.

11.1 Moment of a force

It has already been discussed in Section 10.3 that a force, or a system of forces, causes deflection in beams and other elements of a building. It is also obvious that the amount of deflection depends on the magnitude of the force, i.e. a small force produces a small deflection as compared to a large force that produces larger deflection. The deflection of a beam is due to the turning or rotational effect of a force. This turning effect is known as the **moment of a force** or **bending moment**, and depends on:

- a) the magnitude of force/forces;
- b) the perpendicular distance between the force and point about which the rotation or turning takes place.

The above factors can be combined to determine the moment of a force:

Moment of a force = force $\times$ distance

Figure 11.1 shows two cantilevers, each acted upon by force F . The force tends to cause the rotation of the cantilevers about their supports.

The moment of force F , about point $x = F \times l$

where l is the perpendicular distance between the force and point x

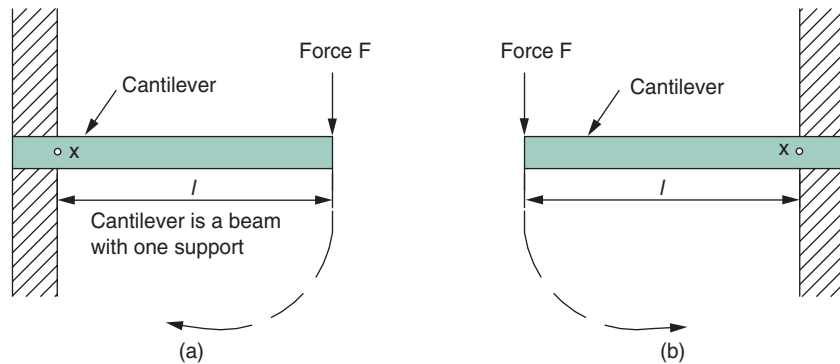


Figure 11.1

Unit: The units of force are newton (N) and kilonewton (kN); the units of distance are millimetres (mm) and metres (m). As the moment of a force is the product of the force and the distance, its unit could be one of the following:

newton metres (Nm); newton millimetres (Nmm); kilonewton metres (kNm).

In Figure 11.1a, the effect of the force is to cause clockwise rotation of the cantilever as shown by the arrow. The moment in this case is known as clockwise moment. The cantilever shown in Figure 11.1b will be subjected to anti-clockwise rotation due to the action of force F , and hence the moment is anti-clockwise.

11.1.1 Sign convention

In the calculation of moments it is important to use sign convention to avoid any confusion. Therefore:

Clockwise (CW) moments are considered to be positive.

Anti-clockwise (ACW) moments are considered to be negative.

Example 11.1

Calculate the moment about point x for the cantilever shown in Figure 11.2.

Solution:

Moment about a point = force $\times$ perpendicular distance

There is only one force (5 kN) acting at a distance of 3 m from point x . Since it tends to cause anti-clockwise rotation of the beam (Figure 11.3), the moment is anti-clockwise.

$$\begin{aligned}\text{Moment at } x &= 5 \text{ kN} \times 3 \text{ m} \\ &= 15 \text{ kNm (anti-clockwise)}\end{aligned}$$

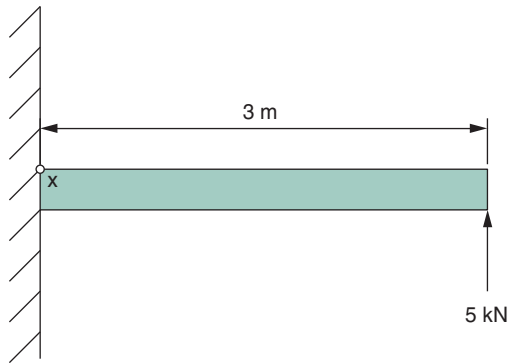


Figure 11.2

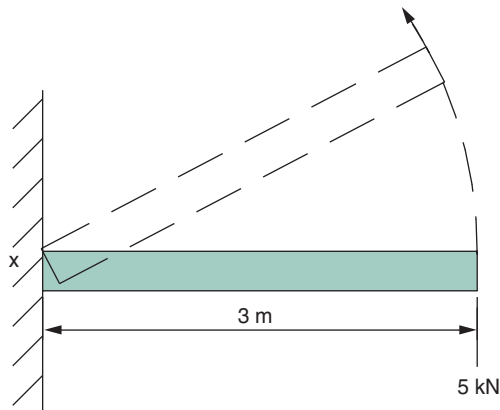


Figure 11.3 Rotational tendency due to 5 kN force.

Example 11.2

Calculate the clockwise and anti-clockwise moments about points A and B, for the beam shown in Figure 11.4.

Solution:

Three forces are acting on the beam. As moment about a point = force $\times$ distance, we need to determine the moments of all the forces about points B and A.

Moments about point B

- 1) The 8 N force is acting upwards and will rotate the beam in a clockwise direction if other forces were not present (Figure 11.5). This produces a clockwise moment.

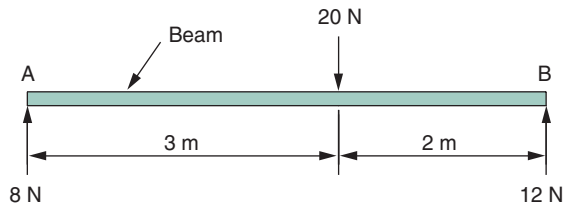


Figure 11.4

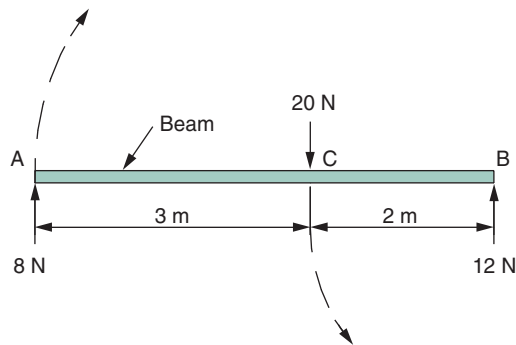


Figure 11.5

Clockwise moment about point B, due to the 8 N force
 = force $\times$ distance between the 8 N force and point B
 = $8 \text{ N} \times 5 \text{ m}$
 = 40 Nm

- 2) The 20 N force is acting downwards and will rotate the beam in an anti-clockwise direction if other forces were not present (Figure 11.5). This produces an anti-clockwise moment.

Anti-clockwise moment about point B, due to the 20 N force
 = force $\times$ distance between the 20 N force and point B
 = $20 \text{ N} \times 2 \text{ m}$
 = 40 Nm

- 3) The 12 N force acts at point B, therefore the distance between the force and point B is zero.

Moment about point B, due to the 12 N force
 = force $\times$ distance between the 12 N force and point B
 = $12 \text{ N} \times 0$
 = 0 Nm

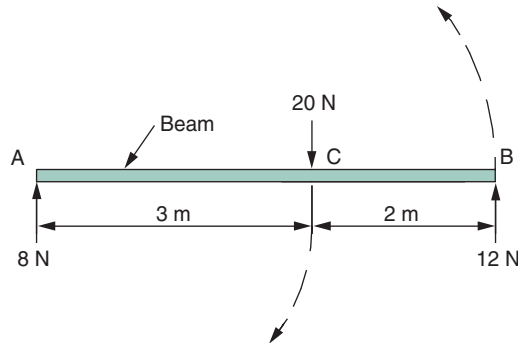


Figure 11.6

Moments about point A

- 1) The 12 N force is acting upwards and will rotate the beam in an anti-clockwise direction if other forces were not present (Figure 11.6). This produces an anti-clockwise moment.

Anti-clockwise moment about point A, due to the 12 N force
 = force $\times$ distance between the 12 N force and point A
 = $12 \text{ N} \times 5 \text{ m}$
 = 60 Nm

- 2) The 20 N force is acting downwards and will rotate the beam in a clockwise direction if other forces were not present (Figure 11.6). This produces a clockwise moment.

Clockwise moment about point A, due to the 20 N force
 = force $\times$ distance between the 20 N force and point A
 = $20 \text{ N} \times 3 \text{ m}$
 = 60 Nm

- 3) The 8 N force acts at point A, therefore the distance between the force and point A is zero.

Moment about point A, due to the 8 N force
 = force $\times$ distance between the 8 N force and point A
 = $8 \text{ N} \times 0$
 = 0 Nm

11.2 Laws of equilibrium

Building elements like beams, slabs, walls and columns are acted upon by a number of external forces. An element is in equilibrium if it is not disturbed from its state of rest by the external forces. In other words, for a building element (or a body) to be in equilibrium, the resultant effect of the forces must be zero. There are three conditions for maintaining the equilibrium of a body:

- a) the sum of vertical forces (V) is zero, i.e. $\Sigma V = 0$

This can also be written as:

The sum of downward acting forces = the sum of upward acting forces.

- b) the sum of horizontal forces (H) is zero, i.e. $\Sigma H = 0$

- c) the sum of moments (M) about any point is zero, i.e. $\Sigma M = 0$

This can also be stated as:

The sum of clockwise moments = the sum of anti-clockwise moments.

These conditions will be used in the next section to determine the beam reactions and bending moments.

11.3 Analysis of beams

In this section we will focus on the analysis of simply supported beams, and cantilevers.

11.3.1 Beam reactions

Newton's third law of motion states that:

To every action there is an equal and opposite reaction.

When a concrete block is placed on the ground, its weight (the action) acts downwards. The ground, due to its strength, offers an upward-acting reaction to counteract the weight of the block. The block will be stable if the reaction equals the weight of the block. If the ground is very loose, the block may sink into it, in which case the action is greater than the reaction.

In the case of a beam, the action is due to the dead, imposed and other loads acting on it. Since beams are supported on walls or columns, the reactions are provided by these supports. The strength of the supports to provide appropriate reaction is of paramount importance. The calculation of beam reactions is necessary for preparing their structural analysis and design, and they are used to check that the stress in the support material is within the permissible limit.

If the loading is symmetrical, then the reactions must be equal. Figure 11.7a shows a simply supported beam, resting on two walls, which is acted upon by a 10 kN force at its centre. For structural calculations, line diagrams of beams are used; Figure 11.7b shows the line diagram of the beam shown in Figure 11.7a. As the beam is resting on walls, the reactions offered by the walls (R_1 and R_2) must be equal to 10 kN (the action) for the stability of the beam. Or, in other words, the downward acting force must be equal to the sum of the upward-acting forces.

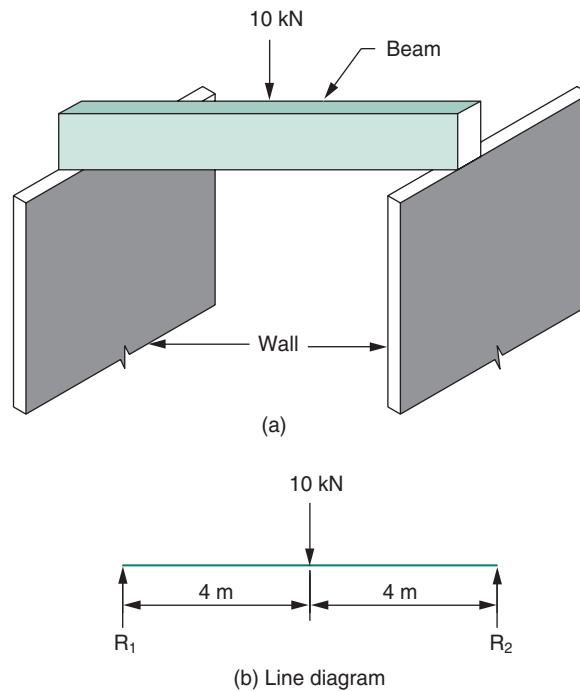


Figure 11.7 Simply supported beam.

$$10 \text{ kN} = R_1 + R_2$$

As the 10 kN force acts at the centre of the beam, R_1 must be equal to R_2 .

$$\text{or, } R_1 = R_2 = 5 \text{ kN}$$

Similarly, we can also find reactions if more than one force is acting, as long as the forces are equal and their action points are symmetrical. Figure 11.8 shows a beam symmetrically loaded by two forces, 3 kN each.

$$3 \text{ kN} + 3 \text{ kN} = R_1 + R_2$$

$$\text{or, } 6 \text{ kN} = R_1 + R_2$$

$$\text{also, } R_1 = R_2$$

$$\text{therefore, } R_1 = R_2 = 3 \text{ kN}$$

The beams shown in Figure 11.9 are not symmetrically loaded. In these cases the magnitude of the reactions will not be the same and cannot be calculated as easily as in previous cases. However, moments of the forces can be taken about the supports to determine the reactions as explained in Example 11.3.

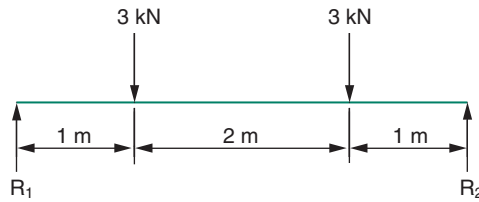


Figure 11.8

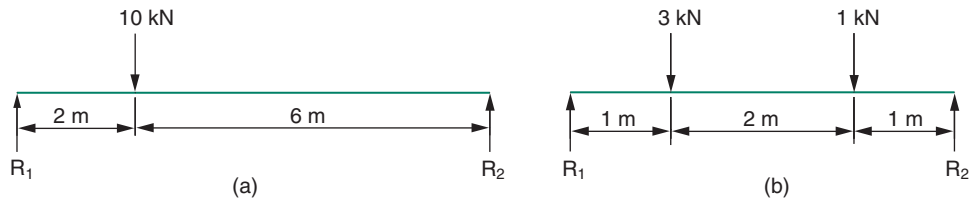


Figure 11.9

Example 11.3

Figure 11.10 shows the line diagram of a beam and the forces acting on it. Calculate reactions R_1 and R_2 .

Solution:

As the loading is not symmetrical, R_1 and R_2 will be unequal, but can be determined by taking moments of the forces about B and/or A.

Calculation of reaction R_1

The forces tend to rotate the beam, about point B, in the directions illustrated in Figure 11.11. Reaction R_1 can be calculated by taking moments of all forces about point B and either equating clockwise moments to anti-clockwise moments or taking the algebraic sum and equating it to zero. We'll use the former approach.

R_1 will cause a clockwise moment, and both 3 kN and 4 kN forces will cause anti-clockwise moments.

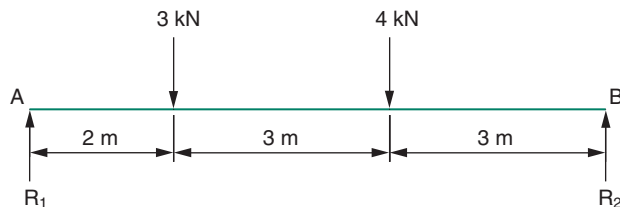


Figure 11.10

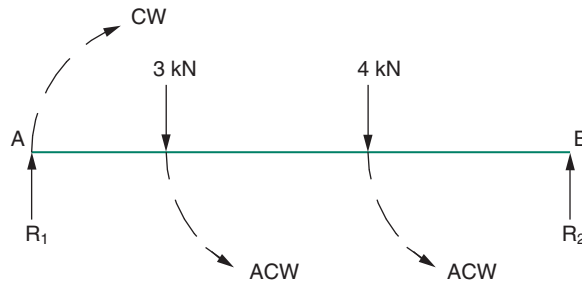


Figure 11.11 Rotational tendency of the forces about B.

$$\begin{aligned}\text{Clockwise moment} &= R_1 \times \text{distance between } R_1 \text{ and point B} \\ &= R_1 \times 8 \text{ m}\end{aligned}$$

$$\begin{aligned}\text{Anti-clockwise moment due to the 3 kN force} \\ &= 3 \text{ kN} \times \text{distance between 3 kN force and point B} \\ &= 3 \text{ kN} \times 6 \text{ m} = 18 \text{ kNm}\end{aligned}$$

$$\begin{aligned}\text{Anti-clockwise moment due to the 4 kN force} \\ &= 4 \text{ kN} \times \text{distance between 4 kN force and point B} \\ &= 4 \text{ kN} \times 3 \text{ m} = 12 \text{ kNm}\end{aligned}$$

$$\text{Total anti-clockwise moment} = 18 + 12 = 30 \text{ kNm}$$

Moment due to R_2 is zero as it acts at point B (see Example 11.2 for explanation).

Clockwise moments must be equal to the anti-clockwise moments to maintain the stability of the beam at point B:

$$\begin{aligned}R_1 \times 8 \text{ m} &= 30 \text{ kNm} \\ \text{or, } R_1 &= \frac{30 \text{ kNm}}{8 \text{ m}} = 3.75 \text{ kN}\end{aligned}$$

Calculation of reaction R_2

Figure 11.12 shows the directions in which the forces tend to rotate the beam about point A. Reaction R_2 will produce an anti-clockwise moment whilst the 3 kN force and 4 kN force produce clockwise moments.

Take moments of all forces about point A:

$$\begin{aligned}\text{Anti-clockwise moment due to reaction } R_2 &= R_2 \times \text{distance between } R_2 \text{ and point A} \\ &= R \times 8 \text{ m}\end{aligned}$$

$$\begin{aligned}\text{Clockwise moment due to the 4 kN force} \\ &= 4 \text{ kN} \times \text{distance between 4 kN force and point A} \\ &= 4 \text{ kN} \times 5 \text{ m} = 20 \text{ kNm}\end{aligned}$$

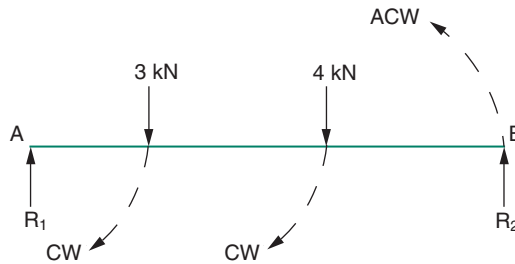


Figure 11.12 Rotational tendency of the forces about A.

Clockwise moment due to the 3 kN force

$$= 3 \text{ kN} \times \text{distance between 3 kN force and point A}$$

$$= 3 \text{ kN} \times 2 \text{ m} = 6 \text{ kNm}$$

$$\text{Total clockwise moment} = 20 + 6 = 26 \text{ kNm}$$

Moment due to R_1 is zero as it acts at point A (see Example 11.2 for explanation).

Clockwise moments must be equal to the anti-clockwise moments to maintain the stability of the beam at point A:

$$R_2 \times 8 \text{ m} = 26 \text{ kNm}$$

$$\text{or, } R_2 = \frac{26 \text{ kNm}}{8 \text{ m}} = 3.25 \text{ kN}$$

Check: The sum of reactions R_1 and R_2 must be equal to the total loading of 7 kN

$$R_1 + R_2 = 3.75 + 3.25 = 7 \text{ kN}$$

Example 11.4

Calculate reactions R_1 and R_2 for the beam shown in Figure 11.13. A uniformly distributed load (u.d.l.) of 2 kN/m acts on the beam.

Solution:

In this example the loading is symmetrical which means that the reactions will be equal. The total force (or load) acting on the beam is $2 \text{ kN/m} \times 6 \text{ m} = 12 \text{ kN}$

$$\text{therefore, } R_1 = R_2 = \frac{12}{2} = 6 \text{ kN}$$

In practice, loading is usually non-symmetrical, therefore, the method of moments is used to determine the reactions. In order to determine the reactions and to make it easier for calculating the moments, the u.d.l. is converted into a point load.

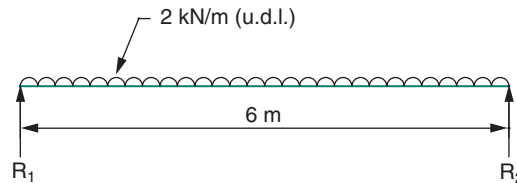


Figure 11.13

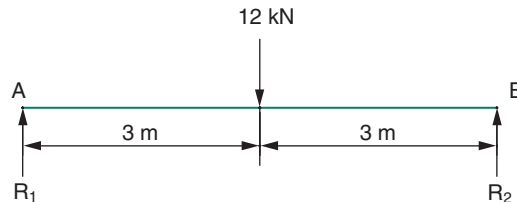


Figure 11.14 U.d.l. converted into point load.

Total load on the beam = 12 kN

The total load (point load) is assumed to act at the centre of the distance over which the u.d.l. acts, as shown in Figure 11.14.

Take moments about B:

Clockwise moment = $R_1 \times 6 \text{ m}$

Anti-clockwise moment = $12 \text{ kN} \times 3 \text{ m} = 36 \text{ kNm}$

For equilibrium, clockwise moment = anti-clockwise moment

$R_1 \times 6 \text{ m} = 36 \text{ kNm}$

or, $R_1 = \frac{36 \text{ kNm}}{6 \text{ m}} = 6 \text{ kN}$

Take moments about A:

Anti-clockwise moment = $R_2 \times 6 \text{ m}$

Clockwise moment = $12 \text{ kN} \times 3 \text{ m} = 36 \text{ kNm}$

For equilibrium, anti-clockwise moment = clockwise moment

$R_2 \times 6 \text{ m} = 36 \text{ kNm}$

or, $R_2 = \frac{36 \text{ kNm}}{6 \text{ m}} = 6 \text{ kN}$

11.3.2 Shear force (S.F.)

As explained in Chapter 10, a **shear force** causes or tends to cause the horizontal or vertical movement of a part of the material against the rest. The values of shear force and bending moment, due to a set of loading, are used for designing beams, slabs and other

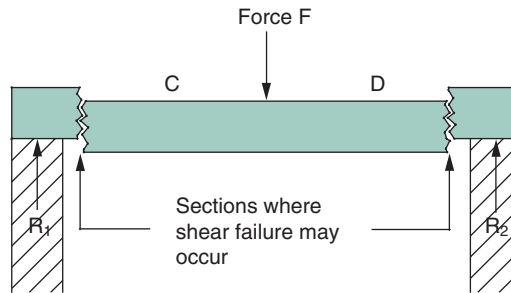


Figure 11.15 Beam failure due to shear force.

building elements. The results of shear force and bending moment are shown in the form of a shear force diagram and a bending moment diagram respectively.

The shear force at any point on a beam is defined as the algebraic sum of all the forces acting on one (either) side. Figure 11.15 shows the sections of a typical beam where failure due to shear force may occur.

$$\begin{aligned}\text{Shear force at point C} &= \text{algebraic sum of all forces to the left of point C} \\ &= R_1\end{aligned}$$

$$\begin{aligned}\text{Shear force at point D} &= \text{algebraic sum of all forces to the left of point D} \\ &= R_1 - F\end{aligned}$$

Shear force at point D may also be calculated by taking the algebraic sum of all the forces that act to the right of point D. There is only one force to the right of point D, i.e. R_2 . Therefore, shear force at D is also equal to R_2 .

Sign convention:

The use of sign convention is important in drawing the shear force diagram without any complexity and confusion. Shear force is considered positive if the forces act 'up on the left and down on the right'. This can also be represented as $\uparrow\downarrow$.

Shear force is negative if the forces act down on the left and up on the right ($\downarrow\uparrow$).

For producing a shear force diagram, a base line is drawn first, and lines are drawn up for upward acting force, and down for downward acting force.

Example 11.5

Draw the shear force diagram for a 6 m long beam carrying a point load of 10 kN at its centre.

Solution:

The beam is shown in Figure 11.16a. Before producing the shear force diagram, we need to calculate reactions R_1 and R_2 . The process has already been explained in Section 11.3.1. Here, $R_1 = R_2 = 5$ kN.

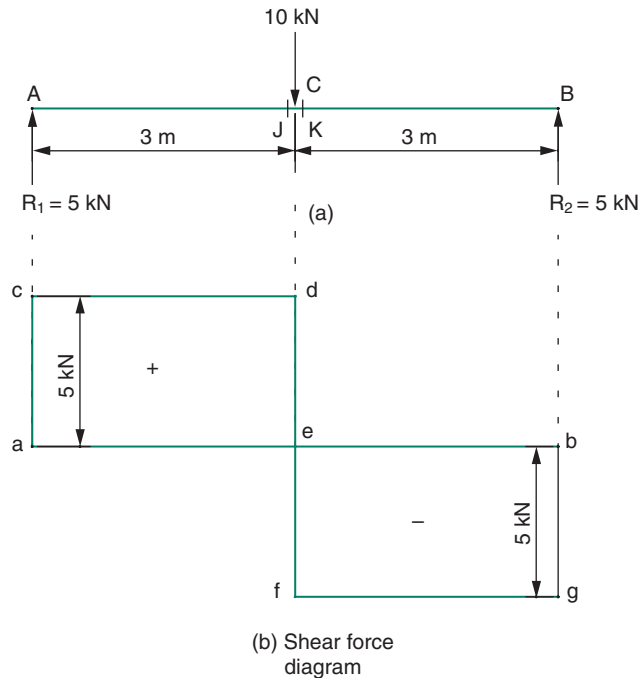
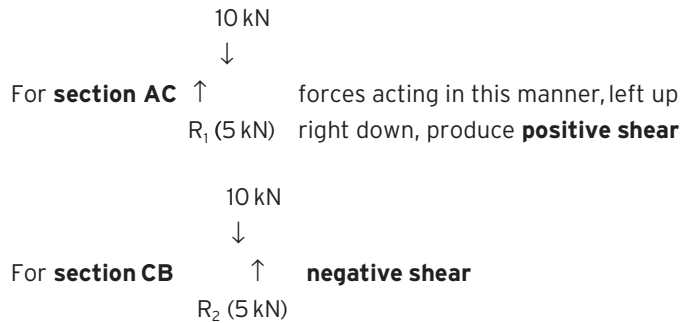


Figure 11.16

To draw the S.F. diagram, draw up for upward acting forces and down for downward acting forces. The process is explained below:

- 1) Select a suitable scale, e.g. $1 \text{ kN} = 4 \text{ mm}$ (see Figure 11.16b).
- 2) Draw base line ab . As 5 kN force (R_1) acts upwards at A , draw line $ac = 20 \text{ mm}$ ($5 \text{ kN} = 20 \text{ mm}$) vertically up from the base line.
- 3) For determining the shear force at point J , which is just to the left of the 10 kN force, take algebraic sum of all forces acting to the left of point J . There is only one force, i.e. reaction R_1 , that acts to the left of point J . Therefore, shear force at J is equal to reaction R_1 , i.e. 5 kN .
- 4) From point c , draw a horizontal line to point d . This shows that the shear force from A to J is the same.
- 5) The 10 kN force acts downwards at point C . From point d , draw vertical line df to represent the downward acting 10 kN force. Measure $df = 40 \text{ mm}$ ($1 \text{ kN} = 4 \text{ mm}$, therefore $10 \text{ kN} = 40 \text{ mm}$).
- 6) At point K , which is just to the right of point C , the shear force is the algebraic sum of forces acting to its left, i.e. $5 \text{ kN} - 10 \text{ kN} = -5 \text{ kN}$. As there is no force between points K and B , the shear force remains -5 kN . Draw horizontal line fg to represent this.
- 7) At point B on the beam, reaction R_2 (5 kN) acts upwards. From point g , draw a vertical line up measuring 20 mm ($5 \text{ kN} = 20 \text{ mm}$) to represent the upward acting reaction R_2 . If this line meets the base line at point b , then the shear force diagram is accurate.

- 8) Figure 11.16b shows the positive and negative portions of the shear force diagram. These have been decided after considering the direction of the forces acting on beam AB.



Example 11.6

Draw the shear force diagram for the beam shown in Figure 11.17a.

Solution:

- 1) The beam is shown in Figure 11.17a. Calculate reaction R_1 and R_2 as explained in Example 11.3.
 $R_1 = 3.75 \text{ kN}$ and $R_2 = 3.25 \text{ kN}$.
- 2) Use a convenient scale to draw the shear force diagram, say $1 \text{ kN} = 6.3 \text{ mm}$.
- 3) Draw base line ab, as shown in Figure 11.17b. As reaction R_1 acts upwards, draw line ac = 23.6 mm ($3.75 \text{ kN} \times 6.3 \text{ mm} = 23.6 \text{ mm}$). 23.6 mm represents 3.75 kN, the shear force at A.
- 4) To determine the shear force at any point between A and D, consider point C which is just to the left of point D and take the algebraic sum of all the forces acting between A and C. There is only one force, i.e. 3.75 kN, that is the shear force between A and C.
- 5) Draw line cd horizontally to show the shear force in this section is 3.75 kN.
- 6) At point D, there is a downward acting force of 3 kN. To represent this force, draw down from point d vertical line de measuring 18.9 mm ($3 \text{ kN} \times 6.3 \text{ mm} = 18.9 \text{ mm}$).
- 7) Shear force at point E, which is just to the right of the 3 kN force, is the algebraic sum of forces acting to the left of E, i.e. $3.75 - 3.0 = 0.75 \text{ kN}$.
- 8) Shear force at point F = $3.75 - 3.0 = 0.75 \text{ kN}$, which is equal to the S.F. at E. Draw a horizontal line from point e to g showing that the S.F. between E and F is 0.75 kN.
- 9) 4 kN force acts downwards at G; draw vertically down from g, line gj = 25.2 mm ($4 \text{ kN} \times 6.3 \text{ mm} = 25.2 \text{ mm}$).
- 10) Shear force at H, which is immediately to the right of point G = $3.75 - 3 - 4 = -3.25 \text{ kN}$. hj represents a shear force of -3.25 kN .

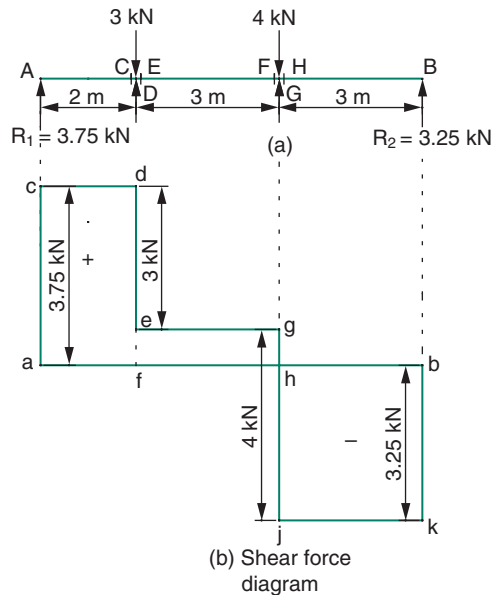


Figure 11.17

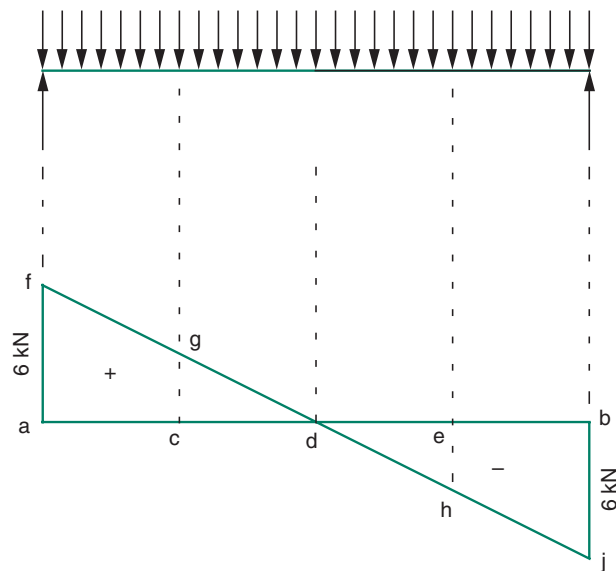
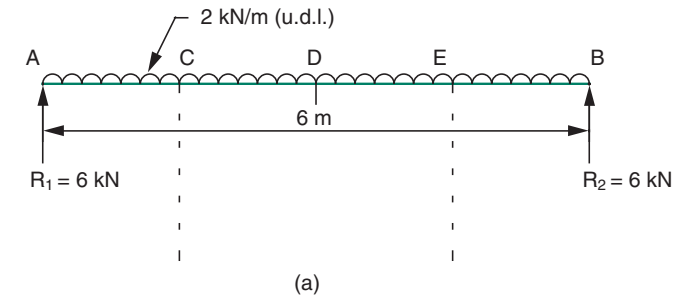
- 11) Shear force at a point immediately to the left of point B $= 3.75 - 3 - 4 = -3.25 \text{ kN}$. This is equal to the S.F. at H, therefore draw a horizontal line from j to k representing a shear force of -3.25 kN .
- 12) Reaction R_2 (3.25 kN) acts upwards at B, therefore draw a 20.5 mm ($3.25 \text{ kN} \times 6.3 \text{ mm} = 20.5 \text{ mm}$) long vertical line from k. If the shear force diagram is accurate, the other end of this line will coincide with point b.
- 13) The positive and the negative portions of the diagram are decided on the same basis as that used in Example 11.5.

Example 11.7

Draw the shear force diagram for a 6 m long beam carrying a u.d.l. of 2 kN/m .

Solution:

- 1) The beam with its loading is shown in Figure 11.18a. Reaction $R_1 = R_2 = 6 \text{ kN}$.
- 2) Use a convenient scale, say $1 \text{ kN} = 3 \text{ mm}$.
- 3) As a u.d.l. is analogous to closely spaced point loads (Figure 11.18b), it is necessary to convert it to a point load for calculating the shear force at a point.
- 4) Draw horizontal line ab as the base line (Figure 11.18c). As reaction R_1 acts upwards, draw vertical line af up from point a to represent it. Measure $af = 18 \text{ mm}$ to represent R_1 ($6 \text{ kN} \times 3 \text{ mm} = 18 \text{ mm}$) and hence the shear force at A.

**Figure 11.18**

- 5) S.F. at point C = net vertical force to the left of C ($AC = CD = DE = EB = 1.5 \text{ m}$)
 $= R_1 - \text{downward acting force between A and C}$
 $= 6 \text{ kN} - (2 \text{ kN/m} \times 1.5 \text{ m})$
 $= 6 \text{ kN} - 3 \text{ kN} = 3 \text{ kN}$
- 6) Mark point g vertically below C to represent the S.F. at C. Distance gc should be 9 mm ($3 \text{ kN} = 9 \text{ mm}$ on the shear force diagram).
- 7) Shear force at D = net vertical force to the left of point D
 $= R_1 - \text{downward acting force between A and D}$
 $= 6 \text{ kN} - (2 \text{ kN/m} \times 3 \text{ m})$
 $= 6 \text{ kN} - 6 \text{ kN} = 0 \text{ kN}$

Mark point d on the base line, vertically below D.
- 8) Shear force at E = net vertical force to the left of point E
 $= R_1 - \text{downward acting force between A and E}$
 $= 6 \text{ kN} - (2 \text{ kN/m} \times 4.5 \text{ m})$
 $= 6 \text{ kN} - 9 \text{ kN} = -3 \text{ kN}$



11) The shear force in the left half of the beam is positive, and, in the right half, negative. This is illustrated in Figures 11.18c and 11.19.

Vertical loading causes, or tends to cause, bending in beams. The amount of bending depends on the magnitude of loading, span and size of the beam. The bending moment is a measure of the amount of bending at a point on the beam. It is calculated by taking the algebraic sum of moments about the point under consideration. Depending on the type of the beam, the forces can cause either sagging or hogging of the beam. Figure 11.20 shows bending in a simply supported beam, and a cantilever. In producing the B.M. diagrams:

- The structural design of a beam is based on the maximum bending moment, which can be determined from the B.M. diagram. The purpose of the next three examples is to show the calculation of bending moment at various points and produce the B.M. diagrams.

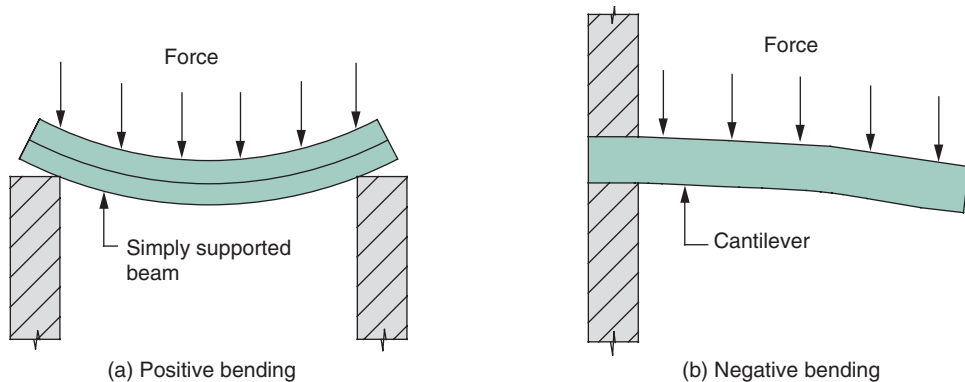


Figure 11.20

Example 11.8

Draw bending moment diagram for the beam shown in Figure 11.21a.

Solution:

Before the B.M. diagram can be drawn, we need to calculate the bending moment at various points, e.g. A, C and B. To determine B.M. at any point, take moments of all forces to its left and find their algebraic sum.

- 1) Determine reactions R_1 and R_2 , as explained earlier. $R_1 = R_2 = 5 \text{ kN}$.
- 2) **B.M. at A:** To calculate the bending moment at point A, we need to take moments of all forces to its left. As there is no force to the left of point A, the B.M. at A is zero. Although reaction R_1 acts at A, the moment produced is zero:

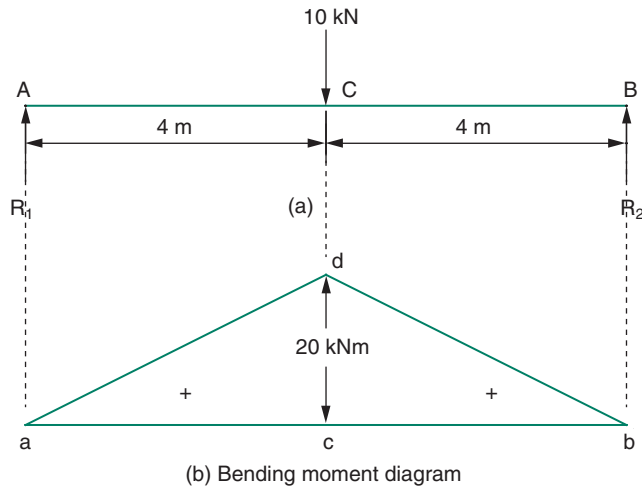
$$\begin{aligned}\text{Moment about A (M}_A\text{) due to } R_1 &= \text{Force } R_1 \times \text{distance between } R_1 \text{ and A} \\ &= 5 \text{ kN} \times 0 = 0 \text{ kNm}\end{aligned}$$

- 3) **B.M. at C:** Consider all forces to the left of point C and take the algebraic sum of their moments about C. There is only R_1 that acts on the left of C, and it produces a clockwise moment (positive):

$$\begin{aligned}\text{Moment about C (M}_C\text{) due to } R_1 &= \text{Force } R_1 \times \text{perpendicular distance between} \\ &\quad R_1 \text{ and point C} \\ &= 5 \text{ kN} \times 4 \text{ m} = 20 \text{ kNm}\end{aligned}$$

- 4) **B.M. at B:** Consider all forces to the left of point B. R_1 and 10 kN act to the left of B; they produce clockwise and anti-clockwise moments respectively.

$$\begin{aligned}\text{Clockwise moment about B} &= R_1 \times \text{perpendicular distance between } R_1 \text{ and} \\ &\quad \text{point B} \\ &= 5 \text{ kN} \times 8 \text{ m} = 40 \text{ kNm (CW moment is positive)}\end{aligned}$$

**Figure 11.21**

Anti-clockwise moment about B = $10 \text{ kN} \times \text{perpendicular distance between } 10 \text{ kN force and B}$
 $= 10 \text{ kN} \times 4 \text{ m}$
 $= 40 \text{ kNm}$ (ACW moment is considered negative)

R_2 will produce zero moment about B as its distance from B is zero.

B.M. at B (M_B) = algebraic sum of moments about B
 $= \text{CW moment} - \text{ACW moment}$
 $= 40 - 40 = 0 \text{ kNm}.$

- 5) The B.M. diagram, like the S.F. diagram, is drawn below the line diagram of the beam.

Select a suitable scale, say $1 \text{ kNm} = 1 \text{ mm}$

Bending moment at C = 20 kNm ; $20 \text{ kNm} = 20 \text{ mm}$

Draw base line acb and mark point d so that $cd = 20 \text{ mm}$. Complete the B.M. diagram as shown in Figure 11.21b. Positive bending moment has been shown above the base line.

Example 11.9

Draw bending moment diagram for the beam shown in Figure 11.22a.

Solution:

- 1) Calculate reactions R_1 and R_2 (refer to Example 11.3)

$R_1 = 3.75 \text{ kN}$ and $R_2 = 3.25 \text{ kN}$

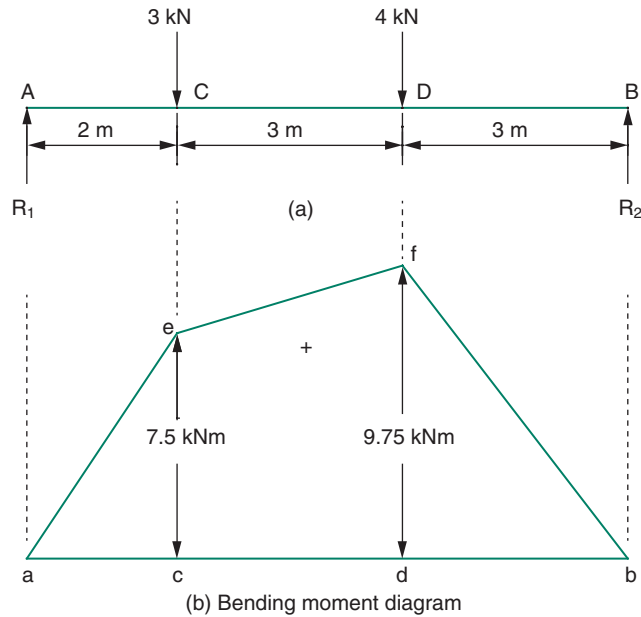


Figure 11.22

- 2) To determine the bending moment at point A, take moments of forces that act to its left. As there are no such forces, B.M. at A is zero.
- 3) **B.M. at C:** Take moments of all forces that act to the left of point C, about point C, and find their algebraic sum. There is only one force (R_1) that will produce a clockwise moment.

Clockwise moment due to $R_1 = R_1 \times \text{perpendicular distance between } R_1 \text{ and point C}$
 $= 3.75 \text{ kN} \times 2 \text{ m} = 7.5 \text{ kNm}$

Moment due to the 3 kN force is zero as the distance between the force and point C is zero.

Therefore, B.M. at C (M_C) = 7.5 kNm (positive)

- 4) **B.M. at D:** Find the algebraic sum of moments about point D, due to the forces that act to its left. R_1 and 3 kN act to the left of D and produce clockwise and anti-clockwise moments respectively:

CW moment due to $R_1 = R_1 \times \text{perpendicular distance between } R_1 \text{ and point D}$
 $= 3.75 \text{ kN} \times 5 \text{ m} = 18.75 \text{ kNm}$

ACW moment due to 3 kN = $3 \text{ kN} \times \text{perpendicular distance between 3 kN and point D}$
 $= 3 \text{ kN} \times 3 \text{ m} = 9 \text{ kNm}$

Moment due to the 4 kN force that acts at D is zero as the distance between the force and point D is zero.

Therefore, B.M. at D (M_D) = algebraic sum of all moments about D
 = CW moment – ACW moment
 = $18.75 - 9.0 = 9.75 \text{ kNm}$

- 5) **B.M. at B:** Take moments about B, of all forces that act to the left of point B:

CW moment due to $R_1 = R_1 \times \text{perpendicular distance between } R_1 \text{ and point B}$
 = $3.75 \text{ kN} \times 8 \text{ m} = 30 \text{ kNm}$

ACW moment due to $3 \text{ kN} = 3 \text{ kN} \times \text{perpendicular distance between } 3 \text{ kN}$
 and point B
 = $3 \text{ kN} \times 6 \text{ m} = 18 \text{ kNm}$

ACW moment due to $4 \text{ kN} = 4 \text{ kN} \times \text{distance DB}$
 = $4 \text{ kN} \times 3 \text{ m} = 12 \text{ kNm}$

Therefore, B.M. at B (M_B) = CW moment – ACW moments
 = $30 - 18 - 12 = 0 \text{ kNm}$

- 6) Select a suitable scale, say $1 \text{ kNm} = 4 \text{ mm}$

$7.5 \text{ kNm} = 7.5 \times 4 = 30 \text{ mm}$

$9.75 \text{ kNm} = 9.75 \times 4 = 39 \text{ mm}$

Draw base line acdb. Mark points e and f so that:

ce = 30 mm (B.M. at C = 7.5 kNm)

df = 39 mm (B.M. at D = 9.75 kNm)

Complete the diagram as shown in Figure 11.22b.

Example 11.10

Draw the bending moment diagram for a 6 m long beam carrying a u.d.l. of 2 kN/m .

Solution:

The beam is shown in Figure 11.23. Distances $AC = CD = DE = EB$.

- 1) Calculate reactions R_1 and R_2 as explained in Example 11.4.

$$R_1 = R_2 = 6 \text{ kN}$$

- 2) **B.M. at A:** As explained in Examples 11.8 and 11.9, the bending moment at A is zero as there is no force acting to the left of point A.

- 3) **B.M. at C:** Take moments about point C, of all forces acting to its left, and find their algebraic sum. Before the moments can be taken, the u.d.l. needs to be converted to a point load. The u.d.l. acting to the left of C is equivalent to a point load of:

$$2 \text{ kN/m} \times 1.5 \text{ m} = 3 \text{ kN}$$

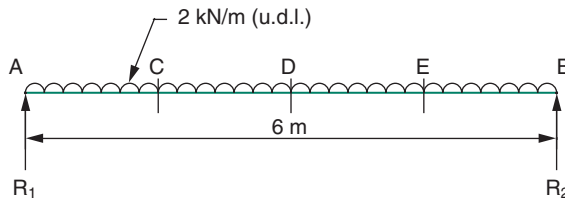


Figure 11.23

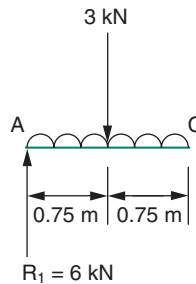


Figure 11.24 Bending moment at C.

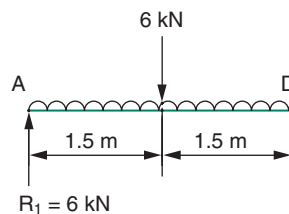


Figure 11.25 Bending moment at D.

The force of 3 kN is supposed to act at the mid-point of AC, as shown in Figure 11.24.

$$\begin{aligned}\text{CW moment about C} &= R_1 \times \text{distance AC} \\ &= 6 \text{ kN} \times 1.5 \text{ m} = 9.0 \text{ kNm}\end{aligned}$$

$$\begin{aligned}\text{ACW moment about C} &= 3 \text{ kN} \times \text{perpendicular distance between 3 kN force} \\ &\quad \text{and point C} \\ &= 3 \text{ kN} \times 0.75 \text{ m} = 2.25 \text{ kNm}\end{aligned}$$

$$\begin{aligned}\text{B.M. at C} &= \text{algebraic sum of CW and ACW moments} \\ &= 9.0 - 2.25 = 6.75 \text{ kNm}\end{aligned}$$

- 4) **B.M. at D:** Repeat Step 3 to determine the bending moment at point D. The u.d.l. acting to the left of D (between A and D) is equivalent to a point load of 6 kN ($2 \text{ kN/m} \times 3 \text{ m} = 6 \text{ kN}$). This is also assumed to act at the mid-point of AD (Figure 11.25).

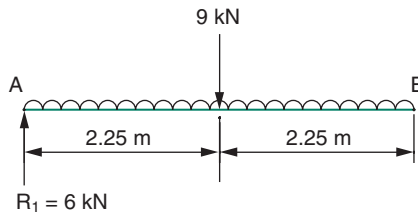


Figure 11.26 Bending moment at E.

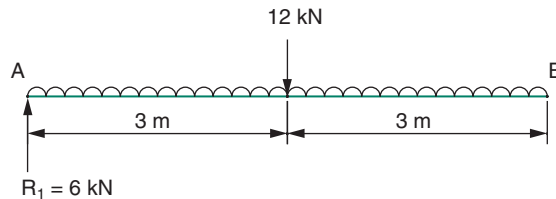


Figure 11.27 Bending moment at B.

$$\begin{aligned}\text{CW moment about D} &= R_1 \times \text{distance AD} \\ &= 6 \text{ kN} \times 3 \text{ m} = 18 \text{ kNm}\end{aligned}$$

$$\begin{aligned}\text{ACW moment about D} &= 6 \text{ kN} \times \text{perpendicular distance between 6 kN force} \\ &\quad \text{and point D} \\ &= 6 \text{ kN} \times 1.5 \text{ m} = 9.0 \text{ kNm}\end{aligned}$$

$$\begin{aligned}\text{B.M. at D} &= \text{algebraic sum of CW and ACW moments} \\ &= 18 - 9.0 = 9.0 \text{ kNm}\end{aligned}$$

- 5) **B.M. at E:** Repeat the procedure already used in Steps 3 and 4. u.d.l. to the left of E (between A and E) is equivalent to a point load of 9 kN ($2 \text{ kN/m} \times 4.5 \text{ m} = 9 \text{ kN}$). This acts at the mid-point of AE (Figure 11.26).

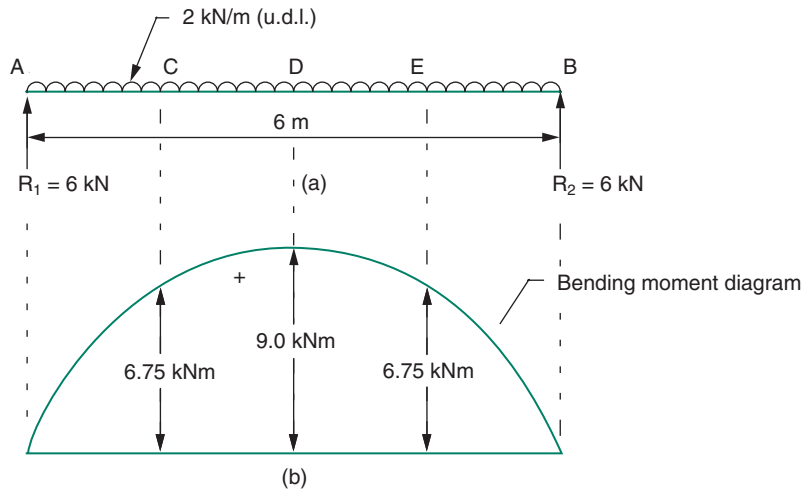
$$\begin{aligned}\text{CW moment about E} &= R_1 \times \text{distance AE} \\ &= 6 \text{ kN} \times 4.5 \text{ m} = 27 \text{ kNm}\end{aligned}$$

$$\begin{aligned}\text{ACW moment about E} &= 9 \text{ kN} \times \text{perpendicular distance between 9 kN force} \\ &\quad \text{and point E} \\ &= 9 \text{ kN} \times 2.25 \text{ m} = 20.25 \text{ kNm}\end{aligned}$$

$$\begin{aligned}\text{B.M. at E} &= \text{algebraic sum of CW and ACW moments} \\ &= 27 - 20.25 = 6.75 \text{ kNm}\end{aligned}$$

- 6) **B.M. at B:** Convert the u.d.l. acting to the left of B into an equivalent point load:
 $= 2 \text{ kN/m} \times 6 \text{ m} = 12 \text{ kN}$

This is supposed to act at the mid-point of AB, i.e. at D (Figure 11.27).

**Figure 11.28**

CW moment about B = $R_1 \times \text{distance AB}$
 $= 6 \text{ kN} \times 6 \text{ m} = 36 \text{ kNm}$

ACW moment about B = $12 \text{ kN} \times \text{perpendicular distance between}$
 $12 \text{ kN force and point B}$
 $= 12 \text{ kN} \times 3.0 \text{ m} = 36 \text{ kNm}$

Moment due to R_2 is zero, as the distance between R_2 and B is zero.

B.M. at B = algebraic sum of CW and ACW moments
 $= 36 - 36 = 0 \text{ kNm}$

The bending moment diagram is shown in Figure 11.28b.

Note: If a u.d.l. acts on the whole length of the beam, and no other force is involved, then the maximum B.M. ($M_{\max}$) can be calculated from the formula:

$M_{\max} = \frac{wl^2}{8}$, where w is the u.d.l. and l is the length of the beam.

In Example 11.10: $M_{\max} = \frac{2 \times 6^2}{8} = 9 \text{ kNm}$

11.4 Triangle of forces

A force can be represented in both magnitude and direction, and hence is a vector quantity. Units of newton (N), kilonewton (kN), or Meganewton (MN) are used to show the magnitude; the direction is shown by using short lines with arrowheads, as explained in Chapter 10.

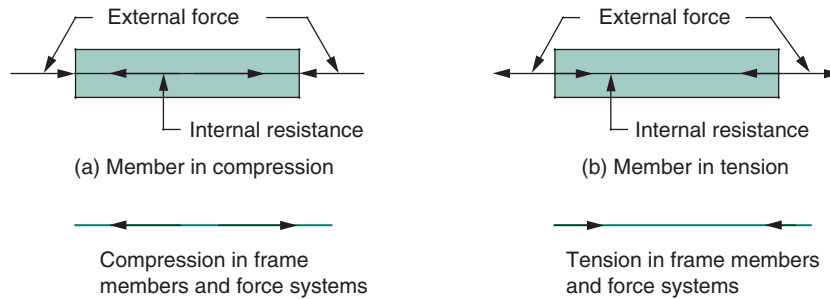


Figure 11.29

Forces meeting at a point are known as **concurrent forces**. Forces, whose line of action lies in the same plane, are called **coplanar forces**. If a body is in equilibrium under the action of three concurrent, coplanar forces, then these forces can be represented by a triangle, with its sides drawn parallel to the direction of the forces. This is known as the law of the **triangle of forces** and can be used to determine the unknown magnitude and/or direction of one or two forces.

If the force system consists of more than three forces, then the law of polygon of forces can be used, which is similar to the law of the triangle of forces.

If a member is subjected to compression or tension, then the internal resistance of the material acts in the opposite direction, as shown in Figure 11.29. In all problems where we use the triangle of forces or the polygon of forces, we use the direction of internal resistance to show compression or tension.

Example 11.11

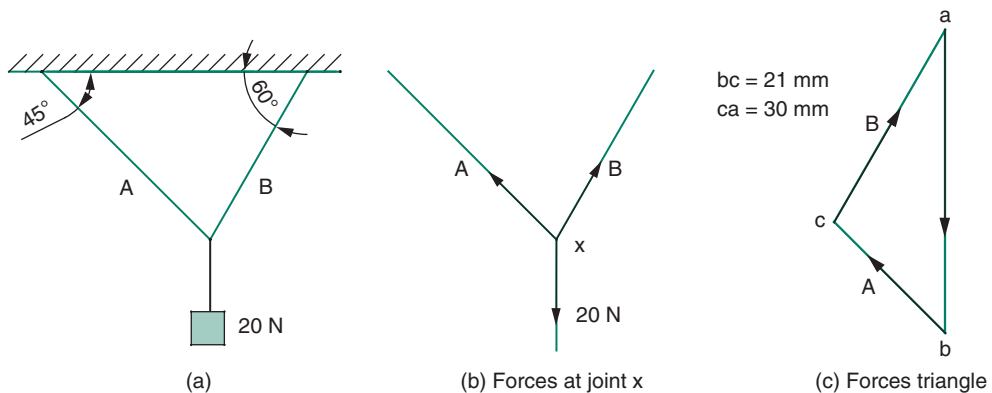
A weight of 20N is supported by two strings, as shown in Figure 11.30a. Determine, graphically, the nature and magnitude of forces in the two strings.

Solution:

The 20N force acts downwards. As the two strings A and B support this force, they must be subjected to upward acting forces to maintain the equilibrium. Figure 11.30b illustrates this by showing details at joint x. For the equilibrium of the system (for the 20N force to stay in position), the total vertical component of forces in the two strings must be equal to 20N. The forces in the strings can be determined from the force triangle.

To draw the force triangle:

- 1) Select a suitable scale, say $1\text{N} = 2\text{mm}$.
- 2) Draw line $ab = 40\text{mm}$, ($1\text{N} = 2\text{mm}$, therefore $20\text{N} = 40\text{mm}$) parallel to the 20N force. The direction of the force in ab should be the same as the direction of the 20N force.
- 3) From point b , draw line bc parallel to string A. As we do not know the magnitude of the force in string A, point c cannot be established as yet.

**Figure 11.30**

- 4) Draw a line passes through point a, and is parallel to string B. This will establish point c, as shown in Figure 11.30c.
- 5) Triangle abc is the force triangle. Side ab represents the 20 N force, sides bc and ca represent the forces in strings A and B respectively.
- 6) Measure bc and ca in millimetres and use the scale of $1\text{ N} = 2\text{ mm}$ (used to draw the force triangle) to convert these into newtons.

$1\text{ N} = 2\text{ mm}$ can also be written as $1\text{ mm} = 0.5\text{ N}$

$bc = 21\text{ mm}$, therefore force in string A $= 21 \times 0.5 = 10.5\text{ N}$

$ca = 30\text{ mm}$, therefore force in string B $= 30 \times 0.5 = 15\text{ N}$

Example 11.12

Two rods, A and B, support an object weighing 250 N, as shown in Figure 11.31a. Determine the nature and magnitude of forces in the two rods.

Solution:

At joint x, the 250 N force acts vertically downwards and is supported by rods A and B. The downward force tends to stretch rod B and hence creates tension. Let us assume that there is tension in rod A as well. The directions of these forces are shown in Figure 11.31b.

To draw the force triangle:

- 1) Only consider the direction of forces at joint x.
- 2) Select a suitable scale, say $5\text{ N} = 1\text{ mm}$.

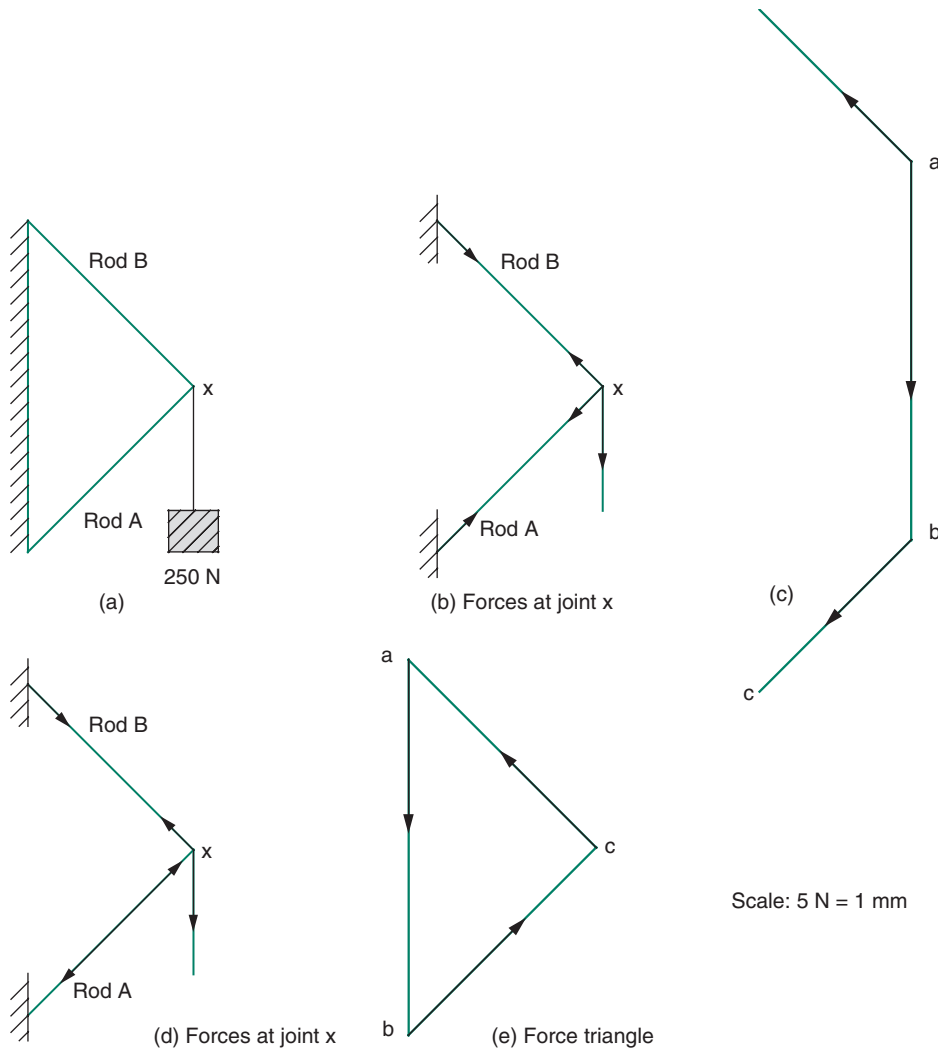


Figure 11.31

- 3) To represent the 250 N force, draw vertical line $ab = 50 \text{ mm}$ ($5 \text{ N} = 1 \text{ mm}$, therefore $250 \text{ N} = 50 \text{ mm}$). The direction of the force in line ab is downwards, as shown in Figure 11.31c.
- 4) From point b , draw a line parallel to rod A in the downward direction. The downward direction represents the direction of the force in rod A. As the magnitude of the force is to be determined, the length of line bc , which represents the force in the rod, cannot be ascertained as yet.
- 5) The force in rod B acts upwards, at joint x . To represent this force in the force triangle, a line should be drawn which passes through point a , is parallel to rod B, and completes the force triangle. Figure 11.31c shows the line that passes through point a and is parallel to rod B. As this does not form a triangle, the assumed direction of force in rod A is wrong.

- 6) Change the direction of force in rod A, as shown in Figure 11.31d. In order to produce the force triangle, repeat the procedure that has already been explained in Steps 3 to 5.
- 7) Draw line $ab = 50 \text{ mm}$ to represent the 250 N force (Figure 11.31e). From point b, draw a line parallel to rod A in the upward direction to represent the force in rod A.
- 8) The next step is to draw a line that passes through point a, and is parallel to rod B. This line will also establish point c, as shown in Figure 11.31e. This procedure results in a triangle, therefore the assumptions regarding the direction of forces in rods A and B are correct.
- 9) From the force triangle, measure lines bc and ca in mm, and using the scale chosen earlier, convert these to newtons to show the forces in rods A and B.
- 10) Draw the arrowheads at the other ends of the rods (Figure 11.31d). The nature of the forces can be ascertained now.

Force in rod A = $35 \text{ mm} \times 5 \text{ N} = 175 \text{ N}$ COMPRESSION

Force in rod B = $35 \text{ mm} \times 5 \text{ N} = 175 \text{ N}$ TENSION

11.4.1 Bow's notation

Bow's notation is used to identify forces in frames and force systems. It involves marking the spaces in the space diagram with capital letters, as shown in Figure 11.32. Any force and any member of the frame can be identified by letters, on either side. For example, reaction R_1 is identified as AB as it has spaces A and B on either side. Similarly 5 kN force is identified as BC.

It is usual practice to start from the left-hand support, and move in the clockwise direction at each joint (node). Although it is not necessary, the first few letters are used exclusively for reactions and external forces.

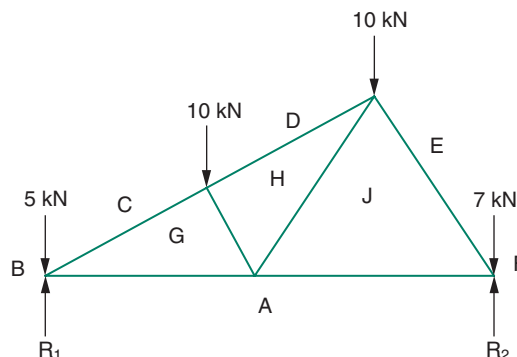


Figure 11.32 Bow's notation.

Example 11.13

For the force system shown in Figure 11.33a, find the nature and magnitude of the unknown forces.

Solution:

- 1) Identify the spaces in the space diagram by letters A, B, C and D (Figure 11.33b).
- 2) Use a scale of $1 \text{ kN} = 8.2 \text{ mm}$. To represent force CD (5 kN), draw line cd parallel to force CD. As $1 \text{ kN} = 8.2 \text{ mm}$, the length of cd is 41 mm (Figure 11.33c).
- 3) Moving clockwise at joint x, the next member of the force system is DA. As the direction of the force in member DA, at joint x, is downwards, draw line da downwards and parallel to member DA. The direction in which da is drawn should be the same as that of the force in member DA at joint x. The force in member DA is 3 kN, therefore the length of da should be 24.6 mm.
- 4) The next member we come across is AB. The magnitude and direction of force in this member are not known, therefore draw a line parallel to AB on either side of point a. Point b cannot be marked yet because the force in member AB is not known.
- 5) The next member of the force system is BC. Again, neither the magnitude nor the direction of force in this member is known. Draw a line that is parallel to BC and passes through point c. This also establishes point b, as shown in Figure 11.33c.
- 6) The directions of forces in the polygon of forces can now be shown. The direction of forces in members of the force system at joint x will be the same as those in the corresponding sides of the polygon of forces.

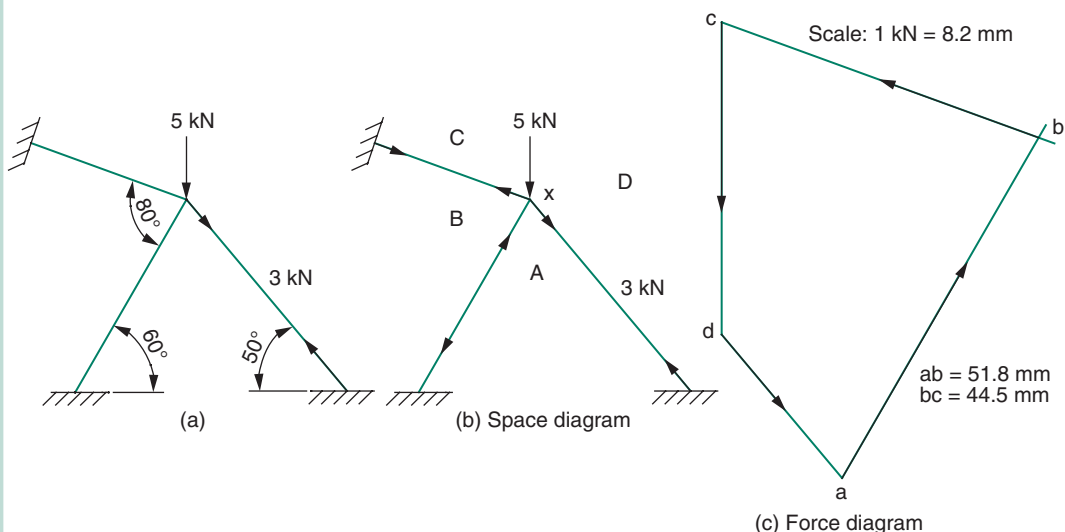


Figure 11.33

- 7) The direction of forces at the other ends of the members should be marked as illustrated in Figure 11.33b.
- 8) Measure sides *ab* and *bc* of the force polygon in centimetres and convert these to kilonewtons using the chosen scale of $8.2 \text{ mm} = 1 \text{ kN}$.

9) **Results:**

Member	Nature of Force	Force (kN)
AB	Compression	6.3
BC	Tension	5.4
DA	Tension	3.0

11.4.2 Frames and roof trusses

Frames and roof trusses contain many members to carry the applied forces in a safe manner. The simplest roof truss consists of 3 members (Figure 11.34a), but a more practical truss, like a trussed rafter, consists of several members (Figures 11.34b and 11.34c).

The number of joints, also called nodes, depends on the number of members of the truss.

In Figure 11.34a, there are 3 members and 3 joints.

In Figure 11.34b, there are 11 members and 7 joints.

In Figure 11.34c, there are 15 members and 9 joints.

A simple frame may be analysed by considering each joint individually and drawing the force diagrams. For frames with many joints, this would prove to be a lengthy process. To simplify the process, only one force diagram is drawn, as explained in Examples 11.14 and 11.15.

Members of a truss that carry compression are called **struts**. The uppermost members of a truss, called rafters, are always in compression. Members in tension are known as **ties**, for instance, the horizontal members at the bottom of a truss.

Example 11.14

Find the nature and the magnitude of forces in members of the truss shown in Figure 11.35a.

Solution:

- Before drawing the force polygon, the magnitudes of reactions R_1 and R_2 should be determined. The truss is not symmetrical, therefore the law of moments should be used to determine the reactions.
- Take moments of all forces about joint 3.

$$R_1 \times 7.0 = 4 \times 2.6$$

$$\text{Therefore, } R_1 = \frac{4 \times 2.6}{7.0} = 1.49 \text{ kN}$$

$$\text{As } R_1 + R_2 = 4.0$$

$$\text{Therefore, } R_2 = 4.0 - 1.49 = 2.51 \text{ kN}$$

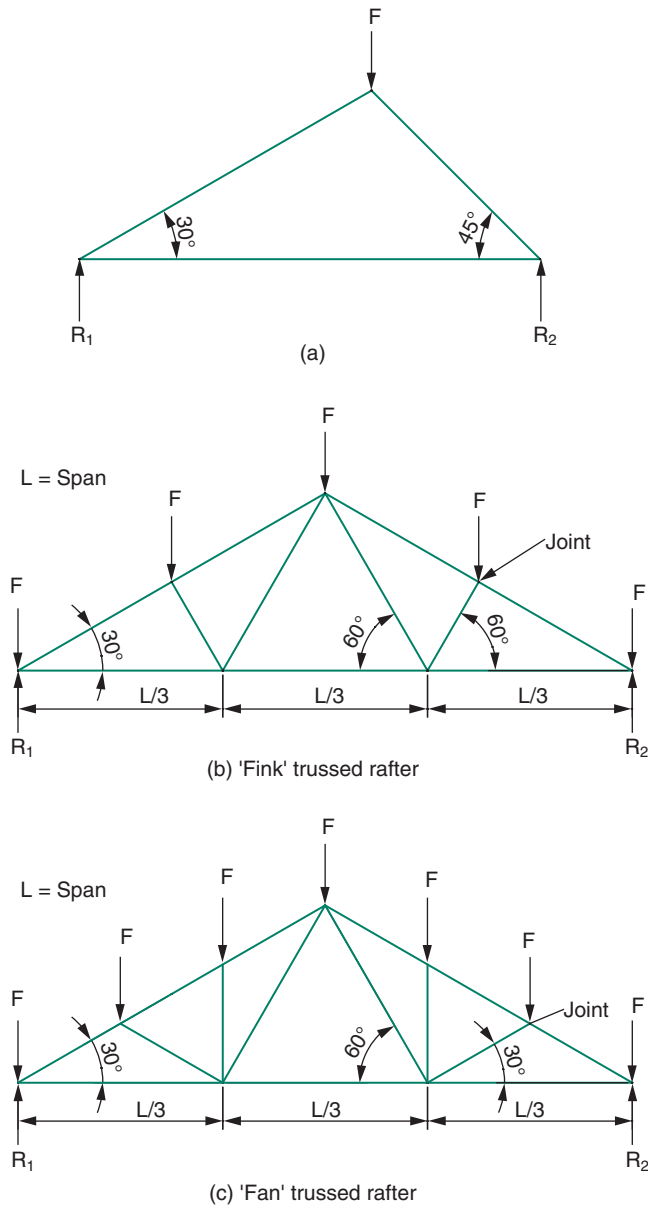


Figure 11.34

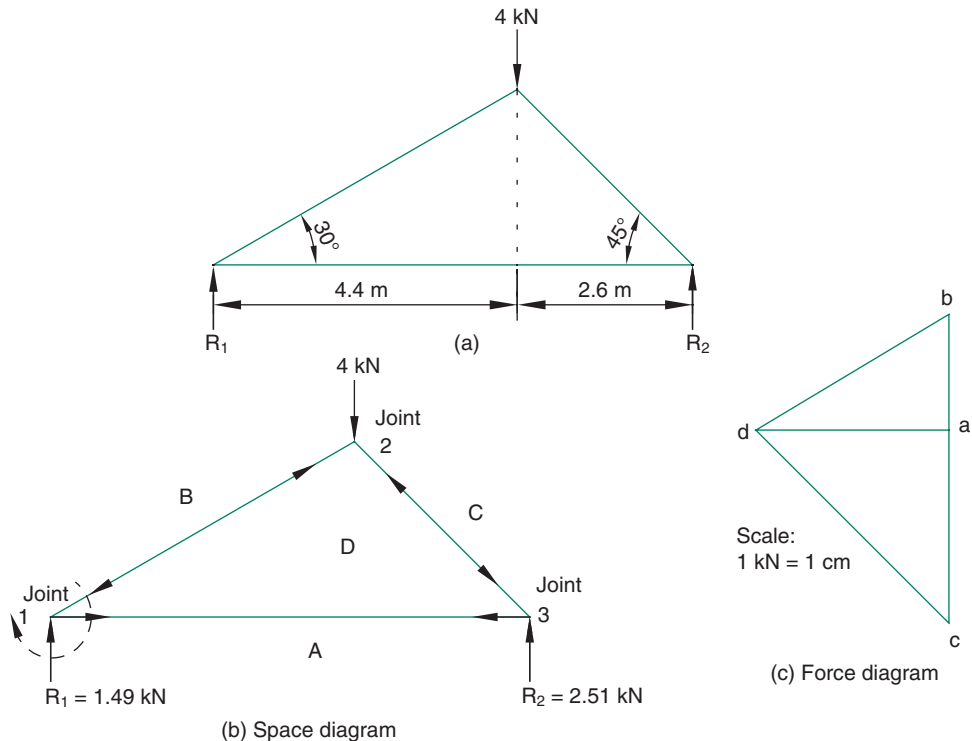


Figure 11.35

- 3) Label the space diagram (Figure 11.35b) with capital letters. As explained earlier, members BD and CD are in compression, and member DA is in tension. The directions of the forces in the three members are shown in the space diagram.
- 4) Select a convenient scale, say $1 \text{ kN} = 10 \text{ mm}$.
- 5) We have to consider all joints, one by one. Let us start at joint 1 and consider reaction R_1 as its value is known. Draw line ab vertically up to represent force AB (reaction R_1). The magnitude of the force is 1.49 kN, therefore line ab should be 14.9 mm long (Figure 11.35c). Line ab is drawn upwards as reaction R_1 (force AB) acts upwards.
- 6) Moving **clockwise** at joint 1, as shown by the dotted arrow, the next member of the truss is BD. The direction of force in member BD, at joint 1, is downwards, therefore draw line bd parallel to BD, in the downward direction. Since the magnitude of force in member BD is not known, point d cannot be established at this stage.
- 7) Moving clockwise again at joint 1, the next member is DA. As it is horizontal, draw a horizontal line that passes through point a, and thus establishes point d on line bd. Lines bd and da will be measured later to determine the magnitude of forces in members BD and DA.
- 8) Let us move on to joint 2. To represent force BC (4 kN force) on the force diagram, draw line bc = 40 mm vertically down, as the force acts downwards.
- 9) Moving clockwise at joint 2, the next member is CD. The direction of the force in this member is upwards, therefore draw a line up from point c to represent the force in member CD. Line cd should be parallel to member CD.

- 10) The next member at joint 2 is DB. Line db, which represents the force in member DB, has already been drawn.
- 11) At joint 3, we have two members of the truss, AD and DC, and reaction CA. These have already been represented on the force diagram.
- 12) The force diagram is now complete. Measure sides bd, cd and da, which represent forces in members BD, CD and DA respectively. Use the scale already selected, i.e. $1 \text{ kN} = 10 \text{ mm}$, and convert the lengths of the measured sides into kilonewtons. The results are shown below:

Member	Nature of Force	Force (kN)
BD	Compression	3.0
CD	Compression	3.6
AD	Tension	2.6

Example 11.15

Find the nature and the magnitude of forces in the members of the trussed rafter shown in Figure 11.36a.

Solution:

- 1) As the truss is symmetrically loaded, $R_1 = R_2$, and:

$$R_1 + R_2 = \text{total force acting on the truss}$$

$$R_1 + R_2 = 30 \text{ kN, therefore } R_1 = R_2 = 15 \text{ kN}$$
- 2) Label the space diagram with capital letters as shown in Figure 11.36b. Members BF, CG, DJ and EK are in compression, and members FA, HA and KA are in tension. The directions of forces in these members are shown in Figure 11.36b. The nature of forces in the remaining members is to be determined.
- 3) The joints are numbered as shown. Select an appropriate scale to draw the force diagram, say $1 \text{ kN} = 2 \text{ mm}$.
- 4) Start from joint 1. Using a scale of $1 \text{ kN} = 2 \text{ mm}$, draw line ab vertically up to represent force AB (R_1). Force AB is 15 kN, therefore ab should be 30 mm long (Figure 11.36c).
- 5) Go clockwise at joint 1 to the next member, i.e. BF. From point b, draw a line parallel to member BF to represent the force in this member. The direction of line bf should be the same as the direction in which the force in member BF acts at joint 1, i.e. downwards. Since the force in member BF is not known, point f cannot be established as yet.
- 6) The next member is FA. As the member is horizontal, draw a horizontal line that passes through point a, and thus establishes point f. This completes the process at joint 1.

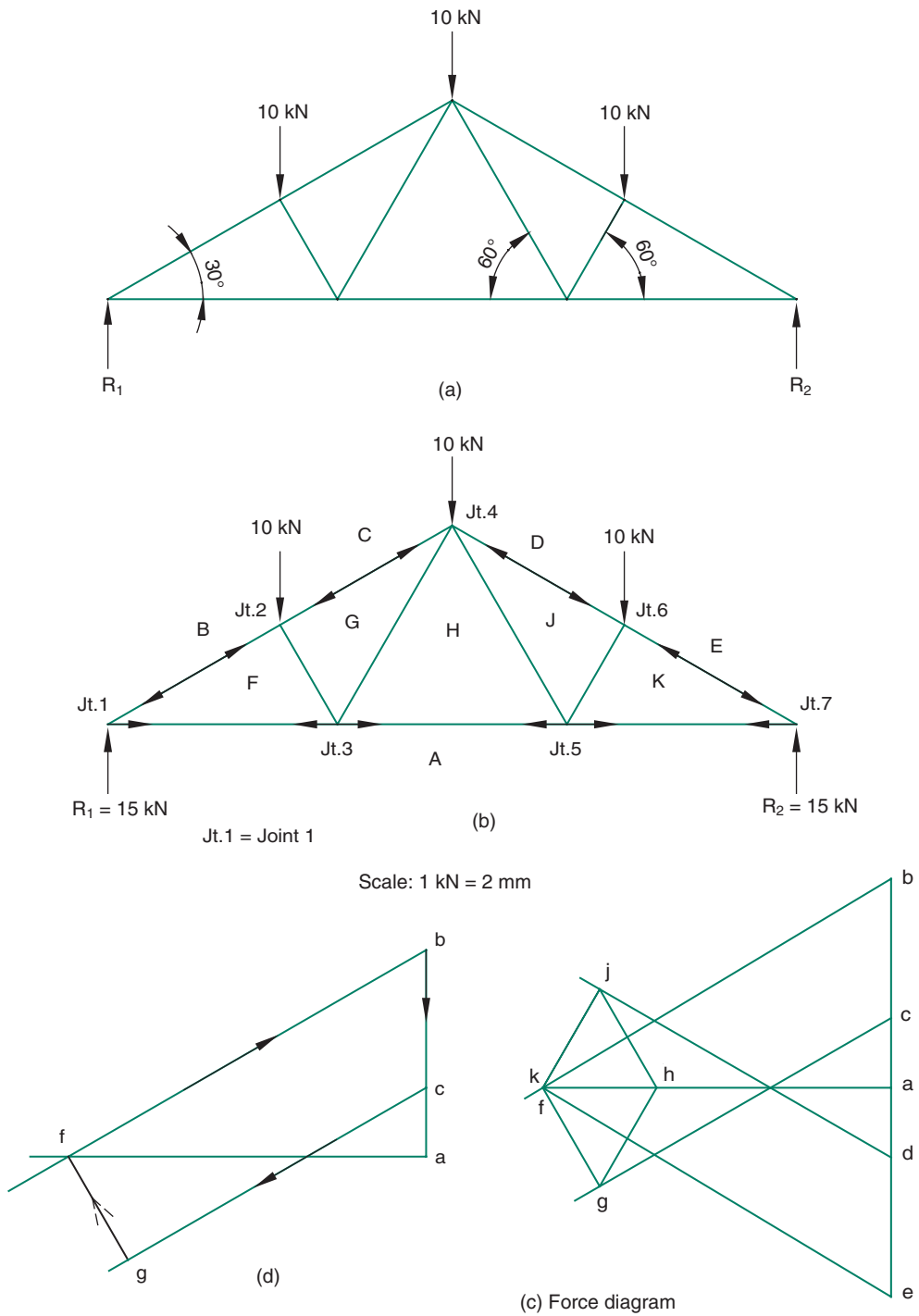


Figure 11.36

- 7) The next joint to be considered is joint 2. At this joint, there are three members of the truss and an external force of 10 kN. On the force diagram, mark $bc = 20 \text{ mm}$ to represent the downward acting vertical force of 10 kN ($1 \text{ kN} = 2 \text{ mm}$, therefore $10 \text{ kN} = 20 \text{ mm}$).
- 8) Go clockwise at joint 2 to the next member, i.e. member CG. To represent the force in member CG at joint 2, draw a line from point c that slopes downwards and is parallel to member CG. Since the force in member CG is not known, point g cannot be established at this stage.
- 9) Moving clockwise at joint 2, the next member is GF. The magnitude, as well as the direction of the force, in this member is not known. To represent the force in member GF, draw a line on the force diagram that is parallel to member GF and passes through point f. This will establish point g as shown.
- 10) The next member is FB, which has already been represented on the force diagram. In order to determine whether there is tension or compression in member GF, let us look at the force diagram from joint 2 (Figure 11.36d). The known directions are marked with bold arrows. The arrows must follow each other around the force diagram. Therefore, the direction of the force in member GF at joint 2 is upwards, as shown by the dotted arrow. This shows that there is compression in member GF.
- 11) The next joint to be considered is joint 3. At this joint, there are four members, two of which are horizontal. Members AF and FG have already been represented on the force diagram. From point g, draw a line parallel to member GH. The direction of the force in member GH is to be determined.
- 12) The next member in a clockwise direction at joint 3 is HA. As the member is horizontal, the line that represents the force in this member must be horizontal. That line is ha.
- 13) The nature of the force in member GH can be determined as explained in Step 10. There is tension in member GH.
- 14) The procedure explained above should be followed at joints 4, 5, 6 and 7 to complete the force diagram.
- 15) To determine the force in each member of the truss, we need to measure the sides of the force diagram and convert them back into kilonewtons.
- 16) The results are shown in Table 11.1.

Table 11.1

Member/s	Compression/tension	Strut/tie	Force (kN)
BF, KE	Compression	Strut	30.0
FA, AK	Tension	Tie	26.0
CG, DJ	Compression	Strut	25.0
GF, KJ	Compression	Strut	8.7
GH, JH	Tension	Tie	8.7
HA	Tension	Tie	17.3

Exercise 11.1

1. Calculate the moment about point x for the cantilevers shown in Figure 11.37.
2. Calculate the clockwise and anti-clockwise moments about points B and A for the beams shown in Figure 11.38.
3. Figure 11.39 shows the line diagrams of four beams subjected to a variety of loading. Calculate reactions R_1 and R_2 .

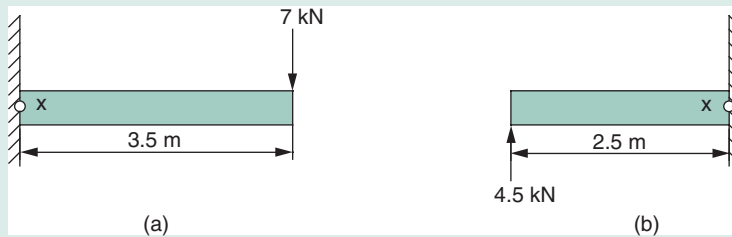


Figure 11.37

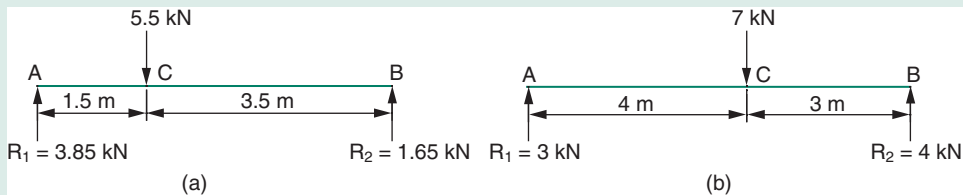


Figure 11.38

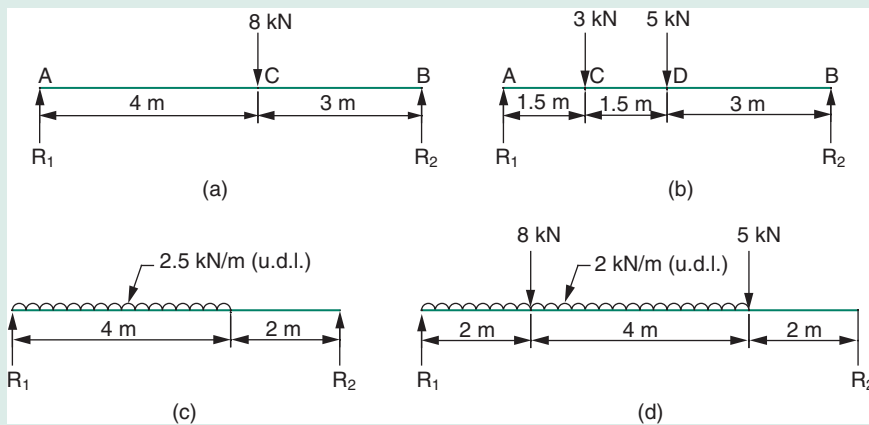


Figure 11.39

4. For the beams shown in Figure 11.39, produce shear force and bending moment diagrams.
5. A weight of 30 N is supported by two strings, as shown in Figure 11.40. Determine, graphically, the nature and magnitude of forces in the two strings.
6. Two rods, A and B, support objects weighing 600 N, 300 N and 400 N, as shown in Figure 11.41. For each case, determine the nature and magnitude of forces in the two rods.
7. Find the magnitude and the nature of forces in members of the trusses shown in Figure 11.42.

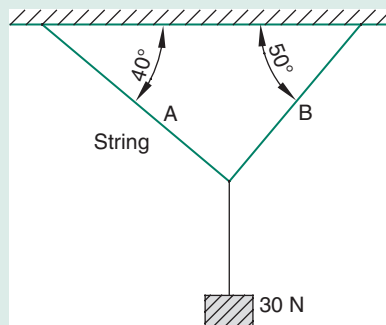


Figure 11.40

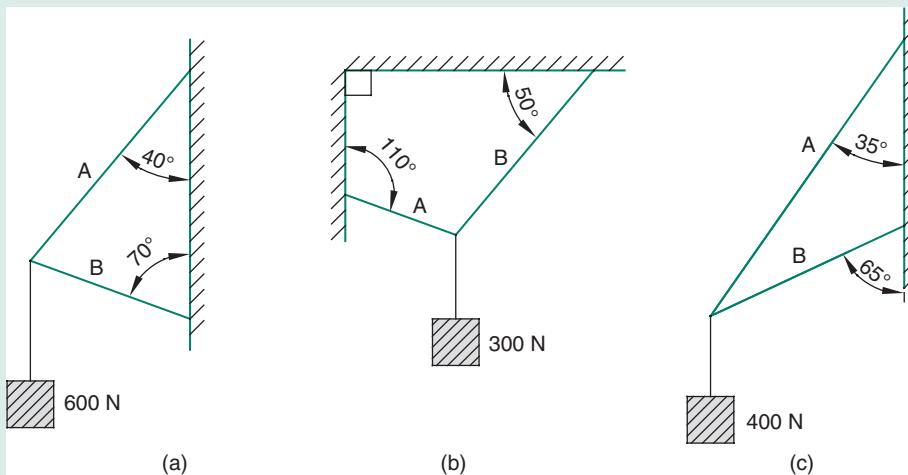


Figure 11.41

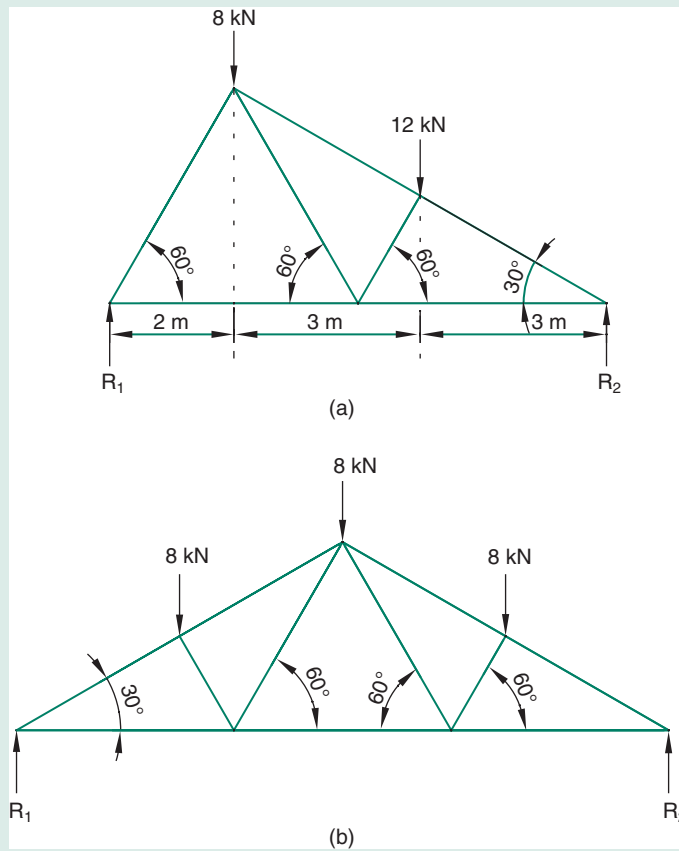


Figure 11.42

References/Further reading

1. Durka, F., Al Nageim, H., Morgan, W. and Williams, D. (2002). *Structural Mechanics*. Harlow: Prentice Hall.
2. Hulse, R. and Cain, J. (2003). *Structural Mechanics*. Basingstoke: Palgrave Macmillan.

12

Fluid mechanics

Learning outcomes:

- 1) Derive equation for determining fluid pressure at a point.
- 2) Derive Bernoulli's equation and apply it to solve practical problems.
- 3) Apply Chézy's equation and Manning's formula to determine the velocity of flow in open channels.

12.1 Introduction

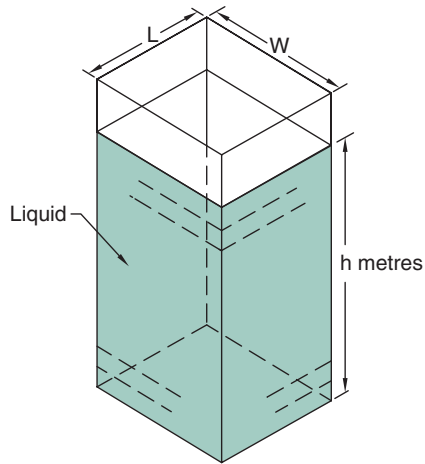
Water, like air, is also necessary for the life of humans, animals and vegetation. However, if it is not controlled properly, water may cause flooding, damage to property and loss of human life. Several types of civil engineering structures, e.g. canals, dams, culverts, elevated water tanks, drains etc., are constructed to control/contain water for useful purposes. In all these cases, water exerts pressure on the structure; this needs to be calculated for preparing the structural design. Water also affects the design of retaining walls, building foundations, roofs, cladding and other structures.

In science both liquids and gases are considered as fluids. Although the principles and theories described here are based on water, they can also be applied to other fluids.

In this chapter some fundamental aspects of pressure exerted by static water (hydrostatic pressure) and pressure exerted by flowing water (hydrodynamic pressure) will be considered.

12.2 Pressure of fluids at rest

Fluids exert pressure on the base and the sides of the container in which they are stored. The pressure at any point in a fluid is due to the weight of the fluid above that point. Consider a vessel having a length of L metres and width of W metres. Let the depth of the liquid in the vessel be h metres (Figure 12.1).

**Figure 12.1**

$$\text{Volume of the liquid} = L \times W \times h \quad (\text{m}^3) \quad (1)$$

From Chapter 3, Section 3.7, we know that density (ρ) = $\frac{\text{mass (m)}}{\text{volume (V)}}$

$$\text{Transposing the above equation, } V = \frac{m}{\rho} \quad (2)$$

From Equations (1) and (2):

$$\frac{m}{\rho} = L \times W \times h \quad (\text{m is the mass of the liquid})$$

$$\begin{aligned} \text{After transposition, } m &= L \times W \times h \times \rho \\ &= A \times h \times \rho \quad (\text{area of the base, } A = L \times W) \end{aligned} \quad (3)$$

$$\text{Weight of a substance (w)} = m \times g, \quad \text{or, } m = \frac{w}{g} \quad (4)$$

From Equations (3) and (4):

$$\begin{aligned} \frac{w}{g} &= A \times h \times \rho \\ \text{or, } w &= A \times h \times \rho \times g \end{aligned}$$

The force at the base of the vessel is due to the weight of the liquid.

$$\text{Force at the base} = A \times h \times \rho \times g$$

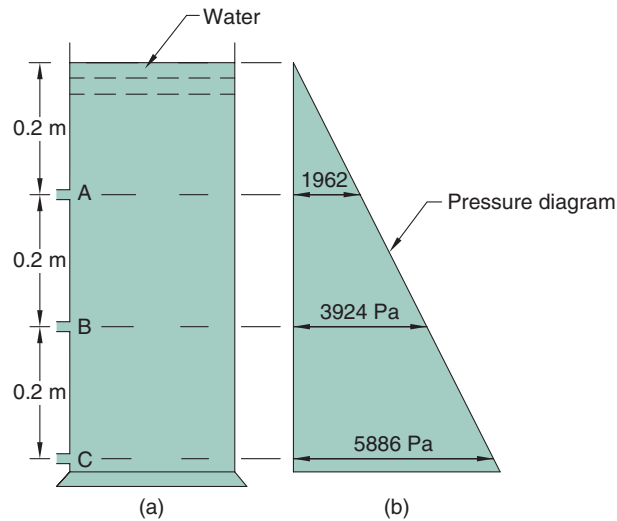


Figure 12.2 Variation of liquid pressure with depth.

Unit: Newton (N)

$$\begin{aligned}\text{We also know that Pressure (p)} &= \frac{\text{Force (F)}}{\text{Area (A)}} \\ &= \frac{A \times h \times \rho \times g}{A} = h \times \rho \times g\end{aligned}$$

Unit: N/m² or Pascal (Pa)

The above equation shows us that the pressure exerted by a liquid is proportional to its depth and density. For a particular liquid, the values of density and g remain unchanged, therefore the pressure depends only on the depth of the liquid. This may be shown by using a tall vessel with a number of side tubes at various depths, as shown in Figure 12.2a. The vessel is filled with water and the side tubes are unblocked. The speed at which water flows out is the greatest for the lowest jet, showing that pressure increases with depth.

The pressure responsible for the flow from the side tubes acts horizontally, hence we can say that in liquids the pressure acts in all directions, not just vertically.

The variation in pressure can be shown as a pressure diagram (Figure 12.2b). Owing to the outflow of water, the pressure decreases continuously as the depth of water is never constant. However, when the depth of water is 0.6 m, i.e. the moment when the test starts, the pressures at points A, B and C are:

$$\begin{aligned}\text{Pressure at point A} &= h \times \rho \times g \quad (g = 9.81 \text{ ms}^{-2}) \\ &= 0.2 \times 1000 \times 9.81 \quad (\text{density of water, } \rho = 1000 \text{ kg/m}^3) \\ &= 1962 \text{ Pa}\end{aligned}$$

$$\text{Pressure at point B} = 0.4 \times 1000 \times 9.81 = 3924 \text{ Pa}$$

$$\text{Pressure at point C} = 0.6 \times 1000 \times 9.81 = 5886 \text{ Pa}$$

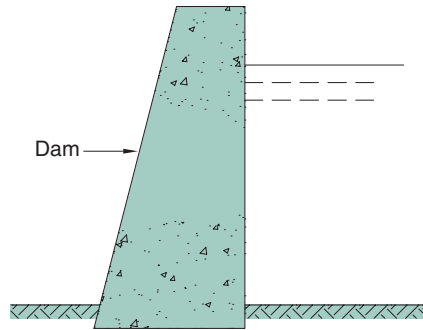


Figure 12.3 Concrete dam.

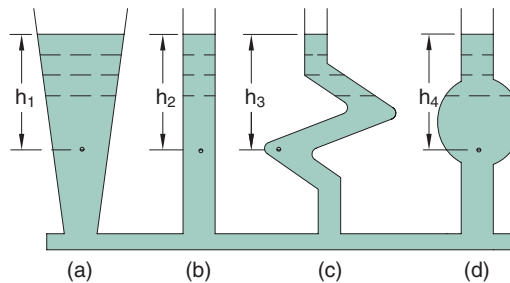


Figure 12.4

The variation in liquid pressure is used in water-retaining and soil-retaining structures to achieve an economical design. Figure 12.3 shows that dams are made much thicker at the bottom as the maximum pressure occurs at the base of the reservoir.

The pressure is independent of the shape of the vessel. In Figure 12.4, there are four vessels of different shapes but filled with the same liquid to identical heights. The density of the liquid and the acceleration due to gravity remain the same in each case.

$$\text{Pressure at point A } (p_A) = h_1 \times \rho \times g; \quad \text{Pressure at point B } (p_B) = h_2 \times \rho \times g$$

$$\text{Pressure at point C } (p_C) = h_3 \times \rho \times g; \quad \text{Pressure at point D } (p_D) = h_4 \times \rho \times g$$

$$\text{If } h_1 = h_2 = h_3 = h_4 = h, \quad \text{then } p_A = p_B = p_C = p_D = h \times \rho \times g$$

The force (or thrust) at points A, B, C or D, due to the weight of the liquid above, will be different as the force depends on the area on which the pressure acts.

12.2.1 Why do the liquids flow?

In solids like bricks, steel, timber etc. the molecules are arranged in regular patterns touching each other. The force of attraction between the molecules is so strong that they cannot move. In liquids the molecules are still close together but not necessarily touching

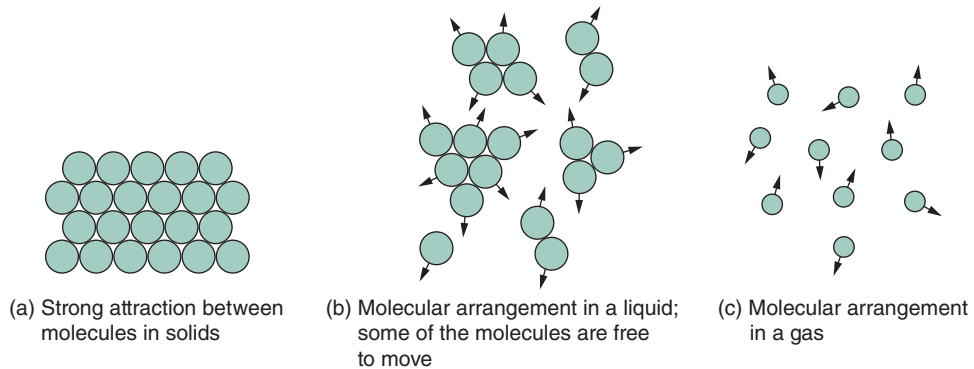


Figure 12.5 Molecular arrangement (2D) in a solid, liquid and gas.

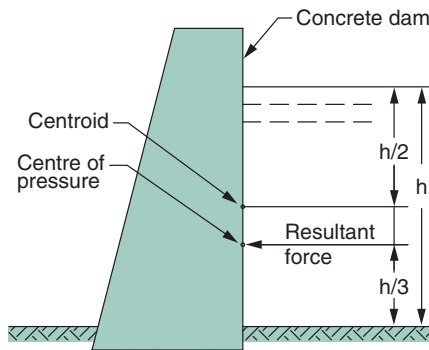


Figure 12.6 Centre of pressure.

others. The forces of attraction between molecules are therefore less than those in solids. The molecules can move about in all directions, hence liquids will flow and take the shape of the container in which they are stored. Figure 12.5 shows the difference between molecular arrangements in solids, liquids and gases.

12.2.2 Centre of pressure

Figure 12.2b shows how pressure varies from zero at the surface of a liquid to its maximum value (hpg) at the base.

$$\text{Average pressure} = \frac{0 + hpg}{2} = \frac{hpg}{2}$$

This is the same as calculating pressure at a depth of $\frac{h}{2}$ and applying it for the whole depth. Average pressure is used in calculating the total thrust on an object or engineering structure.

The centre of pressure is the point through which the resultant force acts. For a rectangular surface, the centre of pressure is at $\frac{2}{3}$ of the immersed depth below the surface, or at $\frac{1}{3}$ of the immersed depth measured from the bottom (see Figure 12.6).

Example 12.1

A 200 m long concrete dam has a vertical face on the reservoir side. Calculate the thrust on the dam if the depth of water is 20 m, and the point of action of this thrust. Density of water = 1000 kg/m^3 , and $g = 9.81 \text{ ms}^{-2}$.

Solution:

Depth of water, $h = 20 \text{ m}$; density, $\rho = 1000 \text{ kg/m}^3$

$$\begin{aligned}\text{Pressure at the centre of area} &= \frac{h\rho g}{2} \\ &= \frac{20 \times 1000 \times 9.81}{2} \\ &= 98100 \text{ N/m}^2 \text{ or } 98.1 \text{ kN/m}^2\end{aligned}$$

Area on which the water pressure acts = $200 \times 20 = 4000 \text{ m}^2$

$$\begin{aligned}\text{Thrust on the dam} &= \text{pressure} \times \text{area} \\ &= 98.1 \times 4000 = 392400 \text{ kN or } 392.4 \text{ MN}\end{aligned}$$

Example 12.2

A lock gate* is 25 m wide. On one side, the water is 9 m above the lower edge of the gate and on the other side, the water is 4.5 m above the lower edge of the gate, as shown in Figure 12.7. Calculate:

- the resultant force on the lock gate
- the point of action of the resultant force

$$\rho = 1020 \text{ kg/m}^3, \quad g = 9.81 \text{ ms}^{-2}.$$

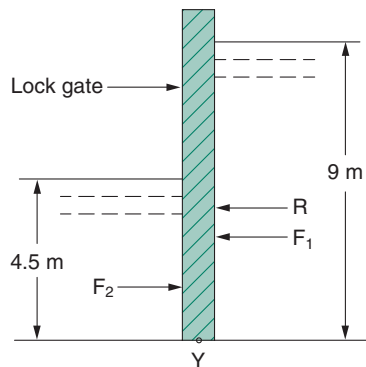


Figure 12.7

Solution:

$$\begin{aligned}
 \text{Force } F_1 &= p_1 \times A_1 \\
 &= \frac{9 \times 1020 \times 9.81}{2} \times (25 \times 9) \\
 &= 1.013 \times 10^7 \text{ N} = 10.131 \text{ MN}
 \end{aligned}$$

This force acts at a distance of $\frac{9}{3}$ or 3.0 m from Y.

$$\begin{aligned}
 \text{Force } F_2 &= p_2 \times A_2 \\
 &= \frac{4.5 \times 1020 \times 9.81}{2} \times (25 \times 4.5) \\
 &= 2.533 \times 10^6 \text{ N} = 2.533 \text{ MN}
 \end{aligned}$$

This force acts at a distance of $\frac{4.5}{3}$ or 1.5 m from Y.

$$\text{Resultant force (R)} = 10.131 - 2.533 = 7.598 \text{ MN}$$

Let us assume that the resultant force acts at a distance of d metres from Y. To find the point of action of the resultant force, take moments about point Y:

$$\begin{aligned}
 7.598 \times d &= 10.131 \times 3 - 2.533 \times 1.5 \\
 &= 26.5935
 \end{aligned}$$

$$\text{Therefore, } d = \frac{26.5935}{7.598} = 3.5 \text{ m}$$

The resultant force on the lock gate is 7.598 MN, which acts at 3.5 m from the base of the gate.

*Lock gates are used to lift or lower boats from one level to another. They are found in many canals and rivers.

12.3 The flow of a fluid

The flow of a fluid may be classified as laminar, transitional or turbulent. In **laminar flow** the particles move in well defined paths which are straight and parallel to the pipe walls. The particles do not cross the flow paths of other particles (Figure 12.8a). The flow is slower close to the pipe walls due to the friction between the fluid and the pipe material, and faster near the middle of the pipe cross-section. Laminar flow is only possible if the fluid has high viscosity but low flow velocity. If the fluid viscosity is low and flow velocity is high, the flow becomes turbulent.

In **turbulent flow** eddy currents form, which do not travel in straight paths and collide with one another (Figure 12.8b). The conditions needed for transitional flow are in-between the laminar flow and turbulent flow.

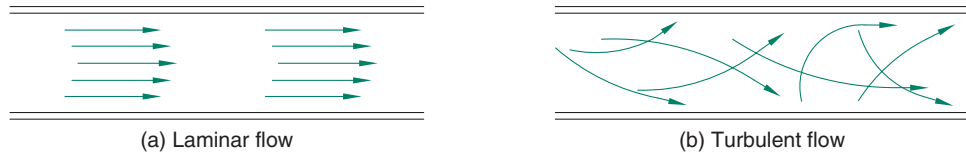


Figure 12.8 Laminar and turbulent flow.

Reynolds' number (R_e) may be used to predict the type of flow:

$$R_e = \frac{\rho v D}{\mu}$$

where ρ is the density of the fluid, v the flow velocity, D the pipe diameter and μ the coefficient of absolute viscosity.

For laminar flow: $R_e < 2300$

For transitional flow: $2300 < R_e < 4000$

For turbulent flow: $R_e > 4000$

12.3.1 Flow rate

The flow of liquids in pipes is very complex, but in order to derive some important relationships, an ideal liquid is considered that is non-viscous and incompressible.

Consider a pipe of uniform cross-sectional area, $A \text{ m}^2$, containing liquid flowing at a velocity of $v \text{ m/s}$.

$$\begin{aligned} \text{Volume of water flowing per second (or flow rate)} &= \text{Area} \times \text{length} \\ &= \text{Area} \times \text{distance travelled per second} \\ &= \text{Area} \times \text{velocity of flow} \end{aligned}$$

therefore flow rate, $Q = Av$.

Unit: m^3/s .

This equation can also be applied to pipework consisting of pipes of different diameters, as shown in Figure 12.9. The quantity of liquid flowing through each pipe in a given interval of time must be the same, i.e.:

$$Q = A_1 v_1 = A_2 v_2$$

This equation means that the velocity of the liquid must increase as it enters the narrower pipe to maintain a constant flow rate.

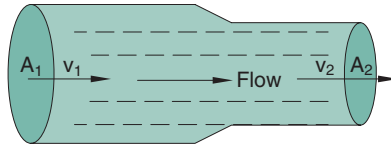


Figure 12.9 Flow through pipework having two cross-sections.

Example 12.3

A pipeline is made by joining two pipes having diameters of 150 mm and 100 mm. If 2.1 m^3 of water flows through the pipe per minute and the pipes run full, find the flow velocities in each pipe.

Solution:

In order to use consistent units, the pipe sizes are converted from millimetres into metres.

$$\begin{aligned}\text{Cross-sectional area of 150 mm diameter pipe, } A_1 &= \pi (r_1)^2 \\ &= \pi (0.075)^2 \quad (r_1 = 75 \text{ mm, or } 0.075 \text{ m}) \\ &= 0.01767 \text{ m}^2\end{aligned}$$

$$\begin{aligned}\text{Cross-sectional area of 100 mm diameter pipe, } A_2 &= \pi (r_2)^2 \\ &= \pi (0.050)^2 \quad (r_2 = 50 \text{ mm, or } 0.050 \text{ m}) \\ &= 0.007854 \text{ m}^2\end{aligned}$$

$$\begin{aligned}\text{Flow rate, } Q &= 2.1 \text{ m}^3 \text{ per minute} \\ &= 2.1 \div 60 = 0.035 \text{ m}^3/\text{s}\end{aligned}$$

$$\text{Now, } Q = A_1 v_1 = A_2 v_2$$

$$\text{From the above equation, } v_1 = \frac{Q}{A_1} = \frac{0.035}{0.01767} = 1.981 \text{ m/s}$$

$$v_2 = \frac{Q}{A_2} = \frac{0.035}{0.007854} = 4.456 \text{ m/s}$$

12.3.2 Bernoulli's theorem

Bernoulli's theorem is used to determine the energy of a moving liquid. It states that the total energy possessed by a moving liquid is constant, assuming that the loss of energy due to friction and other effects is negligible, and can be expressed as:

$$\text{Total energy} = \text{pressure energy} + \text{kinetic energy} + \text{potential energy} = \text{constant}$$

a) Pressure energy

Consider a liquid flowing in a pipe from section 1 to section 2 (see Figure 12.10). If L is the length of the pipe between sections 1 and 2, p is the pressure, and A the

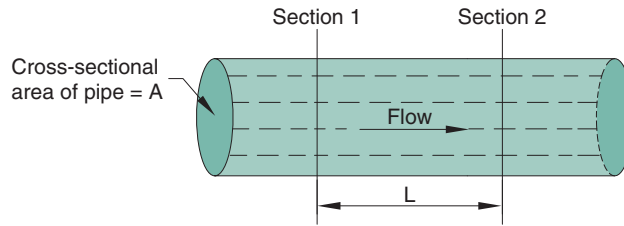


Figure 12.10

cross-sectional area of the pipe, then the force exerted by the flowing water will be equal to:

$$\text{Force exerted} = p \times A$$

Work done in moving the liquid from section 1 to section 2 is:

$$\begin{aligned} &= \text{force} \times \text{distance} \\ &= p \times A \times L \quad (\text{force} = \text{pressure} \times \text{area}) \\ &= p \times V \quad (\text{volume, } V = A \times L) \end{aligned} \quad (5)$$

Weight of the liquid, $W = \text{Volume} \times \text{unit weight}$

$$W = V \times w \quad (\text{unit weight, } w = \rho \times g)$$

$$\text{or, } V = \frac{W}{w} \quad (6)$$

From Equations 5 and 6, pressure energy $= \frac{pW}{w}$ (see Section 3.14)

b) Kinetic energy

Kinetic energy can be defined as the energy due to motion of the mass of liquid.

$$\begin{aligned} \text{Kinetic energy} &= \frac{1}{2}mv^2 \\ &= \frac{1}{2} \times \frac{W}{g}v^2 \quad (\text{mass, } m = W/g) \\ &= \frac{Wv^2}{2g} \end{aligned}$$

c) Potential energy

If a body of mass m (kg) is raised to a height of z metres, the work done is given by:

$$\begin{aligned} \text{Work done} &= \text{force} \times \text{distance} \\ &= m \times g \times z \end{aligned}$$

If this body is allowed to fall from height z to the original level, it will give out energy that is the same as the work done to raise it.

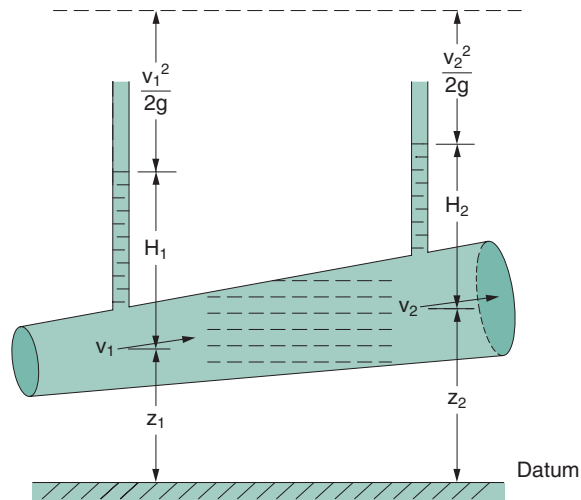


Figure 12.11 Total energy of liquid flow in pipework.

Therefore, potential energy of a liquid = $mgz = Wz$

Total energy, E = pressure energy + kinetic energy + potential energy

$$= \frac{pW}{w} + \frac{Wv^2}{2g} + Wz$$

For simplification, we can look at the energy per kilogram of liquid at any point in the system. This is done by dividing the equation by W .

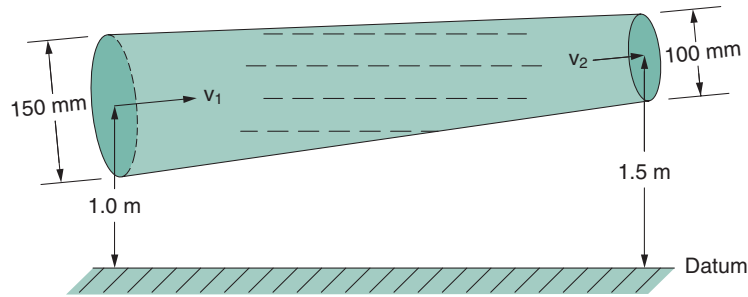
$$\frac{E}{W} = \frac{p}{w} + \frac{v^2}{2g} + z$$

As stated earlier, energy must be constant, therefore, energy at two points in a pipe (Figure 12.11) is equal. Assuming no friction, we have Bernoulli's equation:

$$\frac{p_1}{w} + \frac{v_1^2}{2g} + z_1 = \frac{p_2}{w} + \frac{v_2^2}{2g} + z_2 = \text{constant}$$

Example 12.4

An inclined pipe decreases uniformly from 150 mm diameter to 100 mm diameter in the direction of water flow. The pressure at the narrow section of the pipe is $2 \times 10^5 \text{ N/m}^2$, when the flow rate is $0.08 \text{ m}^3/\text{s}$. The smaller section of the pipe is 0.5 m above the larger section, vertically. Assuming there are no friction losses, calculate the pressure at the 150 mm section. The unit weight of water is 9810 N/m^3 .

**Figure 12.12****Solution:**

In this question we need to take into account the heights of the pipe ends above an arbitrarily fixed datum. This is shown in Figure 12.12.

$$\text{Flow rate, } Q = A_1 v_1 = A_2 v_2$$

$$0.08 = (\pi \times 0.075^2) v_1 = (\pi \times 0.05^2) v_2$$

$$v_1 = \frac{0.08}{\pi \times 0.075^2} = 4.527 \text{ m/s}$$

$$v_2 = \frac{0.08}{\pi \times 0.05^2} = 10.186 \text{ m/s}$$

Pressure at 150 mm section = p_1

Pressure at 100 mm section, $p_2 = 2 \times 10^5 \text{ N/m}^2$

Unit weight (w) of water = 9810 N/m^3

Put these values in Bernoulli's equation:

$$\frac{p_1}{w} + \frac{v_1^2}{2g} + z_1 = \frac{p_2}{w} + \frac{v_2^2}{2g} + z_2$$

$$\frac{p_1}{9810} + \frac{4.527^2}{2 \times 9.81} + 1.0 = \frac{2 \times 10^5}{9810} + \frac{10.186^2}{2 \times 9.81} + 1.5$$

$$\frac{p_1}{9810} + 1.045 + 1.0 = 20.387 + 5.288 + 1.5$$

$$\frac{p_1}{9810} = 20.387 + 5.288 + 1.5 - 1.045 - 1.0$$

$$p_1 = 25.13 \times 9810 = 246525.3 \text{ N/m}^2$$

$$= 246.525 \text{ kN/m}^2$$

12.3.3 The venturimeter

The venturimeter is a device used to measure the quantity of a liquid flowing through a pipe. The simplest form, shown in Figure 12.13, consists of two pipes which narrow to form a throat, and provided with pressure gauges in the pipe and the throat. As a liquid flows

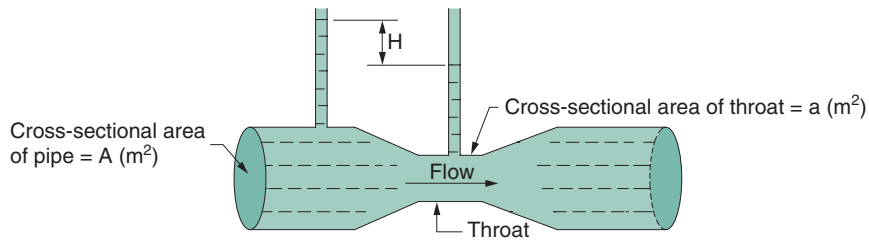


Figure 12.13 Venturimeter.

through the meter, its velocity increases at the throat due to the reduced cross-section. The kinetic energy at the throat increases, but the pressure energy must reduce to keep the total energy constant.

$$\text{Flow rate, } Q = \frac{KAa\sqrt{2gH}}{\sqrt{A^2 - a^2}}$$

where A and a are the cross-sectional areas of the pipe and throat respectively.

H is the difference between the pressure heads.

K is the meter coefficient that is introduced to allow for the loss in head due to friction. Typical value of K is 0.97.

Example 12.5

A venturimeter is provided in a 150 mm diameter water pipe. The diameter of the throat is 90 mm, and the pressure heads in the main pipe and the throat are 15.0 m and 13.0 m respectively. Calculate the flow rate in the pipe if the meter coefficient is 0.97 and the acceleration due to gravity is 9.81 ms^{-2} .

Solution:

$$\begin{aligned} \text{Area of the 150 mm diameter pipe, } A &= \pi r^2 \text{ (} r = 0.075 \text{ m)} \\ &= \pi (0.075)^2 = 0.01767 \text{ m}^2 \end{aligned}$$

$$\begin{aligned} \text{Area of the 90 mm diameter throat, } a &= \pi r^2 \text{ (} r = 0.045 \text{ m)} \\ &= \pi (0.045)^2 = 0.006362 \text{ m}^2 \end{aligned}$$

Difference between the pressure heads, $H = 15.0 - 13.0 = 2.0 \text{ m}$

$$\begin{aligned} \text{Flow rate, } Q &= \frac{KAa\sqrt{2gH}}{\sqrt{A^2 - a^2}} \\ &= \frac{0.97 \times 0.01767 \times 0.006362 \sqrt{2 \times 9.81 \times 2.0}}{\sqrt{(0.01767)^2 - (0.006362)^2}} \\ &= 0.0414 \text{ m}^3/\text{s} \end{aligned}$$

12.3.4 Flow in pipes: energy loss

The Bernoulli theorem assumes that the total energy of a liquid flowing in a pipe remains constant. However, due to the roughness of the pipe, there is a continuous loss of energy due to friction between the pipe surface and the flowing liquid. If a pipe is running full, Darcy's formula can be used to find the loss of pressure head (H):

$$H = \frac{4fLv^2}{2gD}$$

where H = loss of pressure head (m)

f = friction factor

L = length of the pipe (m)

v = mean velocity of flow (m/s)

D = diameter of the pipe (m)

The friction factor f is variable; it depends on the roughness of the pipe material and the Reynolds' number of the flow. For laminar flow, $f = \frac{64}{Re}$; for other types of flow, charts may be used to find the value of f.

Example 12.6

A 200m long pipe has a diameter of 600mm. Use Darcy's formula to predict the pressure head loss if the pipe runs full bore with water at a velocity of 2.0m/s. Assume Darcy's friction factor = 0.01.

Solution: f = 0.01; L = 200m; v = 2.0m/s; D = 0.600m; g = 9.81m/s²

$$\begin{aligned} \text{Loss of pressure head, } H &= \frac{4fLv^2}{2gD} \\ &= \frac{4 \times 0.01 \times 200 \times 2.0^2}{2 \times 9.81 \times 0.600} \\ &= 2.718 \text{ m} \end{aligned}$$

12.4 Flow in open channels

In this section, the Chézy equation and the Manning equation will be discussed and used to calculate the velocity of liquid flow in open channels like drains, partly filled pipes, culverts etc. As the flow in an open channel takes place under atmospheric pressure, it is important to provide the channel with the necessary slope.

Chézy, a French engineer, developed an equation to determine the velocity of water flow in a canal, and considered factors like the slope, the cross-sectional area of the flow, and the wetted perimeter (see Figure 12.14). The formula may, however, be applied to any open channel:

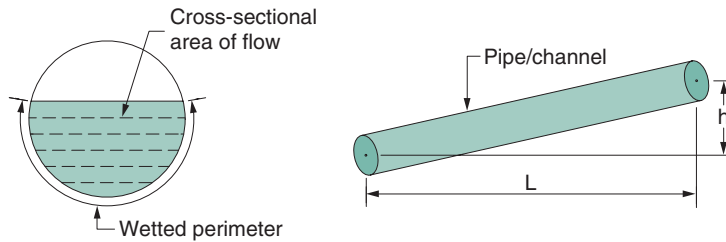


Figure 12.14 Flow in an open channel.

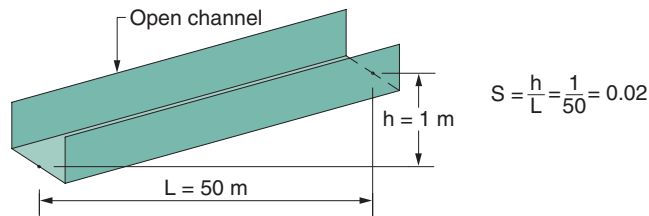


Figure 12.15 Gradient of a channel.

$$v = c\sqrt{RS}$$

where v = the average velocity (m/s)

c = Chézy roughness coefficient (varies from 5 to 77)

R = hydraulic radius (m)

S = slope or gradient of the channel

The hydraulic radius of an open channel is the ratio of its cross-sectional area of flow and wetted perimeter:

$$\text{Hydraulic radius, } R = \frac{\text{cross-sectional area of flow}}{\text{wetted perimeter}}$$

The gradient of an open channel is usually determined from a short length. For example, the gradient may be given as 1 in 50, which means that for every 50 m horizontal distance (L), the vertical distance between the ends of the channel (h) is 1 m, as shown in Figure 12.15.

$$\text{Slope, } S = \frac{h}{L}$$

Robert Manning found that the known data fit the Chézy equation much better if $R^{2/3}$ were used, rather than $R^{1/2}$. The Manning equation is:

$$v = \frac{1}{n} R^{2/3} S^{1/2}$$

where v = the average velocity (m/s)

n = Manning's roughness coefficient

R = hydraulic radius (m)

S = slope or gradient of the channel

Example 12.7

A circular drain of 200 mm diameter runs half-full of water and is laid at a gradient of 1 in 50. If the Chézy coefficient is $50 \text{ m}^{1/2}/\text{s}$, calculate the flow velocity in the drain.

Solution:

$$\begin{aligned}\text{Cross-sectional area of flow} &= \frac{\pi r^2}{2} \quad (r = 0.1 \text{ m}) \\ &= \frac{\pi \times 0.1^2}{2} = 0.0157 \text{ m}^2\end{aligned}$$

$$\begin{aligned}\text{Wetted perimeter} &= \frac{2\pi r}{2} = \pi r \\ &= \pi \times 0.1 = 0.31416 \text{ m}\end{aligned}$$

$$\begin{aligned}\text{Hydraulic radius, } R &= \frac{\text{cross-sectional area of flow}}{\text{wetted perimeter}} \\ &= \frac{0.0157}{0.31416} = 0.05 \text{ m}\end{aligned}$$

$$\text{Slope, } S = \frac{1}{50} = 0.02$$

$$\begin{aligned}\text{Velocity, } v &= c\sqrt{RS} = 50\sqrt{0.05 \times 0.02} \\ &= 50 \times 0.0316 = 1.581 \text{ m/s}\end{aligned}$$

Example 12.8

A rectangular culvert, shown in Figure 12.16, runs half-full of water and is laid at a gradient of 1 in 100. Find the velocity of water flow in the culvert using the Chézy equation and the Manning equation, if:

- the Chézy coefficient is $50 \text{ m}^{1/2}/\text{s}$.
- the Manning's roughness coefficient is 0.012.

Solution:

- Cross-sectional area of flow = $2.0 \times 0.9 = 1.80 \text{ m}^2$
Wetted perimeter = $0.9 + 2.0 + 0.9 = 3.8 \text{ m}$

$$\begin{aligned}\text{Hydraulic radius, } R &= \frac{\text{cross-sectional area of flow}}{\text{wetted perimeter}} \\ &= \frac{1.8}{3.8} = 0.4737 \text{ m}\end{aligned}$$

$$\text{Slope, } S = \frac{1}{100} = 0.01$$

$$\begin{aligned}\text{Chézy equation: } v &= c\sqrt{RS} = 50\sqrt{0.4737 \times 0.01} \\ &= 50 \times 0.0688 = 3.441 \text{ m/s}\end{aligned}$$

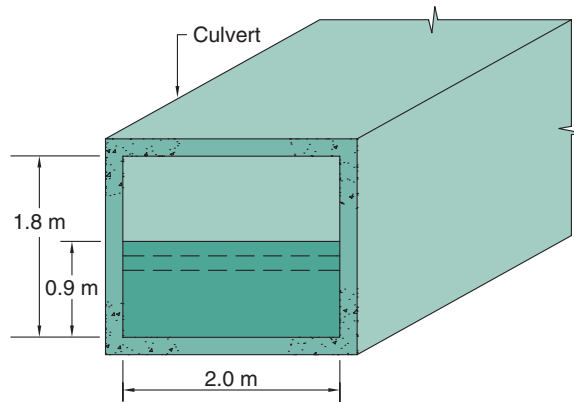


Figure 12.16

b) The Manning equation is: $v = \frac{1}{n} R^{2/3} S^{1/2}$

$$= \frac{1}{0.012} \times 0.4737^{2/3} \times 0.01^{1/2}$$

$$= 5.064 \text{ m/s}$$

(Refer to the chapter on: 'Using a scientific calculator' to determine $R^{2/3}$ and $S^{1/2}$.)

Exercise 12.1

1. A rectangular tank whose base measures 3 m by 2 m contains water to a depth of 1.5 m. Calculate a) the force exerted by the water on the base and the sides; b) the height of the centre of pressure above the base of each side of the tank.
Density of water, $\rho = 1000 \text{ kg/m}^3$, and $g = 9.81 \text{ ms}^{-2}$.
2. A concrete dam 300 m long has a vertical face on the reservoir side. Calculate a) the thrust on the dam if the depth of water is 24 m; b) the point of action of this thrust.
Given: $\rho = 1000 \text{ kg/m}^3$, and $g = 9.81 \text{ ms}^{-2}$.
3. A lock gate is 20 m wide. On one side, the water is 6 m above the lower edge of the gate and on the other side, the water is 1.5 m above the lower edge of the gate. Calculate:
a) the resultant force on the lock gate;
b) the point of action of the resultant force.
Given: $\rho = 1000 \text{ kg/m}^3$, and $g = 9.81 \text{ ms}^{-2}$.
4. A water tank measuring 6 m $\times$ 6 m $\times$ 3 m high has a rectangular door in one of the sides. The door is 1.2 m wide and 1.4 m high, and has a horizontal hinge at the top (see Figure 12.17). If the water is level with the hinge, calculate the horizontal force that must be applied to the lower edge of the door to keep it shut.
(Hint: Determine the thrust on the door and its moment about the hinge. This should be equal to the moment, about the hinge, due to the applied force.)

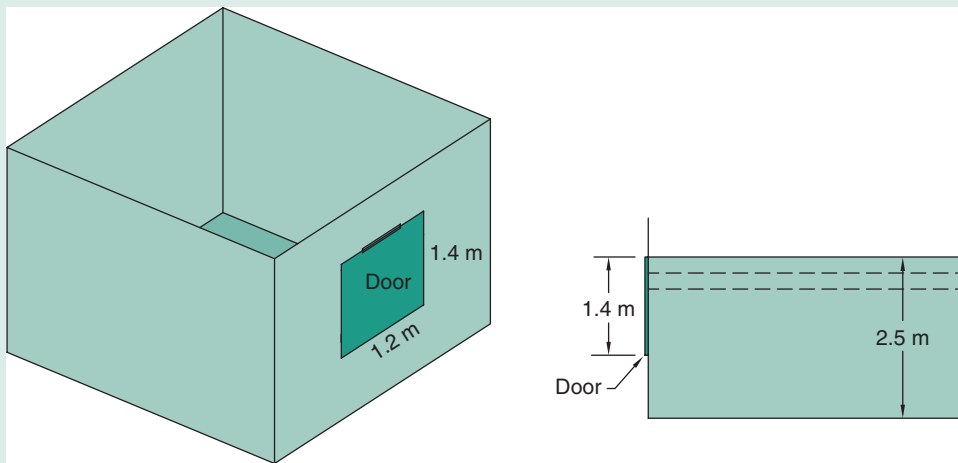


Figure 12.17

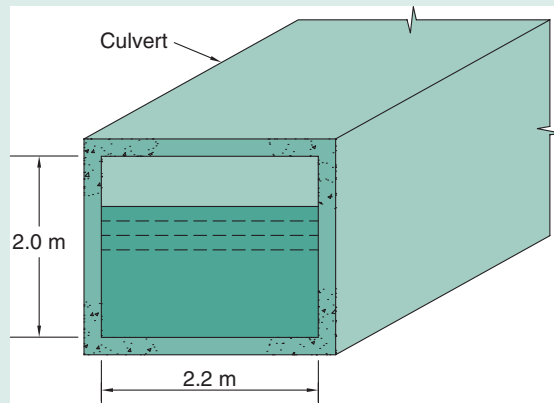


Figure 12.18

5. A pipeline is made by joining two pipes having diameters of 200 mm and 150 mm respectively. If 2.4 m^3 of water flows through the pipe per minute, and the pipes run full, find the flow velocity in each pipe.
6. A horizontal pipe decreases uniformly from 150 mm diameter to 100 mm diameter in the direction of the flow of water. The pressure at the narrow section of the pipe is $2.2 \times 10^5 \text{ N/m}^2$, when the flow rate is $0.12 \text{ m}^3/\text{s}$. Assuming that there are no friction losses, calculate the pressure at the 150 mm section.
7. A venturimeter is provided in a 150 mm diameter water pipe. The diameter of the throat is 75 mm, and the pressure heads in the main pipe and the throat are 15.0 m and 12.1 m

respectively. Calculate the flow rate in the pipe if the meter coefficient is 0.97 and the acceleration due to gravity is 9.81ms^{-2} .

8. A rectangular culvert, shown in Figure 12.18, runs three-quarters full of water and is laid at a gradient of 1 in 200. Find the velocity of water flow in the culvert using the Chézy equation and the Manning equation. The Chézy coefficient is $50\text{m}^{1/2}/\text{s}$ and the Manning's roughness coefficient is 0.011.

References/Further reading

1. Sherwin, K. and Horsley, M. (1995). *Thermofluids*. Abingdon: Spon Press.
2. Fox, R.W., McDonald, A.T. and Pritchard, P.J. (2009). *Introduction to Fluid Mechanics*. Hoboken: Wiley.

13

Sound

Learning outcomes:

- 1) Explain the terms: velocity, wavelength and frequency of sound.
- 2) Explain sound intensity, sound pressure and the decibel scale.
- 3) Explain how sound is transmitted into buildings and discuss the factors that affect sound insulation.
- 4) Discuss sound absorption, reverberation, and reverberation time.
- 5) Calculate reverberation time for a given building, and select appropriate materials/finishes to achieve the optimum reverberation time.

13.1 Introduction

Sound is a physical sensation produced by pressure variations in the air that are caused by sources of vibration. The sound waves, produced by a vibrating object, are transmitted through the medium (solid, liquid or gas) by means of successive compressions and rarefactions of its molecules. Sound waves cannot travel through a vacuum.

Figure 13.1b shows a vibrating tuning fork that is sending out sound vibrations due to the outward and inward movements of its prongs. When the prongs move outwards, the molecules of air are brought closer and hence a compression (C) results. This increases the pressure of the air. When the prongs move inwards, the molecules of air move wider apart, or a rarefaction (R) occurs. A rarefaction will create a region with lower pressure. These pressure variations are then passed on to the neighbouring layers of air, which in turn increase and decrease the pressure of further layers. This phenomenon is known as the **sound wave**.

In Figure 13.1a/b, the vertical lines represent the layers of molecules of air. A close spacing of these lines shows higher pressure whereas a wide spacing shows reduced pressure. Although the molecules of air keep on moving to and fro while the tuning fork vibrates, the sound wave (or the sound energy) travels outwards in all directions. The molecules of air come back to their original positions when the vibrations stop.

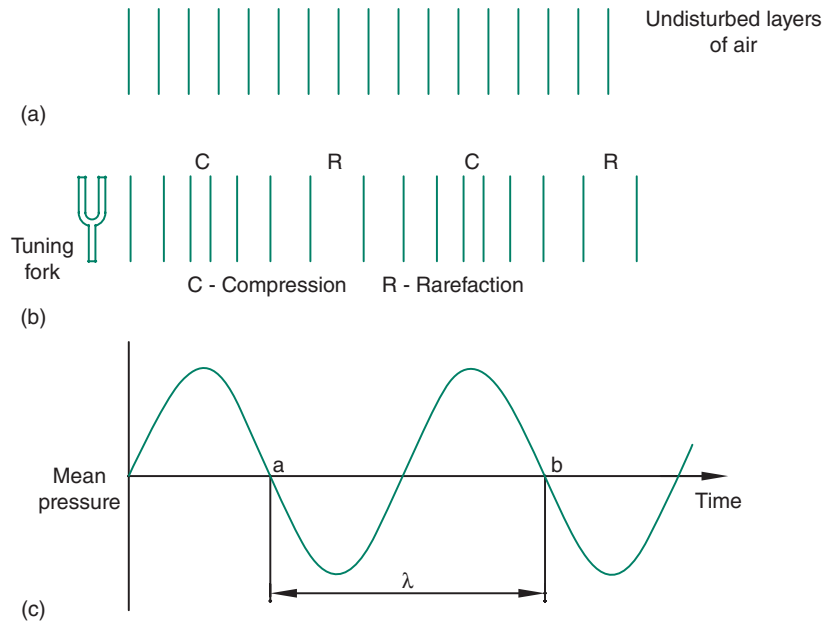


Figure 13.1

13.2 Frequency, wavelength and velocity of sound

13.2.1 Frequency (f)

The frequency of sound is defined as the number of complete waves, or vibrations, produced per second. Figure 13.1c, which represents a pure note of single frequency, shows one complete wave from point a to point b.

Unit: hertz (Hz).

In practice most of the sounds are a mixture of frequencies. The audible range for human beings is between 20 Hz and 20000 Hz, however, the upper limit lowers with age.

13.2.2 Wavelength (λ)

The wavelength of sound is defined as the distance that the wave travels in the course of one complete vibration (Figure 13.1c).

Unit: metre (m)

13.2.3 Velocity (v)

If the frequency of a sound is f hertz, then the wave will travel $f \times \lambda$ metres per second.

In other words, the velocity of sound, $v = f \times \lambda$.

Unit: m/s.

A comparison of the velocity of sound through air, water and some solid materials is given in Table 13.1.

The velocity of sound in a solid depends on its density and modulus of elasticity. Sound travels at a higher velocity in solids as they have high values of modulus of elasticity. The following relationship may be used to determine the velocity of sound in solid materials:

Table 13.1 Velocity of sound

Medium	Velocity (m/s)
Air (0°C)	331
Air (20°C)	344
Fresh water (20°C)	1481
Sea water (20°C)	1522
Wood	3000-4000
Bricks	4000
Aluminium	5100
Steel	5100
Glass	5000-6000

$$\text{Velocity of sound in solids, } v = \sqrt{\frac{E}{d}}$$

where E = modulus of elasticity of the material (N/m²)

d = density of the material (kg/m³)

Example 13.1

A vibrating tuning fork produces a sound wave of 256 Hz frequency and 1.30 m wavelength. Calculate the velocity of sound in air.

Solution:

$$\begin{aligned}\text{Velocity, } v &= f \times \lambda \\ &= 256 \times 1.30 = \mathbf{332.8 \text{ m/s}}\end{aligned}$$

Example 13.2

A musical instrument vibrates at a frequency of 500 Hz. The time for the transmission of vibrations (in air) through a distance of 50 m is 0.147 seconds. Calculate the velocity and wavelength of the sound vibrations in air.

Solution:

$$\begin{aligned}\text{Velocity, } v &= \frac{\text{distance}}{\text{time}} \\ &= \frac{50}{0.147} = \mathbf{340.14 \text{ m/s}}\end{aligned}$$

$$\text{Also, } v = f \times \lambda$$

$$340.14 = 500 \times \lambda$$

$$\text{or, } \lambda \text{ (wavelength)} = \frac{340.14}{500} = \mathbf{0.68 \text{ m}}$$

Example 13.3

Find the velocity of sound in steel if the density and the modulus of elasticity of steel are 7850 kg/m^3 and $2 \times 10^2 \text{ kN/mm}^2$ respectively.

Solution:

$$\text{Velocity of sound, } v = \sqrt{\frac{E}{d}}$$

$$\begin{aligned} E &= 2 \times 10^2 \text{ kN/mm}^2, \text{ but in the above formula the modulus} \\ &\quad \text{of elasticity should be in N/m}^2 \\ &= 2 \times 10^2 \times (1 \times 10^9) \text{ N/m}^2 \times (1 \text{ kN/mm}^2 = 1 \times 10^9 \text{ N/m}^2) \\ &= 2 \times 10^{11} \text{ N/m}^2 \end{aligned}$$

$$d = 7850 \text{ kg/m}^3$$

$$\begin{aligned} v &= \sqrt{\frac{E}{d}} = \sqrt{\frac{2 \times 10^{11}}{7850}} \\ &= \mathbf{5047.5 \text{ m/s}} \end{aligned}$$

13.3 Measurement of sound

Sound is produced when a vibrating source disturbs the air and transmits a sound wave through it in all directions. Our ears are not sensitive to the total sound energy but are sensitive to the rate at which the energy reaches them. This rate determines the loudness of a sound source, therefore, the **power** of a source of sound is the rate at which the energy is produced.

Unit of sound power: watt (W).

Sound waves travel in all directions away from the source. The surface area on which the waves fall increases as the distance from the sound source increases. Hence, the intensity of the sound waves decreases as we move away from the source.

Sound intensity is defined as the sound power per unit area over which the sound waves fall.

$$\text{Sound intensity, } I = \frac{\text{sound power (watts)}}{\text{surface area (m}^2\text{)}}$$

Unit: W/m^2 .

Since audible sound consists of pressure waves, sound pressure may also be used to quantify sound. **Sound pressure** (p) is defined as the pressure variations relative to atmospheric pressure caused by the sound wave.

Unit: N/m^2 or pascals (Pa).

$$1 \text{ N/m}^2 = 1 \text{ Pa}$$

Sound intensity is proportional to the square of the sound pressure and is expressed as:

$$I = \frac{p^2}{\rho v}$$

where I = sound intensity in W/m^2

p = sound pressure in N/m^2

ρ = density of the medium (density of air at $20^\circ\text{C} = 1.2 \text{ kg/m}^3$)

v = velocity of sound

13.3.1 Threshold values of sound

Many sound measurements are made relative to a standard **threshold of hearing**, which is defined as the weakest sound that the average human ear can detect.

The threshold of hearing varies with frequency, but at 1000 hertz the values are:

in terms of intensity: $I_0 = 1 \times 10^{-12} \text{ W/m}^2$

in terms of pressure: $p_0 = 2 \times 10^{-5} \text{ N/m}^2$ (or Pa)

The strongest sound that the human ear can tolerate is defined as **threshold of pain**. Generally, the threshold of pain decreases with age, but the damage done by loud sounds to human hearing is the same, irrespective of age. The values of the threshold of pain are:

in terms of intensity: $I_p = 100 \text{ W/m}^2$

in terms of pressure: $p_p = 200 \text{ N/m}^2$ (or Pa)

13.3.2 The decibel scale

The strength of sound may be specified in terms of sound intensity or sound pressure. However, the range of values between the threshold of hearing and the threshold of pain is so large that their use is not convenient. Another problem is that the response of the ear to any change in pressure is dependent on the existing pressure, i.e. it is a comparison between the new and the old sound levels. In order to have a convenient range of values that compare reasonably well with the way that the ear responds to sound, the **bel** scale was devised. The bel scale is a logarithmic scale and is basically a ratio of two sound levels:

$$\text{Sound intensity level (in bel)} = \log_{10} \left[\frac{I_1}{I_0} \right]$$

where I_1 and I_0 are the sound intensities to be compared.

I_0 is the reference-level sound intensity; in most cases it is the threshold of hearing, i.e. $1 \times 10^{-12} \text{ W/m}^2$.

A tenfold increase in intensity of the sound equates to an increase of one unit on the bel scale. For example, if a sound intensity increases ten times from 0.1 W/m^2 to 1.0 W/m^2 , the corresponding increase on the bel scale is:

$$\text{Sound level} = \log_{10} \left[\frac{I_1}{I_0} \right] = \log_{10} \left[\frac{1.0}{0.1} \right] = \log_{10} 10 = 1.0 \text{ bel}$$

The **decibel** (dB) value of the intensity of a sound is ten times the bel value:

$$\text{Sound intensity level (in dB)} = 10 \times \text{bel value} = 10 \log_{10} \left[\frac{I_1}{I_0} \right]$$

$$\text{Also, Sound pressure level (in dB)} = 20 \log_{10} \left[\frac{p_1}{p_0} \right]$$

where p_1 = sound pressure level in N/m^2

p_0 = reference value of sound pressure. In most cases, it is the threshold of hearing, i.e. $2 \times 10^{-5} \text{ N/m}^2$

Table 13.2 shows the sound levels between the thresholds of hearing and pain, and their equivalent values in bel and decibels.

Table 13.2

Sound pressure	Intensity of sound	Sound level		Sound source/effect
		Bel	Decibels	
2×10^{-5}	1×10^{-12}	0	0	Threshold of hearing
	1×10^{-11}	1	10	Rustling leaves
2×10^{-4}	1×10^{-10}	2	20	Whisper
	1×10^{-9}	3	30	Quiet library
2×10^{-3}	1×10^{-8}	4	40	Quiet office
	1×10^{-7}	5	50	Average office
2×10^{-2}	1×10^{-6}	6	60	Normal conversation
	1×10^{-5}	7	70	Noisy restaurants
2×10^{-1}	1×10^{-4}	8	80	Normal traffic
	1×10^{-3}	9	90	Heavy traffic
2×10^0	1×10^{-2}	10	100	Near a pneumatic drill
	1×10^{-1}	11	110	Riveting machine
2×10^1	1×10^0	12	120	Chain saw
	1×10^1	13	130	Aircraft take-off (threshold of pain)
2×10^2	1×10^2	14	140	Intense physical pain

Example 13.4

The intensity of a sound is $2.5 \times 10^{-6} \text{ W/m}^2$. If the threshold of hearing is $1 \times 10^{-12} \text{ W/m}^2$, find the sound intensity level of this sound in decibels.

Solution:

$$\text{Sound intensity level} = 10 \log_{10} \left[\frac{I_1}{I_0} \right]$$

$$I_1 = 2.5 \times 10^{-6}; \quad I_0 = 1 \times 10^{-12}$$

$$\begin{aligned} \text{Sound intensity level} &= 10 \log_{10} \left[\frac{I_1}{I_0} \right] \\ &= 10 \log_{10} \left[\frac{2.5 \times 10^{-6}}{1 \times 10^{-12}} \right] \\ &= 10 \log_{10} [2.5 \times 10^6] \\ &= 10 \times 6.398 = \mathbf{63.98 \text{ dB}} \end{aligned}$$

Example 13.5

Find the increase in sound level if the sound intensity is:

- a) doubled b) trebled

Solution:

- a) In this question, I_1 is twice I_0 , therefore, $\frac{I_1}{I_0} = 2$

$$\begin{aligned} \text{Sound intensity level} &= 10 \log_{10} \left[\frac{I_1}{I_0} \right] \\ &= 10 \log_{10} 2 = \mathbf{3.01 \text{ dB}} \end{aligned}$$

(When the sound intensity is doubled, the increase in the number of decibels is 3.01.)

- b) In this question, I_1 is three times I_0 , therefore, $\frac{I_1}{I_0} = 3$

$$\begin{aligned} \text{Sound intensity level} &= 10 \log_{10} \left[\frac{I_1}{I_0} \right] \\ &= 10 \log_{10} 3 = \mathbf{4.77 \text{ dB}} \end{aligned}$$

13.4 Addition of sound levels

There are many instances when two or more sources produce sound simultaneously and it is important to find the overall effect. The individual sound levels, which may be specified either as sound intensity (W/m^2) or as sound pressure (N/m^2), may be added like ordinary numbers to find the resulting effect. However, if the sound levels are given in decibels, they cannot be added like ordinary numbers. Since the decibel scale is a logarithmic scale, the sound levels in decibels are converted to sound intensity, or to sound pressure, and then added. The addition of sound levels can be done by using either the equations given in Section 13.3.2 or a scale explained in Section 13.4.1.

13.4.1 Approximate addition of sound levels

The decibel levels can be added quickly by using the scale shown in Figure 13.2.

The calculation firstly involves finding the difference between the two sound levels. The difference is located on the upper scale, and the correction determined from the lower scale. The correction is then added to the higher sound level to find the overall sound level.

Example 13.6

Two car engines were started at the same time and the corresponding noise levels measured at a certain point were $5 \times 10^{-1} \text{ Pa}$ and 1.6 Pa . Calculate the overall noise level in decibels.

Solution:

Overall noise level, $p_1 = 5 \times 10^{-1} + 1.6 \text{ Pa} = 2.1 \text{ Pa}$

$$\begin{aligned} \text{Overall noise level (in dB)} &= 20 \log_{10} \left[\frac{p_1}{p_0} \right] \\ &= 20 \log_{10} \left[\frac{2.1}{2 \times 10^{-5}} \right] \\ &= 20 \log_{10} (1.05 \times 10^5) \\ &= \mathbf{100.42 \text{ dB}} \end{aligned}$$

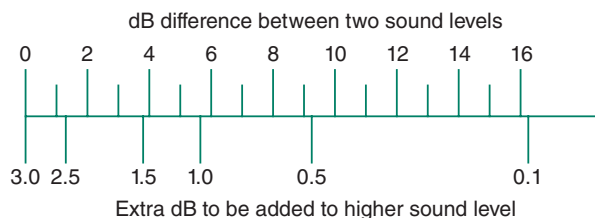


Figure 13.2 Addition of decibel levels.

Example 13.7

Three machines working at the same time produce noise levels of 70 dB, 75 dB and 82 dB. Find the overall noise level using the approximate, and the analytical, method.

Solution:

As explained in Section 13.4, the decibel levels of noise cannot be added like ordinary numbers; $70 + 75 + 82 = 227$ dB will be totally wrong. The overall noise level can be determined by two methods: the approximate, and the analytical, method, which are given below.

a) The approximate method

In this method, the scale shown in Figure 13.2 is used. As only two noise levels can be dealt with at a time, consider 70 dB and 75 dB first.

$$\text{Difference} = 75 - 70 = 5 \text{ dB}$$

The difference of 5 dB is located on the upper scale, and the correction found from the lower scale. Correction = 1.2 dB

$$\text{Overall noise level of 70 and 75 dB} = 75 + 1.2 = 76.2 \text{ dB}$$

Now consider 76.2 and 82 dB:

$$\text{difference} = 82 - 76.2 = 5.8 \text{ dB}$$

$$\text{correction} = 1.0 \text{ dB}$$

$$\text{Overall noise level} = 82 + 1.0 = \mathbf{83 \text{ dB}}$$

b) The analytical method

In this method, we need to change each decibel level into sound intensity. The sound intensities are added and the resulting noise level converted back into decibels. Let us first convert 70 dB into sound intensity.

From Section 13.3.2, sound intensity level (dB) = $10 \log_{10} \left[\frac{I_1}{I_0} \right]$

$$70 = 10 \log_{10} \left[\frac{I_1}{I_0} \right]$$

$$\frac{70}{10} = \log_{10} \left[\frac{I_1}{I_0} \right] \quad \text{or, } \log_{10} \left[\frac{I_1}{I_0} \right] = 7$$

To cancel out $\log_{10}$ take antilog of both sides:

$$\text{antilog} \left(\log_{10} \frac{I_1}{I_0} \right) = \text{antilog} 7$$

$$\frac{I_1}{I_0} = 10^7 \text{ or, } 10000000$$

$$\text{Similarly, } 10 \log_{10} \left[\frac{I_2}{I_0} \right] = 75$$

Take antilog of both sides:

$$\text{antilog}\left(\log_{10}\frac{I_2}{I_0}\right) = \text{antilog}7.5$$

$$\frac{I_2}{I_0} = 3.162 \times 10^7$$

$$\text{and, } 10\log_{10}\left[\frac{I_3}{I_0}\right] = 82$$

After taking antilog of both sides, $\frac{I_3}{I_0} = 1.585 \times 10^8$

Now we can add all the sound intensities:

$$\frac{I_4}{I_0} = \frac{I_1}{I_0} + \frac{I_2}{I_0} + \frac{I_3}{I_0}$$

$$\begin{aligned}\frac{I_4}{I_0} &= 10^7 + 3.162 \times 10^7 + 1.585 \times 10^8 \\ &= 2.001 \times 10^8\end{aligned}$$

Finally, convert the total intensity into decibels:

$$\begin{aligned}\text{sound intensity level (dB)} &= 10\log_{10}\left[\frac{I_4}{I_0}\right] \\ &= 10\log_{10}(2.001 \times 10^8) \\ &= \mathbf{83.01\text{ dB}}\end{aligned}$$

13.5 Transmission of sound in buildings

Sound is transmitted into buildings as **airborne** sound and **impact** sound. Airborne sound is defined as the sound that is produced by a vibrating object and travels through air as waves. Typical examples are the sound produced by musical instruments, speech, traffic noise etc. Impact sound, also known as structure-borne sound, occurs when a building component is set into vibrations by impact, e.g. footsteps, vibrating machinery and slammed doors (Figure 13.3).

A building should provide adequate insulation from airborne as well as from impact sound. Sound waves, produced by sources like traffic, travel through air as airborne sound and fall on the roof, windows, external doors and external walls, and set these elements into vibrations. Some of the sound energy is used in this process, the rest transmitted to the interior of the building. Any gaps or cracks, which may exist around doors and windows, allow an easy passage for the sound waves.

Sound may also travel through walls, floors and other components to other parts of the building by **flanking transmission**, as shown in Figure 13.3.

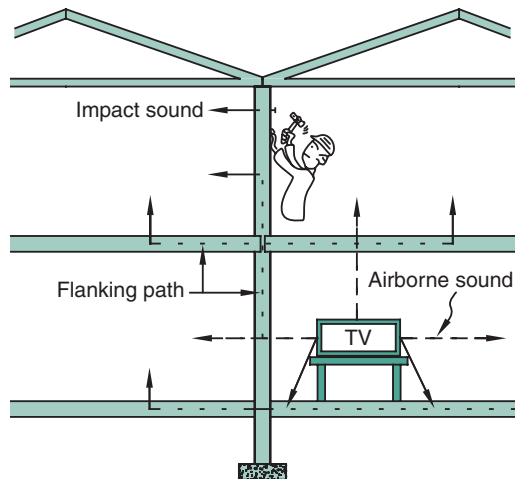


Figure 13.3

13.5.1 Noise

Disturbance by noise is one of the most annoying aspects of life in the modern world. There are several sources of noise, for example, noisy neighbours, road traffic, low-flying aircraft etc. Even music is noise when someone is trying to sleep or concentrate on some activity.

Any unwanted sound is called noise. Traffic noise accounts for a major proportion of the total noise generated outside dwellings in the UK. It is caused by the engine noise and the vibrations of tyres on the road surface. Low speeds can reduce noise levels; a 20–24 kph (kilometres per hour) increase in speed results in noise levels rising by 4–5 decibels. Traffic-calming measures may reduce the vehicles' speed but could cause an increase in noise levels if the result is several stop-go vehicle movements.

Aircraft noise also harms people's health. Many people who live under the flight path suffer high levels of annoyance, stress and sleep deprivation.

Exposure to intense noise, for a few hours, causes a temporary loss of hearing sensitivity known as temporary threshold shift (TTS). After some rest, the person usually recovers. If someone is exposed to intense occupational noise over a period of several years, the TTS changes to permanent threshold shift as there is not enough time to recover.

13.5.2 Requirements of sound insulation

Before describing the techniques for achieving sound insulation, it is important to understand the underlying principles of good sound insulation; these are:

a) Mass

The insulation provided by a partition is directly proportional to its mass. As the mass of a material also depends on its density, dense materials provide greater mass and hence

higher sound insulation. Sound waves can easily set light partitions into vibrations and transmit noise into a building. Sound insulation of walls may therefore be improved either by increasing the thickness or by using materials of higher density. However, for external walls, lighter materials are preferred as they provide better thermal insulation.

Generally, doubling the mass of a partition increases its sound insulation by 5 dB. A one-brick thick wall (215 mm + plaster) has a mass of 415 kg/m² and gives an average sound insulation of about 50 dB.

b) Completeness

The external envelope of a building contains doors for access and windows for light and ventilation. The insulation provided by doors and windows is less than that provided by a brick wall due to lower mass per unit area. The doors and windows are fitted into openings in the wall and it is possible that the gaps between their frames and the wall are not sealed properly. Sound waves can easily pass through gaps and cracks and reduce the sound insulation of an otherwise well insulated wall. Before other measures are taken to increase the sound insulation of a wall, elimination of gaps around doors and windows should be considered first.

c) Discontinuous construction

Discontinuous construction may be used where we have to use materials that are light in weight, e.g. cavity wall construction involving aerated concrete blocks. For better results, the cavity should be wider than 50 mm, the gap filled with sound-absorbent materials, and the panels not connected by ties or other methods of construction. Typical examples of discontinuous construction are double-glazed windows, cavity walls and upper-floor construction.

d) Resonance and coincidence effects

If the sound waves have the same frequency as the natural frequency of the partition, **resonance** will occur, i.e. the vibrations are amplified. Resonance occurs at low frequencies and reduces the sound insulation of the building component.

Sound waves can cause a partition to bend inwards and outwards. When the incident sound reaches a partition at angles less than 90°, its projected wavelength may be the same as that of the resonant bending waves. The frequency at which the two wavelengths coincide is known as the critical frequency. The phenomenon, which occurs at high frequencies, is known as **coincidence** and causes efficient transfer of sound energy from one side of the panel to the other. The vibrations are amplified, causing a reduction in the sound insulation.

13.5.3 Sound-insulation techniques

Buildings should be designed to reduce the external and internal noise to acceptable levels. Typical examples of the **external noise** are traffic, aircraft, trains, construction work and noisy neighbours. The sources of **internal noise** are usually people and their

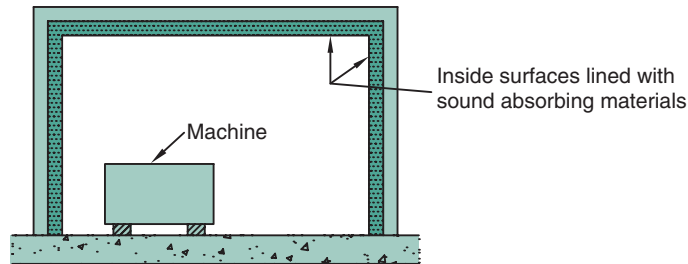


Figure 13.4

activities, and noisy machines/equipment. They could be either in another part of the building or in the same room as the affected people.

As the sound intensity is inversely proportional to the square of the distance from the source, the building should be sited as far away from the source of noise as possible. This can only be done at the design stage, but may not be feasible due to reasons such as shortage of suitable building sites.

Noise can be controlled in three ways: at the source; in its path (airborne sound); and at the receiver.

- a) **At source:** Some construction activities and machines in factories create noise that can be controlled at the source. Piling is a construction activity that creates a lot of noise if piling hammers are used. If possible, alternative methods of piling should be used, but otherwise the top of the pile should be provided with a hardwood or plastic block, called a dolly, to absorb the impact of the pile hammer and hence reduce noise. Machines in factories should be regularly serviced, but if a machine still produces excessive noise, then isolated rooms should be used to enclose such a machine (Figure 13.4). The material used in constructing an isolated room should have an appropriate sound-reduction index (see Section 13.5.5). Where pipes and ducts are used, they should enter through the walls with all the gaps properly sealed with mastic or similar sealant. Any gaps around doors and windows should also be sealed. For the safety of the machine operators or other personnel inside the enclosure, it is important to reduce the noise level within the room. This can be achieved by lining the walls and ceiling with absorbent material like mineral wool. The vibrations produced by a machine can travel through the floor to other parts of the building, and should be minimised by installing the machine on anti-vibration mountings made from springs, rubber, corkboard or other suitable materials.

The most common sources of impact noise are the footsteps or falling objects on floors with a hard surface. The impact can be reduced by covering the floor with a thick carpet and underlay or with tiles made of resilient materials. A floating floor may also be used as insulation against impact noise, and involves the provision of a layer of resilient material in between the top surface and the main supporting structure. Figure 13.5 shows two examples of floor construction to achieve sound insulation.

- b) **Airborne sound:** Noise can be minimised by putting a barrier in the path of the sound waves. Noise barriers can be made from a variety of materials such as timber,

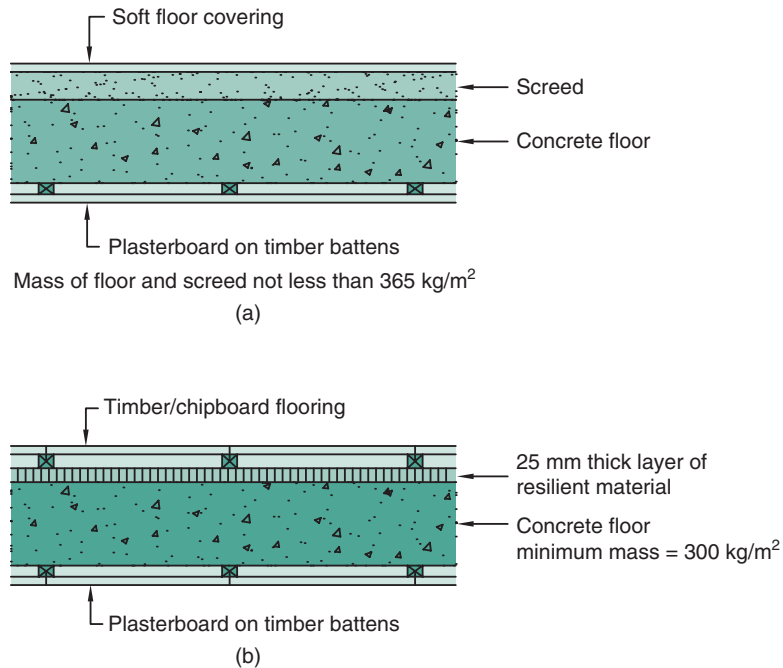


Figure 13.5

concrete, steel, bricks and plastic. For a barrier to be effective, it must be as dense as possible, of sufficient height, and have a mass of about 10 kg/m^2 . The cheapest solution is a close-boarded timber fence, high enough to maximise the path difference, as shown in Figure 13.6. Barriers formed by landscaping using earth embankments are quite effective in reflecting and absorbing traffic noise.

Trees and hedges may be used as noise barriers, but they can only be effective if there are several rows of them to provide dense vegetation. It is also important to bear in mind that the rustle of leaves may produce noise levels as high as 40 dB.

Noise from one room to another in the same building can be transmitted as direct sound and/or flanking transmission. Noise as direct sound is transmitted in the same way as noise from external sources and it can be dealt with by providing walls as heavy as possible. Doors and windows are weak points and, if not fitted carefully, they can reduce the overall insulation of a wall. They should fit properly without creating any gap between their frames and the wall. Noise may also travel through the flanking walls, floors and ceilings, which could be reduced by providing a layer of resilient material between the joints of the building elements.

- c) **At receiver:** When exposure to intense noise is unavoidable and the methods described previously are not practical, then measures must be taken to protect the receiver. This solution should be considered as a last resort in some situations. In others this may be the only solution, e.g. operatives using pneumatic drills. There are a variety of possibilities, for example, the use of ear protection.

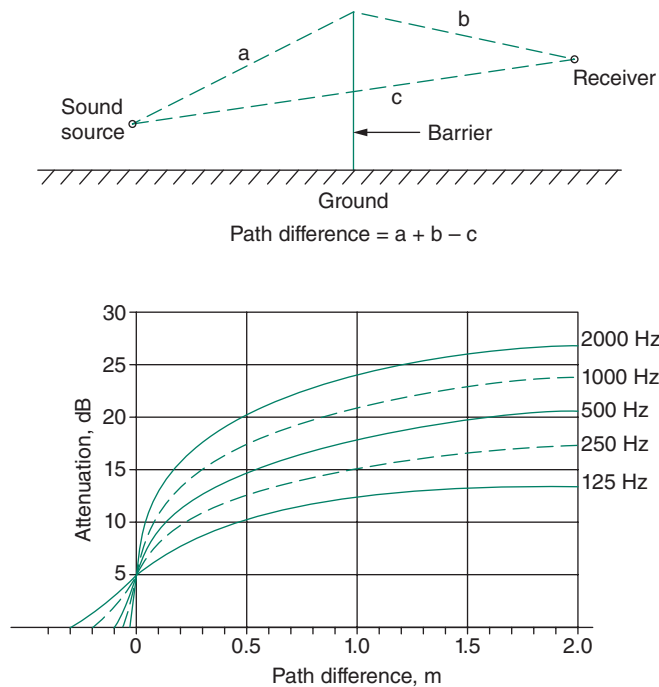


Figure 13.6

13.5.4 Noise in a workplace

The Noise Regulations require the employer to take specific action at certain noise levels:

- lower exposure action values:
daily or weekly exposure of 80 dB
peak sound pressure of 135 dB
- upper exposure action values:
daily or weekly exposure of 85 dB
peak sound pressure of 137 dB

There are also levels of noise exposure that must not be exceeded:

- daily or weekly exposure of 87 dB
- peak sound pressure of 140 dB

At and above a lower exposure action value: suitable hearing protection must be made available to any employee who requests it.

At and above an upper exposure action value: the exposure must be reduced to as low a level as possible by organisational and technical measures, excluding hearing protectors. These measures could include the choice of appropriate equipment, design and layout of workplaces, regular maintenance of equipment and appropriate work schedules. For more details, refer to the Health and Safety Executive's publication, Noise at work.

13.5.5 Measurement of sound insulation

The **sound reduction index** (R) of a building element is a measure of the sound insulation (in decibels) that the element provides. Its value depends on the magnitudes of incident and the transmitted sound energy, and is given by the expression:

$$R = 10 \log_{10} \left(\frac{\text{Incident sound energy}}{\text{Transmitted sound energy}} \right)$$

Example 13.8

The intensity of traffic noise incident on a building wall is $5 \times 10^{-5} \text{ W/m}^2$. If the wall transmits $2 \times 10^{-7} \text{ W/m}^2$ into the building, find the sound reduction index of the wall.

Solution:

$$\begin{aligned} \text{Sound reduction index (R)} &= 10 \log_{10} \left(\frac{\text{Incident sound energy}}{\text{Transmitted sound energy}} \right) \\ &= 10 \log_{10} \left(\frac{5 \times 10^{-5}}{2 \times 10^{-7}} \right) \\ &= 10 \times 2.398 = \mathbf{23.98 \text{ dB}} \end{aligned}$$

Example 13.9

The sound reduction index of a wall is 30 dB. Calculate what percentage of incident sound would be transmitted into the building.

Solution:

Let the incident sound be 100%, and the transmitted sound be x%.

$$\text{Sound reduction index (R)} = 10 \log_{10} \left(\frac{\text{Incident sound energy}}{\text{Transmitted sound energy}} \right)$$

$$30 = 10 \log_{10} \left(\frac{100}{x} \right)$$

$$\frac{30}{10} = \log_{10} \left(\frac{100}{x} \right)$$

$$\text{Take antilog, antilog } 3 = \text{antilog} \left[\log_{10} \left(\frac{100}{x} \right) \right]$$

$$1000 = \frac{100}{x} \quad \text{or, } x = \mathbf{0.1}$$

The transmitted sound is **0.1%** of the incident sound.

13.6 Sound absorption

In this section the quality of sound produced in a room or a hall will be discussed. When sound is produced in a room, the waves strike the walls, ceiling, floor and other surfaces. Depending on the surface material, some of the sound is reflected, some absorbed, and the rest transmitted through the structure, as shown in Figure 13.7.

Different materials and surface finishes absorb different amounts of incident sound and it is the total amount of sound absorbed by the surfaces of a room that affects the quality of sound. Sound absorption coefficients are available for a range of building materials and surface finishes, and given by the ratio:

$$\text{Sound absorption coefficient, } (\alpha) = \frac{\text{amount of sound energy absorbed by a surface}}{\text{amount of incident sound energy}}$$

The best sound-absorber is an open window as none of the incident sound can be reflected back into the room. Table 13.3 shows typical values of sound absorption coefficients for some common materials.

The absorption of sound by a surface is the product of its area (m^2) and its absorption coefficient. In a room, there are several types of surfaces, for example, carpet as floor finish, plaster on brick/block walls, plasterboard ceiling, and furniture. As people absorb sound as well, the total sound-absorption units for a room are the sum of absorption by all the surfaces, including people.

Total sound absorption of a room = Σ (area of a surface $\times$ absorption coefficient)

The acoustic requirements for a room depend on the purpose for which it is to be used. Some of the requirements for good room acoustics are:

- i) Even distribution and adequate levels of sound to all listeners.
- ii) Adequate insulation against external noise.
- iii) Appropriate reverberation time.
- iv) Absence of acoustic defects like echoes, acoustic shadow etc.

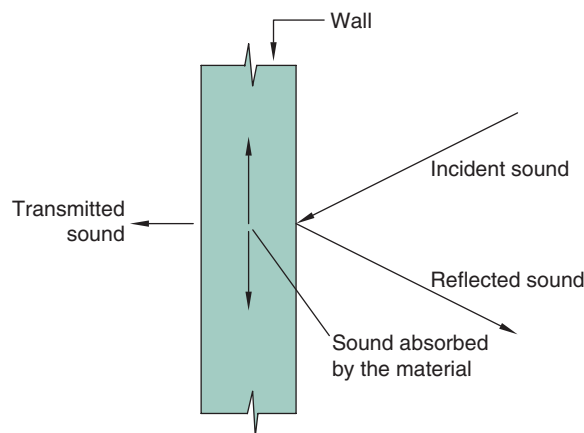


Figure 13.7

Table 13.3 Absorption coefficients

Material	Absorption coefficient		
	500 Hz	2000 Hz	4000 Hz
Brickwork	0.03	0.04	0.05
Carpet (medium) on timber floor	0.30	0.50	0.60
Carpet (medium) on concrete floor	0.20	0.30	0.40
Concrete	0.02	0.02	0.02
Curtains (medium fabrics) folded away from walls	0.45	0.50	0.50
Curtains (medium fabrics) straight, close to wall	0.25	0.30	0.40
Doors - panelled	0.08	0.10	0.10
Floor tiles - hard	0.03	0.05	0.05
Glass - 4 mm thick	0.10	0.05	0.05
Linoleum on solid backing	0.05	0.10	0.10
Plaster (gypsum) on a solid backing	0.02	0.04	0.03
Plasterboard ceiling (9.5 mm thick)	0.05	0.07	0.09
Suspended ceiling of plasterboard (large airspace behind)	0.10	0.05	0.05
Wood blocks on solid floor	0.05	0.10	0.10
Window (open)	1.00	1.00	1.00
Other items			
Air (per m ³)	-	0.007	0.02
Audience in fully upholstered seats (per person)	0.46	0.51	0.47
Seats (unoccupied) fully upholstered (per seat)	0.28	0.28	0.35

Like reverberations, **echoes** are also the result of reflection of sound. The former occurs when a reflected sound wave reaches the ear in less than 0.1 second after the original sound wave. If a reflected sound wave reaches the ear in more than 0.1 second after the original sound wave, it is known as an echo.

Acoustic shadow is also an acoustic defect. Areas that do not receive any sound are affected by acoustic shadow. In a hall, the front rows receive the direct sound whereas people sitting at the back receive only the reflected sound waves. Acoustic shadows also occur behind pillars and under low, deep balconies. To improve the hearing conditions in cinema halls and auditoria, the rows of seats are raked so that the direct sound is not obstructed (see Figure 13.8).

13.6.1 Reverberation

Reverberation is the continued presence of sound in an enclosure due to repeated reflections of sound from the surfaces. Consider a source of sound, e.g. a CD player, in a room where there is a listener 8.25 m away from the CD player. Sound produced by the CD player may reach the listener directly by path **d** and after reflections from the walls and other surfaces, as shown in Figure 13.9.

$$\text{Time taken for the direct sound to reach the listener} = \frac{\text{distance}}{\text{velocity}} = \frac{8.25}{344} = 0.024 \text{ s}$$

$$\text{Time taken for reflected sound } a_1 \text{ to reach the listener} = \frac{\text{distance}}{\text{velocity}} = \frac{16.0}{344} = 0.047 \text{ s}$$

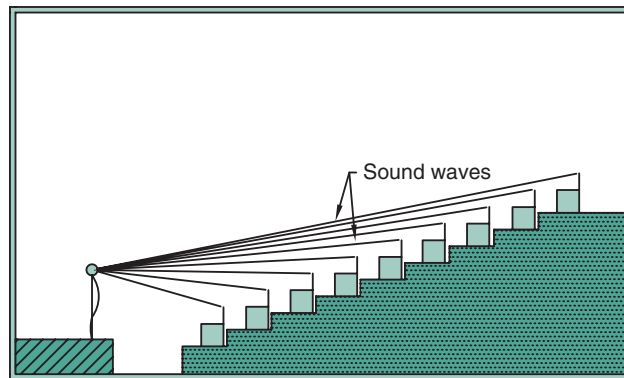


Figure 13.8 Raking of rows of seats to give unobstructed path for direct sound.

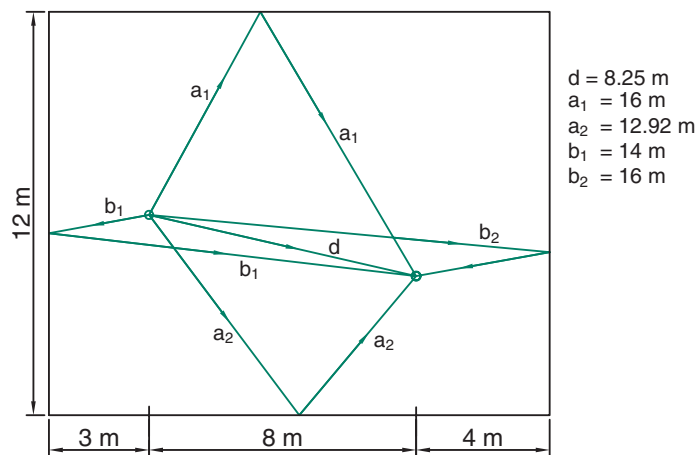


Figure 13.9 Sound paths in a room.

Similarly, the times taken for reflected sounds a_2 , b_1 , and b_2 are 0.038 s, 0.041 s and 0.047 s respectively. The multiple reflections cause two effects:

- distortion due to sound reaching the listener at different times;
- increase in the loudness of sound when several waves reach the listener simultaneously. Fortunately, when a sound wave strikes a surface, only a part of it is reflected, the rest is absorbed and/or transmitted.

13.6.2 Reverberation time

The reverberant sound in a room dies away with time as the sound energy is absorbed by the room surfaces. The time taken for a sound to decay by 60 dB is known as the **reverberation time** (RT). Figure 13.10 shows that a source that produced a sound level of 90 dB was stopped suddenly. The time taken for the sound level to decay by 60 dB

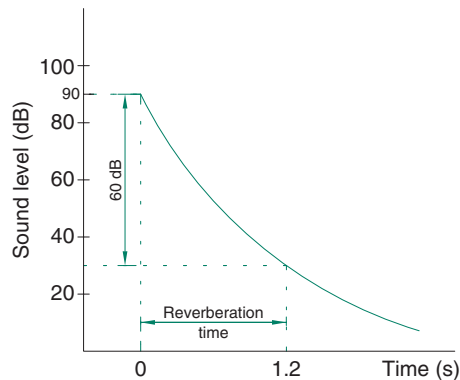


Figure 13.10

(from 90 to 30 dB) is 1.2 s, which is the reverberation time of the room. The main factors that affect the reverberation time of a room are its size and the sound-absorption properties of its surfaces.

The actual reverberation time in a room or a hall may be calculated from Sabine's formula:

$$RT = \frac{0.16V}{A}$$

where RT = reverberation time in seconds (s)

V = volume of room/hall in cubic metres (m³)

A = total absorption of room surfaces (m² sabins)

The optimum reverberation time is different from the actual reverberation time as it depends only on the size of the room and its use. Stephen and Bate's formula may be used to determine the optimum reverberation time:

$$RT \text{ (optimum)} = r[0.0118 \sqrt[3]{V} + 0.107]$$

where RT = reverberation time in seconds (s)

V = volume of room/hall in cubic metres (m³)

r = a constant: 4 for speech; 5 for orchestra; 6 for chorus

Example 13.10

A hall measuring 30 m × 25 m × 6 m high has the following surface finishes:

floor: medium-pile carpet on solid floor

walls: plaster on blockwork

ceiling: plasterboard on joists

doors: three - 2 m × 2 m high

windows: ten - 1.5 m × 2 m high

- Calculate the actual reverberation times at 500 Hz and 2000 Hz, if the capacity of the hall is 500 people. Assume that there is an acoustic shadow on 50% of the floor area.
- Calculate the optimum reverberation time if the hall is to be used for speech.
- Calculate the optimum reverberation time if the hall is to be used for orchestra.

Solution:

- To keep the calculations simple, the area of light fittings will be ignored. Due to the acoustic shadow, 50% of the floor area will be considered in the calculations.

$$\text{Floor area} = \text{ceiling area} = 30 \times 25 = 750 \text{ m}^2$$

$$\text{Wall area} = 2(30 \times 6 + 25 \times 6) = 660 \text{ m}^2$$

$$\text{Area of doors} = 2 \times 2 \times 3 \text{ no.} = 12 \text{ m}^2$$

$$\text{Area of windows} = 1.5 \times 2 \times 10 \text{ no.} = 30 \text{ m}^2$$

$$\text{Net wall area} = 660 - 12 - 30 = 618 \text{ m}^2$$

$$\text{Volume of hall, } V = 30 \times 25 \times 6 = 4500 \text{ m}^3$$

Surface	Area (m ²)	500 Hz		2000 Hz	
		Absorption coefficient	Absorption units	Absorption coefficient	Absorption units
	(a)	(b)	(= a × b)	(c)	(= a × c)
Walls	618	0.02	12.36	0.04	24.72
Floor	50% of 750 = 375	0.20	75.0	0.30	112.5
Ceiling	750	0.05	37.5	0.07	52.5
Windows	30	0.10	3.0	0.05	1.5
Doors	12	0.08	0.96	0.10	1.2
Audience	500 people	0.46	230	0.51	255
Air	Volume = 4500 m ³	-	-	0.007	31.5
			Total (A) = 358.82	Total (A) = 478.92	

$$\begin{aligned} \text{Actual RT at 500 Hz} &= \frac{0.16 V}{A} \\ &= \frac{0.16 \times 4500}{358.82} = \mathbf{2.0 \text{ s}} \end{aligned}$$

$$\text{Actual RT at 2000 Hz} = \frac{0.16 \times 4500}{478.92} = \mathbf{1.50 \text{ s}}$$

$$\text{b) Optimum RT} = r[0.0118 \sqrt[3]{V} + 0.107]$$

$$r \text{ (for speech)} = 4, \text{ Volume, } V = 4500 \text{ m}^3$$

$$\begin{aligned} \text{Optimum RT} &= 4[0.0118 \times \sqrt[3]{4500} + 0.107] \quad (\sqrt[3]{4500} = \text{cube root of } 4500) \\ &= 4[0.0118 \times 16.51 + 0.107] \\ &= 4[0.1948 + 0.107] = \mathbf{1.21 \text{ s}} \end{aligned}$$

The reverberation time at 2000 Hz is slightly more than the optimum value, but at 500 Hz the actual RT is 0.79 s higher than the optimum. This needs to be brought down to about 1.2 s by using alternative finishes.

$$\text{c) } r \text{ (for orchestra)} = 5, \text{ Volume, } V = 4500 \text{ m}^3$$

$$\begin{aligned} \text{Optimum RT} &= 5[0.0118 \times \sqrt[3]{4500} + 0.107] \\ &= 5[0.0118 \times 16.51 + 0.107] \\ &= \mathbf{1.51 \text{ s}} \end{aligned}$$

This is very close to the actual reverberation time at 2000 Hz, but 0.49 s lower than the actual reverberation time at 500 Hz. Some of the finishes need to be altered to achieve a match between the actual and the optimum reverberation times.

(A spreadsheet of this example is given in Appendix 2.)

Example 13.11

In Example 13.10, the actual reverberation time at 500 Hz is 2.0 s. Suggest suitable materials to bring the reverberation time down to 1.2 s.

Solution:

$$\text{Total absorption units (from Example 13.10)} = 358.82$$

$$\text{Total absorption units required for a reverberation time of 1.2 s}$$

$$= \frac{0.16 V}{1.2} = \frac{0.16 \times 4500}{1.2} = 600$$

$$\text{Extra absorption units required} = 600 - 358.82 = 241.18$$

Acoustic panels ($\alpha = 0.8$) may be used to provide the extra absorption

$$\text{Area of acoustic panels required} = \frac{241.18}{0.8} = \mathbf{301.5 \text{ m}^2}$$

13.6.3 Types of sound absorbers

The frequency of sound affects the choice of materials that can be used as sound absorbers. Usually the absorption is considered for low-frequency, medium-frequency and high-frequency sounds. The absorption of low-frequency sound (up to about 400 Hz) is achieved

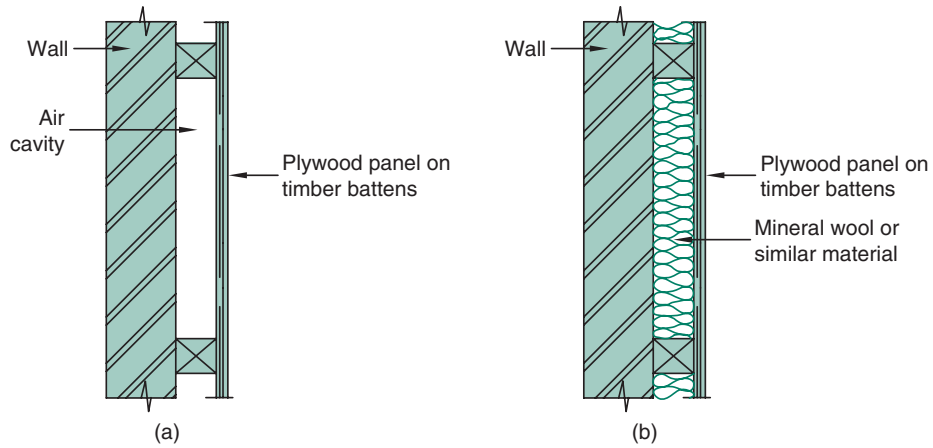


Figure 13.11

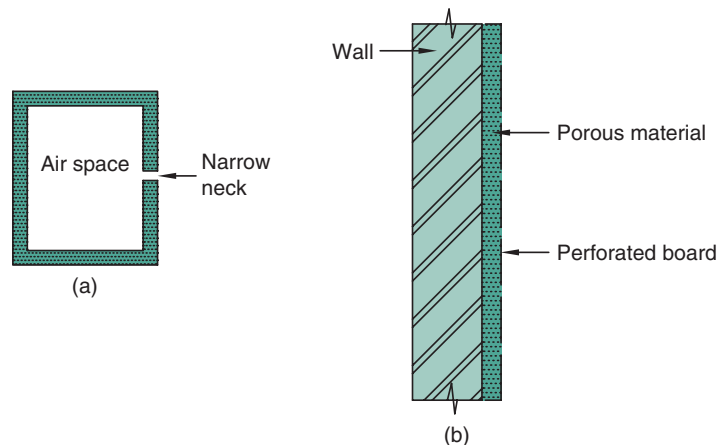


Figure 13.12

by panels of flexible material provided over a solid background with an air gap in-between. For slightly better results, the air gap may be filled with porous materials like mineral wool or glass fibre, as shown in Figure 13.11.

A cavity absorber, or Helmholtz resonator, which can be used to absorb sound of single specific frequency, consists of an enclosure of air with one narrow opening (Figure 13.12). Sound enters the air enclosure, resonates, and loses energy. A simple solution is to provide a perforated panel on a wall or a ceiling with an air space in-between. The absorption of sound can be enhanced by filling the air space with mineral wool or a similar material. The area of the panel used for perforations determines the performance of the absorber.

Porous materials like mineral wool, glass fibre, curtains and felt, either on their own or provided against a solid backing, will absorb a high-frequency sound, 500Hz and over.



Figure 13.13 Sound level meter.

13.7 Sound level meter

The digital sound level meter, illustrated in Figure 13.13, is a device to measure industrial noise, environmental noise and other sound levels. The sound is detected and sampled by the microphone, and then processed by electronic circuits in the meter. The sound level is finally shown, in decibels, as a digital LCD display. The 'A' frequency weighting can be used for all types of noise, whereas the 'C' frequency weighting is used for measuring the peak value of a noise.

Exercise 13.1

1. A vibrating tuning fork produces a sound wave of 256 Hz frequency and 1.35 m wavelength. Calculate the velocity of sound in air.
2. A musical instrument vibrates at a frequency of 512 Hz. The time for the transmission of vibrations (in air) through a distance of 50 m is 0.15 seconds. Calculate the velocity and wavelength of the sound vibrations in air.
3. Find the velocity of sound in a metal if its density and the modulus of elasticity are 2720 kg/m^3 and 70 kN/mm^2 respectively.
4. The intensity of a sound is $4.5 \times 10^{-7} \text{ W/m}^2$. If the threshold of hearing is $1 \times 10^{-12} \text{ W/m}^2$, find the sound intensity level of this sound in decibels.
5. The noise level produced by a machine is 90 Pa. Find the sound pressure level in decibels if the threshold of hearing (p_0) is $2 \times 10^{-5} \text{ Pa}$.
6. Two machines working at the same time produce noise levels of 6×10^{-1} and 1.3 Pa respectively. Calculate the overall noise level in decibels.

7. Two power drills and a chainsaw, working at the same time, produce noise levels of 90dB, 92dB and 105dB respectively. Find the overall noise level using the approximate, and the analytical, method.
8. The intensity of traffic noise incident on a building wall is $5 \times 10^{-5} \text{ W/m}^2$. The wall transmits $8 \times 10^{-8} \text{ W/m}^2$ into the building. Find the sound reduction index of the wall.
9. A hall measuring $40 \text{ m} \times 30 \text{ m} \times 6 \text{ m}$ high has the following surface finishes:
 floor: hardwood blocks on solid floor
 walls: plaster on blockwork
 ceiling: gypsum plaster on concrete
 doors: three - $2 \text{ m} \times 2 \text{ m}$ high
 windows: twelve - $1.5 \text{ m} \times 2 \text{ m}$ high
 - a) Calculate the actual reverberation times at 500Hz and 2000Hz, if the capacity of the hall is 500 people. Assume that there is 100% audience and that there is an acoustic shadow on 50% of the floor area.
 - b) Calculate the optimum reverberation time if the hall is to be used for speech.
 - c) Calculate the optimum reverberation time if the hall is to be used for orchestra.
10. For Question 9, calculate the actual reverberation times at 500Hz and 2000Hz, if the audience is only 50% of the capacity of the hall. Assume that there is an acoustic shadow on 40% of the floor area.

References/Further reading

1. DfES (2003). Building Bulletin 93, Acoustic Design of Schools.
2. Health and Safety Executive (2005). *Noise at work - Guidance for employers on the Control of Noise at Work Regulations 2005*.
3. Tecpel Co. Ltd., Taiwan. Website: www.tecpel.net

14

Light

Learning outcomes:

- 1) Define solid angle, luminous intensity, luminous flux and illuminance, and state their units.
- 2) Explain the inverse square law and the cosine law of illuminance.
- 3) Perform calculations to determine illuminance directly under, and at a distance away from, a lamp.
- 4) Use the lumen design method to design the lighting scheme for a room.

14.1 Introduction

Light is a form of energy and forms part of the electromagnetic spectrum. The electromagnetic spectrum ranges from radio waves to gamma rays (Figure 14.1) with light as the only radiation that is visible to the human eye. All **electromagnetic waves** consist of energy in the form of electric and magnetic fields that fluctuate and can transport energy from one location to another. Light waves come in many sizes; the size of a wave is measured as its wavelength. The wavelengths of light waves range from 400 to 700 nanometres (nm).

Many scientists, including Isaac Newton, thought light to be made up of particles of matter that were emitted in all directions from a source. They assumed that light travelled only in straight lines whereas waves bend around obstacles. Robert Hooke and others thought that light was emitted in all directions as a series of waves. Both theories had many flaws but could explain some of the phenomena associated with light. Michael Faraday and James Maxwell proposed that light was a high-frequency electromagnetic radiation that could propagate in the absence of a medium. Finally, in 1905, Albert Einstein's ideas formed the basis for wave-particle dual theory. His theory explained that everything has a particle nature as well as a wave nature.

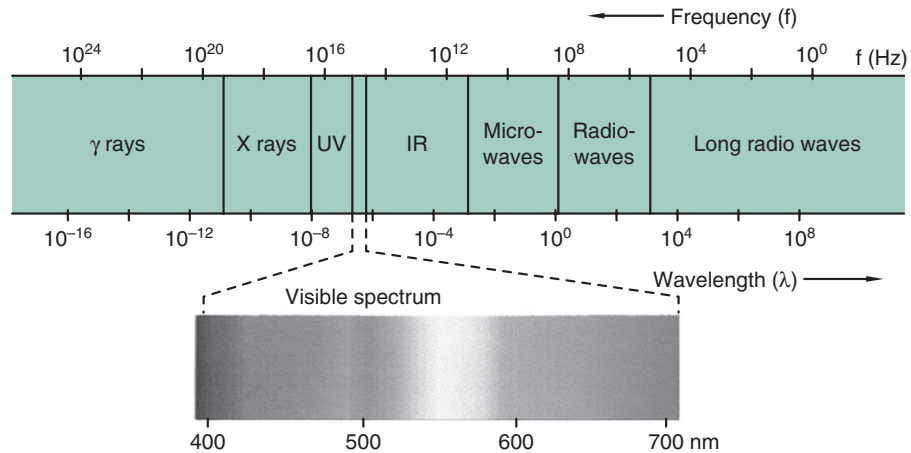


Figure 14.1 Electromagnetic spectrum. (See colour insert.)

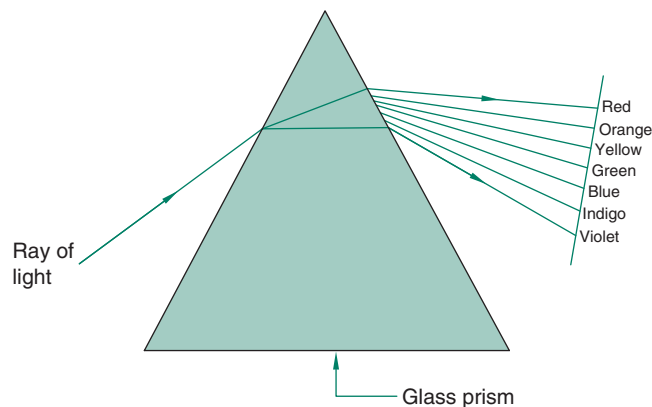


Figure 14.2 Dispersion of light.

Isaac Newton discovered that a glass prism, placed in the path of a narrow beam of sunlight, caused a series of overlapping coloured images to be formed on the screen. He called this phenomenon 'dispersion of light', i.e. the splitting of light into its component colours, as shown in Figure 14.2. This shows that sunlight is a mixture of seven colours, the same colours that we find in a rainbow. The coloured band is called a spectrum.

Like all other waves in the electromagnetic spectrum, light can also be reflected, refracted and diffracted. The two types of reflection that are important to interior designers and lighting engineers are explained in Section 14.7.4.

14.2 Additive and subtractive colours

White light can be produced by mixing three colours, i.e. red, blue and green, which are known as primary colours. When beams of coloured light are mixed to produce other colours, the process is known as additive colour mixing. For example:

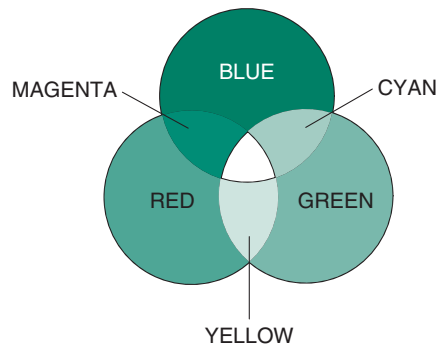


Figure 14.3 (See colour insert.)

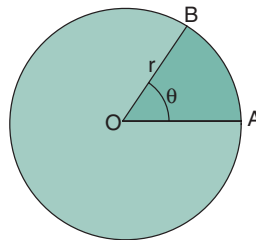


Figure 14.4 The radian.

Blue + green = cyan (white minus red will also produce the same effect)

Green + red = yellow

Red + blue = magenta

Red + blue + green = white (see Figure 14.3)

Subtractive colour mixing is based on the concept of taking colours away from white light. For example, a blue surface appears blue when white light falls on it because all the light is absorbed except the blue component, which is reflected. Similarly, a red surface appears red when white light falls on it because all the components are absorbed except the red.

14.3 Units for measuring light

14.3.1 Angular measure

The radian is a unit of measuring two-dimensional angles, for example, angles drawn on paper. In Figure 14.4, arc AB subtends angle θ at the centre of a circle of radius r . The value of angle θ , expressed in radians = $\frac{\text{length of arc AB}}{\text{radius}}$.

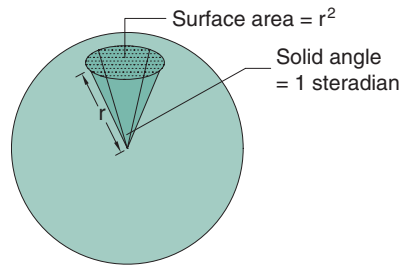


Figure 14.5 The steradian.

Angle $\theta = 1$ radian, when the length of arc AB equals the radius of the circle.

Circumference of the circle $= 2\pi r$

$$\begin{aligned}\text{Number of radians in circle} &= \frac{\text{circumference of the circle}}{\text{radius}} \\ &= \frac{2\pi r}{r} = 2\pi\end{aligned}$$

14.3.2 Solid angle

A source of light emits the rays of light in all directions. For the measurement of light, it becomes necessary to use a three-dimensional angle through which light rays travel. This three-dimensional angle is known as the **solid angle**.

Unit: steradian

Consider a small portion of the surface of the sphere shown in Figure 14.5. By joining the edges of the surface to the centre of the sphere by drawing several lines, a three-dimensional angle is created.

$$\text{The magnitude of the solid angle thus created} = \frac{\text{area of the surface}}{(\text{radius})^2} \text{ steradians}$$

When the surface area is equal to the square of the radius:

$$\text{Solid angle} = 1 \text{ steradian}$$

One **steradian** may be defined as the solid angle subtended at the centre of a sphere of radius r by an area of surface equal to the square of the radius.

$$\text{Total surface area of the sphere} = 4\pi r^2$$

$$\begin{aligned}\text{Total number of steradians in a complete sphere} &= \frac{\text{area of the surface}}{(\text{radius})^2} \\ &= \frac{4\pi r^2}{r^2} = 4\pi\end{aligned}$$

Therefore, the total solid angle at the centre of a sphere is 4π steradians.

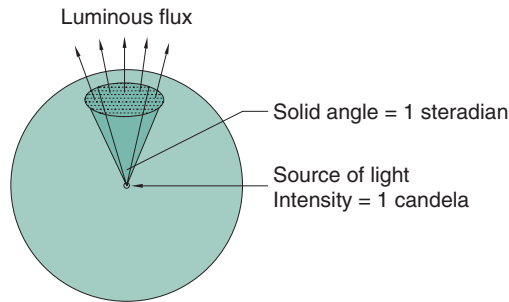


Figure 14.6 The lumen.

14.3.3 Luminous intensity (I)

The brightness or intensity of a source of light used to be compared with that of a standard candle. The unit used was known as candle power. The unit of luminous intensity used now is known as candela (cd) and is defined as:

The **luminous intensity** of a source that emits monochromatic radiation of frequency 540×10^{12} Hz and of which the radiant intensity in that direction is $\frac{1}{683}$ watt per steradian.

14.3.4 Luminous flux (F)

Luminous flux is a measure of the amount of energy emitted in a given time and is defined as the rate at which light energy flows from a source.

Unit: lumen (lm).

Figure 14.6 shows a point source of light of one candela luminous intensity. The luminous flux emitted within a solid angle of 1 steradian by a point source of light, having a uniform luminous intensity of 1 candela, is known as 1 lumen, or, in other words, 1 lumen is the quantity of light energy passing per second within the solid angle of 1 steradian.

The total energy radiated from a source is measured in watts. Because we can see only part of this radiation as visible light, we use lumen as the unit of light energy.

The total luminous flux (F) radiated by a uniform source of light, having luminous intensity of I candelas, is **$4\pi I$** lumens.

Mathematically, $F = 4\pi I$,

or, $F = SI$, where S is the solid angle.

14.3.5 Illuminance (E)

The light energy travels from a source and falls on surfaces to brighten them up. The quantity of light energy falling per second on a unit area of a surface is known as **illuminance**.

$$E = \frac{F}{A}$$

where F is the luminous flux in lumens (lm); A is the surface area in m^2 .

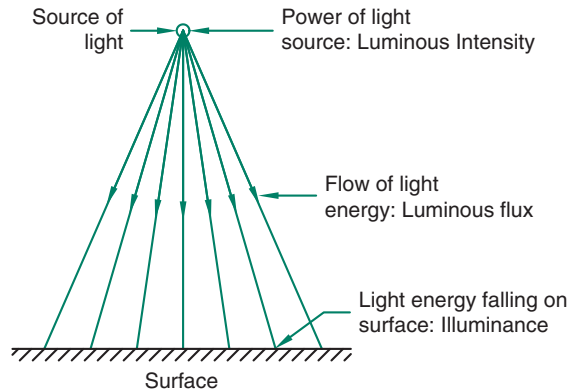


Figure 14.7 Summary of definitions.

Unit: the unit of illuminance is lux (lx)

$$1\text{ lux} = 1\text{ lm/m}^2$$

Figure 14.7 shows a point source of light having luminous intensity of 1 candela. Assume that the solid angle through which light is emitted is 1 steradian. Then, by definition, the luminous flux emitted by the source is 1 lumen. The luminous flux falls on a surface with an area of 1 m^2 and produces illuminance of 1 lux.

14.3.6 Luminance

The intensity of light emitted by a unit area of a reflecting or luminous surface in a given direction is known as **luminance**.

Unit: cd/m^2

Example 14.1

A point source of light has a luminous intensity of 150 cd and radiates in all directions. Calculate the total luminous flux emitted by the source.

Solution:

$$\begin{aligned}\text{Total luminous flux, } F &= 4\pi I \\ &= 4\pi \times 150 \quad (\text{luminous intensity, } I = 150\text{ cd}) \\ &= \mathbf{1884.96\text{ lm}}\end{aligned}$$

14.4 Inverse square law of illuminance

The illuminance or brightness produced on a surface depends on the distance from the light source. The inverse square law of illuminance states that the illuminance produced on a surface varies inversely as the square of the distance between the source

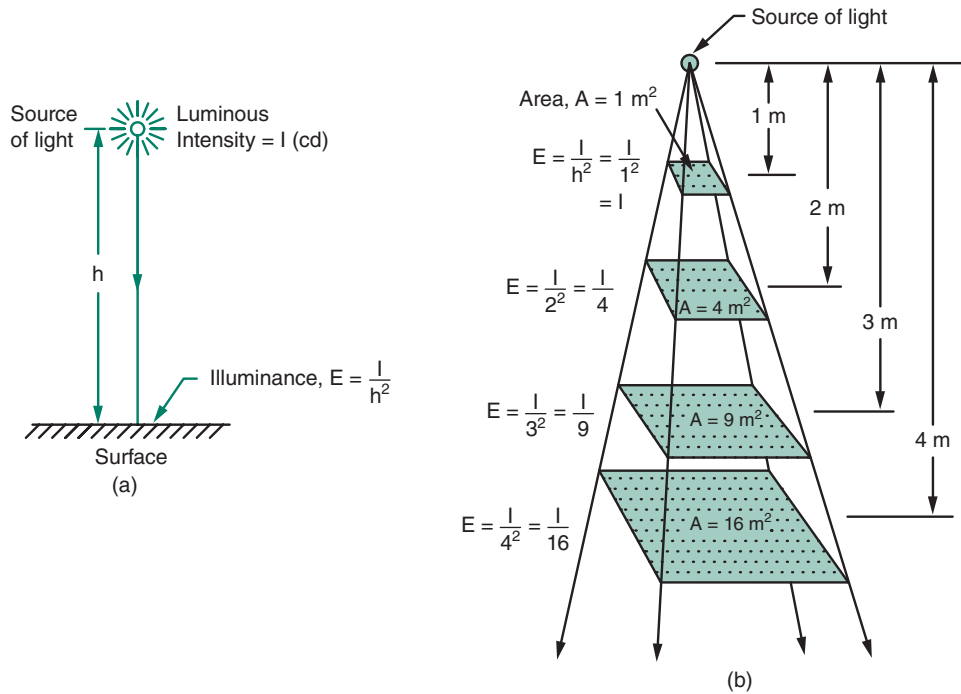


Figure 14.8 Inverse square law.

and the surface. The surface is normal to the direction of luminous flux, as shown in Figure 14.8a.

$$E = \frac{I}{h^2}$$

where E is the illuminance on a surface (lx)

I is the intensity of the light source (cd)

h is the perpendicular distance between the light source and the surface.

Figure 14.8b shows how illuminance varies as the reciprocal of the square of the distance between the source and the surface. When the surface is 1m away from the light source (assume $I = 720 \text{ cd}$), the illuminance produced is 720 lx . As the distance from the source increases, the flux reaches a bigger area, hence the illuminance is reduced; for example, at a distance of 2 m:

$$E = \frac{I}{h^2} = \frac{720}{2^2} = 180 \text{ lx}$$

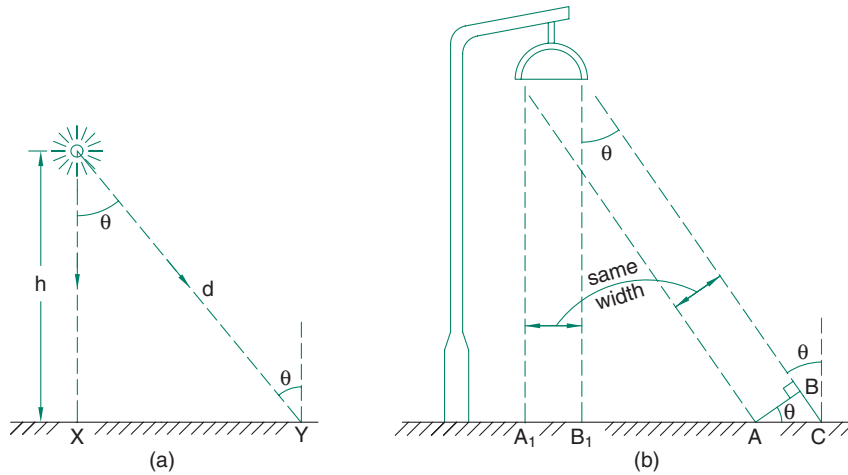


Figure 14.9 Cosine law of illuminance.

14.5 Lambert's cosine law of illuminance

The inverse square law is only applicable to the points on a surface that receive light rays from a source at right angles. However, lamps emit light at various angles, therefore the inverse square law needs to be corrected in order to study rays of light that are inclined.

Figure 14.9a shows that light falls normally at X , but obliquely (inclined) at Y . The illuminance at X is greater than that at Y because distance h is less than distance d . Also, light falls on a greater area at Y , and therefore results in decreased illuminance.

Consider a beam of light, inclined at angle θ to the normal. Draw line AB normal to the light rays.

In $\triangle ABC$ (Figure 14.9b), $AC = \frac{AB}{\cos \theta}$ (this can also be written as $\text{Area } AC = \frac{\text{Area } AB}{\cos \theta}$)

When $\theta = 0^\circ$, $\cos \theta = 1$; therefore $AC = AB = A_1B_1$

When $\theta = 90^\circ$, no point on the floor receives any light, as the light rays are horizontal.

For any angle between 0° and 90° , area AC will be greater than area AB .

When $\theta = 60^\circ$, $\cos \theta = 0.5$; therefore $AC = 2 AB$.

The inverse square law $\left(\frac{I}{d^2}\right)$ is modified for light falling obliquely on a horizontal surface and is known as Lambert's cosine law of illuminance:

$$E = \frac{I}{d^2} \cos \theta \quad (1)$$

$$\text{From Figure 14.9a, } \frac{h}{d} = \cos \theta, \text{ therefore } d = \frac{h}{\cos \theta}, \text{ or, } d^2 = \frac{h^2}{\cos^2 \theta} \quad (2)$$

$$\text{Combining Equations 1 and 2, } E = \frac{I}{h^2} \cos^3 \theta \quad (3)$$

Equations 1 and 3 can be used to solve problems that involve light falling obliquely on surfaces.

Example 14.2

A street lamp (point source), having a luminous intensity of 1000 cd, is suspended 6 m above the edge of a road. If the road is 5 m wide, calculate the illuminance:

- at point A on the road surface, which is directly under the lamp;
- at a point, on the other edge of the road, directly opposite point A.

Solution:

a) $I = 1000 \text{ cd}$, $h = 6 \text{ m}$

$$\text{Illuminance, } E = \frac{I}{h^2} = \frac{1000}{6^2} = 27.78 \text{ lx}$$

b) From Figure 14.10, $d^2 = 6^2 + 5^2 = 61$

$$d = \sqrt{61} = 7.81 \text{ m}$$

$$\cos \theta = \frac{6}{7.81} = 0.76822$$

$$\begin{aligned} \text{Illuminance, } E &= \frac{I}{h^2} \cos^3 \theta \\ &= \frac{1000}{6^2} \times (0.76822)^3 = 12.59 \text{ lx} \end{aligned}$$

This question can also be solved by using the formula $E = \frac{I}{d^2} \cos \theta$

$$E = \frac{1000}{7.81^2} \times 0.76822 = 12.59 \text{ lx}$$

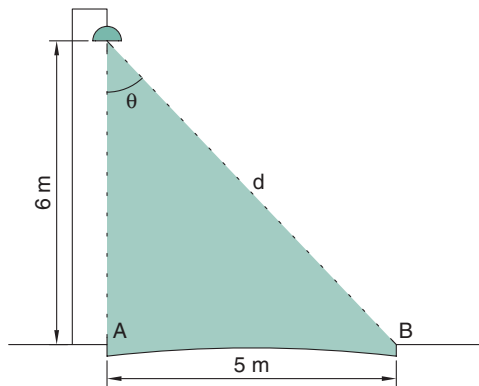


Figure 14.10

Example 14.3

Calculate the illuminance at A, due to two light sources shown in Figure 14.11.

Solution:

$$AB = AD = \sqrt{3^2 + 4^2} = 5 \text{ m}$$

$$\cos \theta = \frac{4}{5} = 0.8; \quad h = 4 \text{ m}$$

$$\begin{aligned} \text{Illuminance at A due to 200 cd source} &= \frac{I}{h^2} \cos^3 \theta \\ &= \frac{200}{4^2} \times 0.8^3 = 6.4 \text{ lx} \end{aligned}$$

$$\text{Similarly, illuminance at A due to 500 cd source} = \frac{500}{4^2} \times 0.8^3 = 16 \text{ lx}$$

$$\text{Total illuminance at A} = 6.4 + 16 = \mathbf{22.4 \text{ lx}}$$

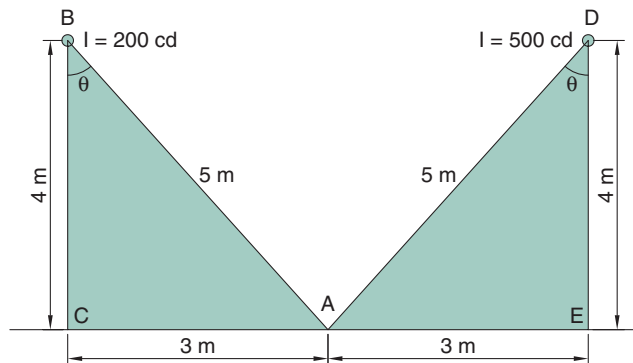


Figure 14.11

14.6 Lamps and luminaires

There are several types of lamp for indoor and outdoor use but in this section the discussion will be limited to a small selection. The first electric lamp that became popular in domestic and commercial applications is the **incandescent lamp** that consists of a tungsten filament in a glass enclosure (Figure 14.12a/b). When electric current is passed through the filament, it becomes red hot due to its resistance and gives off white light at a temperature of about 2500 °C. The common light bulb, technically known as the general lighting service (**GLS**) lamp, has a coiled tungsten filament. The space in the lamp is filled with inert gases, like argon and nitrogen, to prevent the oxidation of tungsten. The

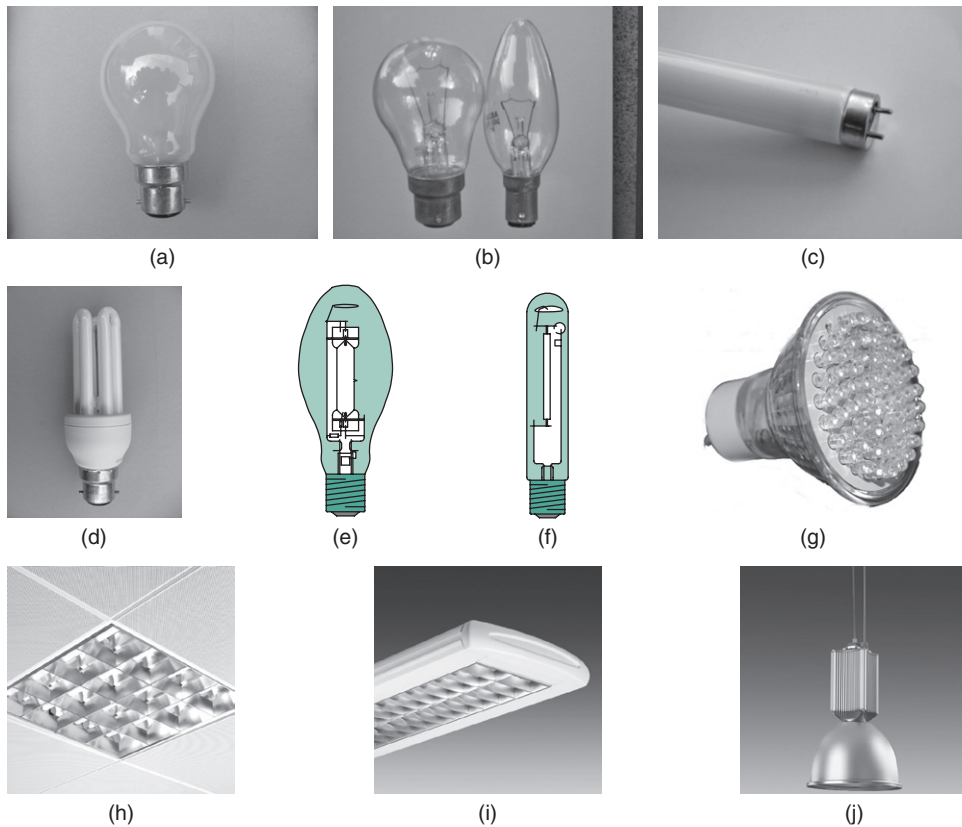


Figure 14.12 Lamps and luminaires. (See colour insert.)

efficacy (ability to convert electrical energy into light energy) is about 10–14 lumens/watt, with an operational life of about 1000 hours. The GLS lamp is cheap, easy to replace, and does not require any special device such as a ballast, which is required in fluorescent lamps. But it is the least efficient, as only about 5% of the electrical energy is converted to visible light. In the UK, the production and sale of the GLS lamp are being phased out gradually.

A **fluorescent lamp** or fluorescent tube (MCF) consists of a pair of electrodes, one at each end of a glass tube (Figure 14.12c). Mercury vapour and inert gas, like argon, are provided at low pressure inside the glass tube. As a current is passed, the mercury atoms become energised and produce ultraviolet (UV) radiation. The inside of the tube is coated with a chemical compound called phosphor which produces visible light when excited with UV radiation. Fluorescent lamps require a ballast (control gear) to provide a starting pulse of high voltage. A fluorescent lamp is more efficient than an incandescent lamp, having efficacy of 66–94 lm/W (tri-phosphor, linear fluorescent) and operational life of more than 15000 hours. The **compact fluorescent lamp** (CFL) is a miniature version of the fluorescent tube. Many CFLs are designed to replace GLS lamps and can fit into most existing standard lamp sockets (Figure 14.12d). There are two main parts in a CFL: the gas-filled tube; and the electronic/magnetic ballast. CFLs consume less electrical energy, as

compared to incandescent lamps, to produce the same amount of visible light. They have a longer operational life but are more expensive initially. Their disposal is not easy as they contain mercury. Their luminous efficacy ranges from 50 to 120 lm/W and their operational life ranges from 6000 hours to 15000 hours. Their use in domestic and other applications is becoming more popular despite objections from some people about the possibility of UV radiation and poor light quality.

Mercury vapour lamp (Figure 14.12e) is a gas discharge lamp that uses mercury in an excited state to produce light. The discharge takes place in a small, fused, quartz arc tube provided within a larger glass bulb. Like fluorescent lamps, mercury vapour lamps also utilise a ballast to provide a starting pulse of high voltage to cause ionisation of gas. Mercury vapour lamps are relatively efficient, offer a long operational life and give intense light for use in shops, factories and street lighting.

A **sodium vapour lamp** (Figure 14.12f) is also a gas discharge lamp that uses sodium in an excited state to produce light. The low-pressure sodium lamp (SOX) has an inner U-tube containing solid sodium and small amounts of neon and argon gas. The gases start the discharge and produce enough heat to vaporise sodium. These lamps produce yellow light and can be used where colour distinction is not important, as in street lighting and security lighting. High-pressure sodium lamps (SON) are smaller than low-pressure sodium lamps and additionally contain a small quantity of mercury. They give a whiter light and can be used where distinction between colours is important.

LEDs (light emitting diodes) are small, energy-efficient bulbs, illuminated by the movement of electrons in semiconductor material. They last for several years, give off virtually no heat and do not contain any harmful substances such as mercury. Depending on the material they are made of, they can produce different colours of light. LED bulbs are usually grouped in clusters to produce higher illuminance, as shown in Figure 14.12g. Their consumption is very low; the following table shows their comparison with incandescent bulbs:

Incandescent bulb	LED	Lumen	Colour
25 W	5 W	>210	White
40 W	7 W	>350	Warm white

A **luminaire** is the light fitting that protects and holds the lamp in position. Made from a range of materials like polycarbonate, aluminium, steel and glass, they may also have reflectors and diffusers, and hold the ballast. Depending on their intended use, they should withstand wet or dry conditions or even corrosive chemicals. Figure 14.12h/i/j shows a selection of luminaires.

14.7 Design of interior lighting

The design of interior lighting consists of selecting suitable lamps and luminaires to achieve the desired level of illuminance on the working surface (also called the working plane). Many companies have developed sophisticated computer programs to design interior lighting, but the student technician should be able to prepare the design using

the properties of lamps and luminaires, room surfaces, room environment etc. These are discussed in the following sections.

14.7.1 Light output ratio

A lamp is normally provided in a suitable fitting, called the luminaire. The amount of light emitted by a source does not reach the working surface in full; some of the light energy is lost by transmission through the luminaire. The **light output ratio** (LOR) of a luminaire is defined as the percentage of light emitted by it compared with the flux output of the light source.

$$\text{LOR} = \text{Upward LOR (ULOR)} + \text{Downward LOR (DLOR)}$$

$$\text{ULOR} = \frac{\text{total upward light output of the fitting}}{\text{total light output of the fitting}}$$

$$\text{DLOR} = \frac{\text{total downward light output of the fitting}}{\text{total light output of the fitting}}$$

Figure 14.13 shows light fittings with various DLORs.

A source does not emit light equally in all directions, which can be checked by drawing a **polar curve** of the luminaire. The polar curve of a luminaire is drawn by measuring its luminous intensity at different points in a given direction and plotting the points on a

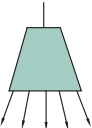
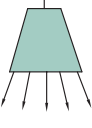
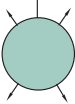
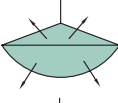
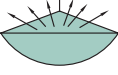
	Classification	DLOR
	Direct	> 90%
	Semi-direct	60–90%
	General diffusing	40–60%
	Semi-indirect	10–40%
	Indirect	< 10%

Figure 14.13

polar coordinate paper. This fact is considered in the lighting design by taking into account quantities such as the utilisation factor, downward light output ratio (DLOR) and direct ratio. The reflectance of room surfaces and the room index also affect the illuminance produced on the working plane.

14.7.2 Direct ratio

Direct ratio is the proportion of the total downward flux from the luminaire that falls directly on the working plane. The plot of direct ratio against room index (explained in Section 14.7.3) gives a curve which is compared to the standard curves and classed as one to which it is closest, i.e. BZ 1, BZ 3 etc. The whole range of possible lamp types is covered by a theoretical set of curves corresponding to ten different light concentrations.

14.7.3 Room index

Room index is also an important factor in calculating the level of illuminance. It is based on the length and the width of the room, and on the distance between the lamp and the working plane:

$$\text{Room index, } k = \frac{L \times W}{H_m(L + W)}$$

where L is the length of the room

W is the width of the room

H_m is the height of the light fitting above the working surface.

14.7.4 Reflection of light

Like all other waves in the electromagnetic spectrum, light can also be reflected. There are two types of reflection that are important to lighting engineers: direct reflection; and diffuse reflection.

Direct or regular reflection occurs when rays of light are reflected from a smooth surface without scatter. The angle of incidence is equal to the angle of reflection, as shown in Figure 14.14a.

Angle of incidence, i = angle of reflection, r

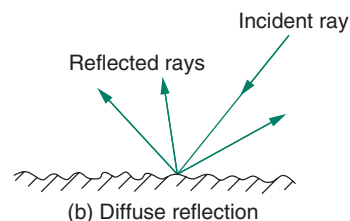
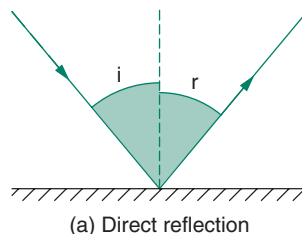


Figure 14.14 Reflection of light.

Table 14.1 Reflectance of building materials

Surface	Reflectance (%)
Brickwork	10-30
Concrete (new)	40-50
Wallpaper (light-coloured)	55-65
White oil-based paint	75-85
White emulsion (matt)	60-70
Timber (beech, pine)	40-60

Diffuse reflection occurs from rough surfaces, as shown in Figure 14.14b. The rays of light are not parallel after reflection, but for any ray the angle of incidence is equal to the angle of reflection.

Reflectance is defined as the ratio of the light reflected from a surface to the total light incident on the surface, and usually expressed as a percentage. Typical values of reflectance for some materials are listed in Table 14.1.

14.7.5 Level of illuminance

Illumination levels for a wide variety of environments and tasks can be found in BSEN 12464-1: 2002 and in the Society of Light and Lighting's Code for Lighting. The levels stated are maintained illuminance, which are the minimum average illumination levels that should be achieved at the point of scheduled maintenance. Table 14.2 shows a selection taken from BSEN 12464-1: 2002.

14.7.6 Utilisation factor (UF)

The **utilisation factor** is defined as the total flux reaching the working plane compared to the total flux emitted by the luminaire. Utilisation factors can be calculated for any surface or layout of luminaires, but are generally calculated for luminaires arranged in regular arrays. Most manufacturers publish tables of utilisation factors for their luminaires. It is necessary to determine the room index and the reflectance of the room surfaces before finding the utilisation factors from manufacturers' tables. Tables 14.3 to 14.6 show utilisation factors (numbers in *italics*) for a selection of luminaires manufactured by Thorn Lighting Company. Similar information is also published by other manufacturers.

Tables 14.3 to 14.5 are based on recessed luminaires with fluorescent tubes, an example of which is shown in Figure 14.12h. Figure 14.12j shows a surface-mounted/suspended fluorescent luminaire. T16 and T26 are the diameters of the fluorescent tube lamps.

14.7.7 Maintenance factor (MF)

New lamps and luminaires produce maximum light output. After some time, their surfaces will become dirty due to deposition of dust. A dirty lamp will be unable to emit as much light as when it was clean. The maintenance factor takes into account the loss in

Table 14.2 Maintained illuminance

Building/room	Lux
Schools/colleges	
Canteen	200
Classrooms, schools	300
Classrooms, colleges	500
Corridor, passageway, stairs	100-150
Laboratories	500
Lecture hall	500
Kitchen	500
Offices	
Offices: filing, copying etc.	300
CAD workstations	500
Conference rooms, meeting rooms	500
Places of public assembly	
Exhibition halls	300
Library, reading area	500
Lecture theatre	500
Ticket office	300
Restaurants and hotels	
Conference rooms	500
Entrance hall	100
Kitchen	500
Reception desk	300
Self-service restaurant	200

(Source: BSEN 12464-1: 2002)

illuminance due to various factors that include dirt collecting on lamps, luminaires and room surfaces, and lamp failures:

$$MF = LLMF \times LSF \times LMF \times RSMF$$

LLMF is **lamp lumen maintenance factor**, and is the proportion of the initial light output that is produced after a specified time. See Table 14.7.

LSF is the **lamp survival factor** and takes into account the failure of lamps. It is considered if the lamps are replaced at regular intervals. The value of LSF is 1.0 if the lamps are replaced immediately after their failure.

Dirt deposited on/in the luminaire will cause a reduction in its light output. The amount of dirt deposited at a particular time depends on how clean, or how dirty, the room environment is. **LMF (luminaire maintenance factor)** is used in the maintenance factor equation to consider the effect of dirt on the light output of luminaires (Table 14.8).

Dirt can also be deposited on room surfaces and can affect the amount of light reflected. This is taken into account by using the **room surface maintenance factor (RSMF)** (Table 14.9).

Table 14.3 Utilisation factors for 664 × 599 mm recessed modular luminaires (Quattro C Body 4 × 18 W T26 Lamps. Flux = 1350 lumens/lamp)

Utilisation factors									
Room Reflectance (%)	Room Index								
Ceiling/Walls/Floor	0.75	1.00	1.25	1.50	2.00	2.50	3.00	4.00	5.00
70 / 50 / 20	0.54	0.59	0.62	0.65	0.68	0.70	0.72	0.74	0.75
70 / 30 / 20	0.50	0.55	0.59	0.62	0.66	0.68	0.70	0.72	0.73
70 / 10 / 20	0.47	0.52	0.57	0.60	0.64	0.66	0.68	0.70	0.72
50 / 50 / 20	0.52	0.57	0.61	0.63	0.66	0.68	0.70	0.71	0.72
50 / 30 / 20	0.49	0.54	0.58	0.61	0.64	0.66	0.68	0.70	0.71
50 / 10 / 20	0.47	0.52	0.56	0.59	0.62	0.65	0.66	0.69	0.70
30 / 50 / 20	0.52	0.56	0.60	0.62	0.65	0.66	0.67	0.69	0.70
30 / 30 / 20	0.49	0.54	0.57	0.60	0.63	0.65	0.66	0.68	0.69
30 / 10 / 20	0.47	0.52	0.55	0.58	0.61	0.63	0.65	0.67	0.68
0 / 0 / 0	0.45	0.50	0.54	0.56	0.59	0.61	0.62	0.64	0.65
DLOR = 69%		ULOR = 0%			SHR Nom = 1.5		SHR Max = 1.66		

(Source: Thorn Lighting Company)

Table 14.4 Utilisation factors for 610 × 600 mm recessed modular luminaires (Quattro T Body 2 × 40 W TC-L Lamps. Flux = 3500 lumens/lamp)

Utilisation factors									
Room Reflectance (%)	Room Index								
Ceiling/Walls/Floor	0.75	1.00	1.25	1.50	2.00	2.50	3.00	4.00	5.00
70 / 50 / 20	0.54	0.59	0.63	0.66	0.69	0.71	0.73	0.75	0.76
70 / 30 / 20	0.50	0.56	0.60	0.63	0.67	0.69	0.71	0.73	0.74
70 / 10 / 20	0.47	0.53	0.57	0.60	0.64	0.67	0.69	0.71	0.73
50 / 50 / 20	0.53	0.58	0.62	0.64	0.67	0.69	0.70	0.72	0.73
50 / 30 / 20	0.50	0.55	0.59	0.61	0.65	0.67	0.69	0.71	0.72
50 / 10 / 20	0.47	0.52	0.57	0.59	0.63	0.65	0.67	0.69	0.71
30 / 50 / 20	0.52	0.57	0.60	0.63	0.65	0.67	0.68	0.70	0.71
30 / 30 / 20	0.49	0.54	0.58	0.60	0.64	0.65	0.67	0.69	0.70
30 / 10 / 20	0.47	0.52	0.56	0.59	0.62	0.64	0.66	0.68	0.69
0 / 0 / 0	0.46	0.51	0.54	0.57	0.60	0.62	0.63	0.65	0.66
DLOR = 70%		ULOR = 0%			SHR Nom = 1.5		SHR Max = 1.52		

(Source: Thorn Lighting Company)

Table 14.5 Utilisation factors for 610 × 600mm recessed modular luminaires (Quattro T Body 2 × 34 W TC-L Lamps. Flux = 2800 lumens/lamp)

Utilisation factors									
Room Reflectance (%)	Room Index								
Ceiling/Walls/Floor	0.75	1.00	1.25	1.50	2.00	2.50	3.00	4.00	5.00
70 / 50 / 20	0.51	0.56	0.59	0.62	0.65	0.67	0.68	0.70	0.71
70 / 30 / 20	0.47	0.52	0.56	0.59	0.63	0.65	0.66	0.69	0.70
70 / 10 / 20	0.44	0.50	0.54	0.57	0.60	0.63	0.65	0.67	0.69
50 / 50 / 20	0.50	0.54	0.58	0.60	0.63	0.65	0.66	0.68	0.69
50 / 30 / 20	0.47	0.52	0.55	0.58	0.61	0.63	0.65	0.66	0.68
50 / 10 / 20	0.44	0.49	0.53	0.56	0.59	0.62	0.63	0.65	0.67
30 / 50 / 20	0.49	0.53	0.57	0.59	0.61	0.63	0.64	0.65	0.66
30 / 30 / 20	0.46	0.51	0.54	0.57	0.60	0.62	0.63	0.64	0.65
30 / 10 / 20	0.44	0.49	0.53	0.55	0.58	0.60	0.62	0.63	0.65
0 / 0 / 0	0.43	0.48	0.51	0.53	0.56	0.58	0.59	0.61	0.62
	DLOR = 65%		ULOR = 0%		SHR Nom = 1.5		SHR Max = 1.52		

(Source: Thorn Lighting Company)

Table 14.6 Utilisation factors for 1515 × 217 × 90mm surface-mounted and suspended fluorescent luminaires (College 2 × 49 W T16 Lamps. Flux = 4350 lumens/lamp)

Utilisation factors									
Room Reflectance (%)	Room Index								
Ceiling/Walls/Floor	0.75	1.00	1.25	1.50	2.00	2.50	3.00	4.00	5.00
70 / 50 / 20	0.40	0.45	0.50	0.53	0.57	0.61	0.63	0.66	0.68
70 / 30 / 20	0.34	0.40	0.45	0.48	0.53	0.57	0.59	0.63	0.65
70 / 10 / 20	0.31	0.36	0.41	0.45	0.50	0.54	0.56	0.60	0.63
50 / 50 / 20	0.38	0.43	0.47	0.50	0.55	0.57	0.59	0.62	0.64
50 / 30 / 20	0.33	0.39	0.43	0.46	0.51	0.54	0.56	0.60	0.62
50 / 10 / 20	0.30	0.35	0.40	0.43	0.48	0.52	0.54	0.58	0.60
30 / 50 / 20	0.36	0.41	0.45	0.48	0.52	0.54	0.56	0.59	0.60
30 / 30 / 20	0.33	0.37	0.42	0.45	0.49	0.52	0.54	0.57	0.59
30 / 10 / 20	0.30	0.34	0.39	0.42	0.46	0.50	0.52	0.55	0.57
0 / 0 / 0	0.28	0.32	0.36	0.39	0.43	0.46	0.48	0.51	0.53
	DLOR = 62%		ULOR = 6%		SHR Nom = 1.5		SHR Max = 1.69		

(Source: Thorn Lighting Company)

Table 14.7 Typical values of LLMF

Lamp	Operation time						14000 hours
	2000	4000	6000	8000	10000	12000	
Fluorescent tri-phosphor	0.94	0.91	0.87	0.86	0.85	0.84	0.83
Mercury	0.93	0.87	0.80	0.76	0.72	0.68	0.64
High pressure sodium	0.96	0.93	0.91	0.89	0.88	0.87	0.86

(Source: The Society of Light and Lighting/CIBSE)

Table 14.8 Typical values of LMF

Time between cleaning	1.0			2.0			3.0 Years		
Environment (see Table 14.10)	C	N	D	C	N	D	C	N	D
Luminaire category (see Table 14.10)									
A	0.93	0.89	0.83	0.89	0.84	0.78	0.85	0.79	0.80
B	0.90	0.86	0.83	0.84	0.80	0.75	0.79	0.74	0.79
C	0.89	0.81	0.72	0.80	0.69	0.59	0.74	0.61	0.64
D	0.88	0.82	0.77	0.83	0.77	0.71	0.79	0.73	0.73
E	0.94	0.90	0.86	0.91	0.86	0.81	0.90	0.84	0.83
F	0.86	0.81	0.74	0.77	0.66	0.57	0.70	0.55	0.65

(Source: The Society of Light and Lighting/CIBSE)

Table 14.9 Typical values of RSMF

Time between cleaning		1.0			2.0			3.0 Years		
Room index K	Luminaire distribution	C	N	D	C	N	D	C	N	D
Small (0.7)	Direct	0.97	0.94	0.93	0.95	0.93	0.90	0.94	0.92	0.98
	Direct/Indirect	0.90	0.86	0.82	0.87	0.82	0.78	0.84	0.79	0.74
	Indirect	0.85	0.78	0.73	0.81	0.73	0.66	0.75	0.68	0.59
Medium to Large (2.5-5.0)	Direct	0.98	0.96	0.95	0.96	0.95	0.94	0.96	0.95	0.94
	Direct/Indirect	0.92	0.88	0.85	0.89	0.85	0.81	0.86	0.82	0.78
	Indirect	0.88	0.82	0.77	0.84	0.77	0.70	0.78	0.72	0.64

(Source: The Society of Light and Lighting/CIBSE)

Table 14.10 Luminaire categories and environmental conditions

Category	Description	Environment	Typical locations
A	Bare lamp batten	Clean (C)	Clean rooms, computer centres, hospitals
B	Open top reflector	Normal (N)	Offices, shops, schools, restaurants, ware houses, laboratories
C	Closed top reflector		
D	Enclosed	Dirty (D)	Steelworks, chemical works, woodwork areas, welding, polishing, foundries
E	Dustproof		
F	Indirect uplighter		

(Source: The Society of Light and Lighting/CIBSE)

14.7.8 Lumen design method

Several factors need to be considered before designing a lighting scheme; some of these are:

appropriate lamps and luminaires; the task that will be performed in the room/building; level of illuminance on the working plane; energy efficiency; and the problem of glare.

The lumen design method can be used to design lighting schemes in square or rectangular rooms with a regular array of luminaires. The method takes into account the area of the room (**A**), utilisation factor (**UF**) and maintenance factor (**MF**) of the lamps/luminaires, luminous flux (**Φ**) of lamps and the average illuminance (**E**) required on the working plane. The procedure involves the selection of appropriate lamps/luminaires and then calculating the number of luminaires required to produce the necessary level of illuminance.

$$\text{The number of lamps required, } N = \frac{E \times A}{\Phi \times UF \times MF}$$

14.7.9 SHR

The SHR (spacing to height ratio) is the ratio of the distance between the luminaires and their height above the working plane. Most manufacturers publish the values of SHR for their luminaires. From $SHR_{\max}$ we can calculate the maximum spacing between the luminaires that can be allowed and still achieve uniformity in illuminance.

Example 14.4

A room measures 7.0m × 6.0m × 2.6m high. The lamps are surface mounted on the ceiling and the desks are 0.75m high. Find the room index.

Solution:

The room index is given by the formula, $k = \frac{L \times W}{H_m(L + W)}$ (see also Section 14.7.3)

$$\begin{aligned} H_m &= \text{height of the light fitting above the working plane} \\ &= 2.6 - 0.75 = 1.85\text{m} \end{aligned}$$

$$\begin{aligned} \text{Room index} &= \frac{7 \times 6}{1.85 \times (7 + 6)} \\ &= \frac{42}{1.85 \times (13)} = \mathbf{1.75} \end{aligned}$$

Example 14.5

A room measuring 12.0m × 10.0m × 4.0m high is provided with Quattro T 610 × 600mm recessed modular luminaires with 2 × 40W TC-L Lamps. The height of the working surface is 0.72m. Determine the utilisation and maintenance factors if:

- i) the ceiling, wall and floor reflectance are 70%, 50% and 20% respectively
- ii) the lamps are changed when they fail; assume operation time = 10000 hours
- iii) the lamps, luminaires and room surfaces are cleaned annually
- iv) the room environment is clean

Solution:

$$\text{Room index} = \frac{12.0 \times 10.0}{3.28 \times (12 + 10)} = 1.66 \quad (H_m = 4.0 - 0.72 = 3.28)$$

UF: Refer to Table 14.4. For the given room reflectance and room index of 1.66, the **UF = 0.67**

$$MF = \text{LLMF} \times \text{LSF} \times \text{LMF} \times \text{RSMF}$$

LLMF = 0.85 (Table 14.7 - for fluorescent tri-phosphor lamps whose operation time is 10000 hours)

LSF = 1 (lamps are changed immediately after their failure)

LMF = 0.89 (Table 14.8 - for clean environment; luminaire category: C; one year time between cleaning)

RSMF = 0.97 (Table 14.9 - for clean environment, luminaire distribution: direct; one year time between cleaning)

Multiplying all the above factors, $MF = 0.85 \times 1 \times 0.89 \times 0.97 = \mathbf{0.73}$

Example 14.6

A room measuring $12.2\text{ m} \times 9.7\text{ m} \times 4.2\text{ m}$ high is to be used as a seminar room. The required illuminance on the desks is 500 lux . The $610 \times 600\text{ mm}$ recessed Quattro T Body modular luminaires have been specified for use in the room. Use the lumen design method to determine the number of luminaires required.

- Given: i) the ceiling, wall and floor surface reflectance are 70%, 50% and 20% respectively
 ii) there is a spot replacement programme for replacing lamps; operation time of each lamp is 10000 hours
 iii) the room environment is clean; the luminaires and the room surfaces are cleaned annually

Solution:

$$\text{Number of lamps, } N = \frac{E \times A}{\Phi \times UF \times MF}$$

$$\begin{aligned}\text{Room area, } A &= 12.2 \times 9.7 = 118.34\text{ m}^2 \\ E &= 500\text{ lx}\end{aligned}$$

Use two TC-L/40 W lamps per luminaire. Luminous flux of each lamp = 3500 lm
 Luminous flux of each luminaire, $\Phi = 2 \times 3500 = 7000\text{ lm}$

$$H_m = 4.2 - 0.7 = 3.5\text{ m} \quad (\text{assume the desks are } 0.7\text{ m high})$$

$$\text{Room index} = \frac{L \times W}{H_m(L + W)} = \frac{12.2 \times 9.7}{3.5 \times (12.2 + 9.7)} = 1.54$$

From Table 14.4, $UF = 0.66$

$$\begin{aligned}MF &= LLMF \times LSF \times LMF \times RSMF \\ &= 0.85 \times 1 \times 0.89 \times 0.97 = 0.73 \\ &(\text{Refer to Tables 14.7, 14.8, 14.9 and Example 14.5})\end{aligned}$$

$$N = \frac{500 \times 118.34}{7000 \times 0.66 \times 0.73} = 17.5$$

The first trial shows that it is not possible to have 18 luminaires in regular arrays. Increase the number of luminaires to 20, as shown in Figure 14.15, to have a regular array. An alternative is to use lamps of different lumen output.

$$SHR = \frac{2.4}{3.5} = 0.69 < SHR_{\max}$$

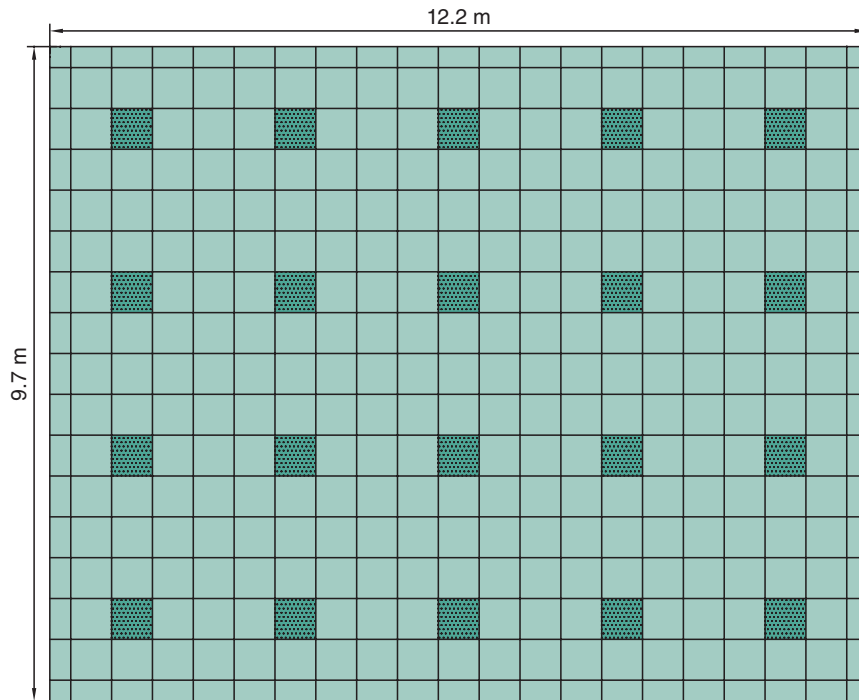


Figure 14.15 Spacing of 600 × 600 mm modular luminaires (shaded squares).

Example 14.7

A room measuring 10.0 m × 8.0 m × 3.5 m high is to be used as an office. The required illuminance on the working plane is 500 lux. Surface-mounted luminaires measuring 1515 × 217 × 90 mm have been specified. Each luminaire will house 2 × 49 W T16 fluorescent lamps, flux of each lamp being 4350 lumens. Use the lumen design method to determine the number of luminaires required, if:

- the ceiling, wall and working surface reflectance are 70%, 50% and 20% respectively
- there is a spot replacement programme for replacing lamps; operation time of each lamp is 10000 hours
- the room environment is clean; the luminaires and the room surfaces are cleaned annually

Solution:

$$\text{Number of lamps, } N = \frac{E \times A}{\Phi \times UF \times MF}$$

$$\text{Room area, } A = 10.0 \times 8.0 = 80.0 \text{ m}^2$$

$$E = 500 \text{ lx}$$

Use two 49W T16 fluorescent lamps per luminaire. Luminous flux of each lamp = 4350 lm

Luminous flux of each luminaire, $\Phi = 2 \times 4350 = 8700 \text{ lm}$

$H_m = 3.5 - 0.7 = 2.8 \text{ m}$ (assume the desks are 0.7 m high)

$$\text{Room index} = \frac{L \times W}{H_m(L + W)} = \frac{10.0 \times 8.0}{2.8 \times (10.0 + 8.0)} = 1.59$$

From Table 14.6, UF = 0.54

$$\begin{aligned} \text{MF} &= \text{LLMF} \times \text{LSF} \times \text{LMF} \times \text{RSMF} \\ &= 0.85 \times 1 \times 0.89 \times 0.97 = 0.73 \end{aligned}$$

(Refer to Tables 14.7, 14.8, 14.9 and Example 14.5)

$$N = \frac{500 \times 80.0}{8700 \times 0.54 \times 0.73} = 11.7, \text{ say } 12$$

The arrangement of luminaires is shown in Figure 14.16.

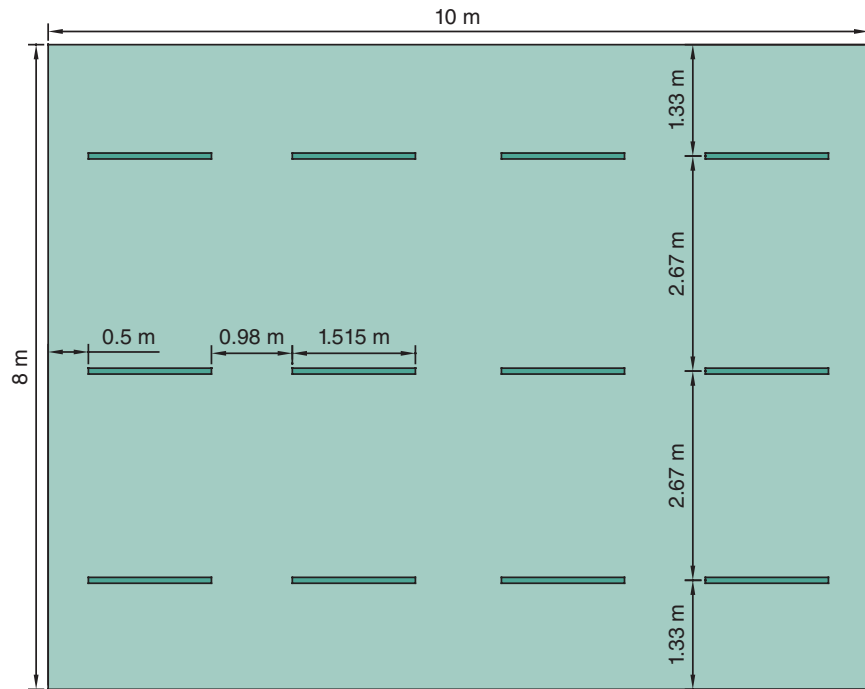


Figure 14.16 Spacing of 1515 × 217 mm modular luminaires.



Figure 14.17 Light meter.

14.8 Light meter

A light meter is used to measure the illuminance produced by a light source in lux or other units. Most modern light meters use silicon or cadmium sulphide sensors. The silicon sensor, which is connected to the meter, will generate a voltage proportional to the level of light. A battery and an amplification circuit are incorporated to amplify the voltage generated by the sensor. In a digital light meter, the light level is displayed as lux on an LCD screen. Figure 14.17 shows a typical light meter.

14.9 Daylighting

Daylight, or natural light, is provided directly by the sunlight and/or the sky. Sunlight, which is direct light from the sun, is so variable that it is not of much use in lighting design. Illuminance from the sky is also variable; it varies during the day and through the year. In countries where the climate is not reliable (e.g. the UK), an overcast sky is considered to be the main source of daylight. It also represents the worst type of daylight.

14.9.1 Uniform sky

The uniform sky is an overcast sky considered to have the same luminance for the entire hemispherical sky.

14.9.2 CIE standard overcast sky

In the CIE (Commission Internationale de l'Eclairage) sky, the luminance varies with the angle above the horizon. This has close resemblance to the luminance distribution of a real overcast sky.

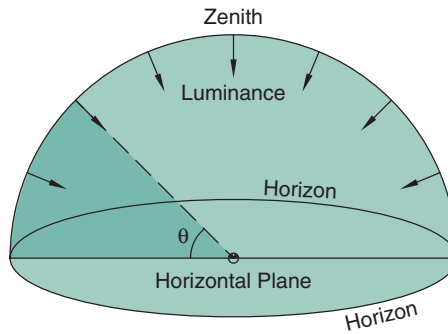


Figure 14.18

Luminance at an angle θ (L_θ) from the horizon, as shown in Figure 14.18, is given by:

$$L_\theta = L \left(\frac{1 + 2\sin\theta}{3} \right)$$

where L is the luminance at the zenith.

The luminance at the zenith is three times the luminance at the horizon.

14.9.3 Daylight factor

Daylight enters the interior of a building through windows or roof lights. The illuminance due to daylight inside a building will reduce rapidly as the distance from the side window/patio door increases. The amount of daylight that is able to penetrate to a point in a building is expressed as the daylight factor.

The **daylight factor** is defined as the ratio of the natural illuminance at a particular point on a horizontal plane to the simultaneously occurring external illuminance of the unobstructed overcast sky. In the UK, the standard sky is assumed to give at least 5000 lx of illuminance on the ground.

$$\text{Daylight factor (DF)} = \frac{\text{Internal illuminance}}{\text{External illuminance}} \times 100$$

14.9.4 Components of daylight factor

The daylight reaching any point inside a room is made up of three components (Figure 14.19):

- a) Sky component (SC): Light received directly from the sky through windows. Direct light is not considered for calculating the sky component.
- b) Externally reflected component (ERC): Light received directly from external reflecting surfaces like buildings, vegetation etc.

Example 14.8

Calculate the illuminance at a point in a building if a daylight factor of 3% is required. Assume that the external illuminance due to an unobstructed standard sky is 5000 lx.

Solution:

$$DF = \frac{\text{Internal illuminance}}{\text{External illuminance}} \times 100$$

Transpose the formula to make Internal illuminance the subject:

$$\begin{aligned} \text{Internal illuminance} &= \frac{DF \times \text{external illuminance}}{100} \\ &= \frac{3 \times 5000}{100} = \mathbf{150 \text{ lx}} \end{aligned}$$

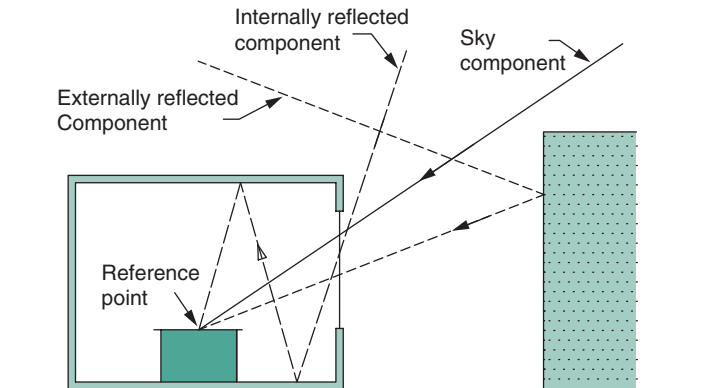


Figure 14.19 Components of daylight factor.

- c) Internally reflected component (IRC): Light received after multiple reflections off floor, walls and ceiling.

The daylight factor is the sum of the three components:

$$DF = SC + ERC + IRC$$

The sky component and the internally reflected component are the more important components; the externally reflected component makes a very small contribution to the daylight factor.

In side-lit rooms, the maximum DF is near the windows, and it is mainly due to the sky component. Both the sky component and the externally reflected component decrease

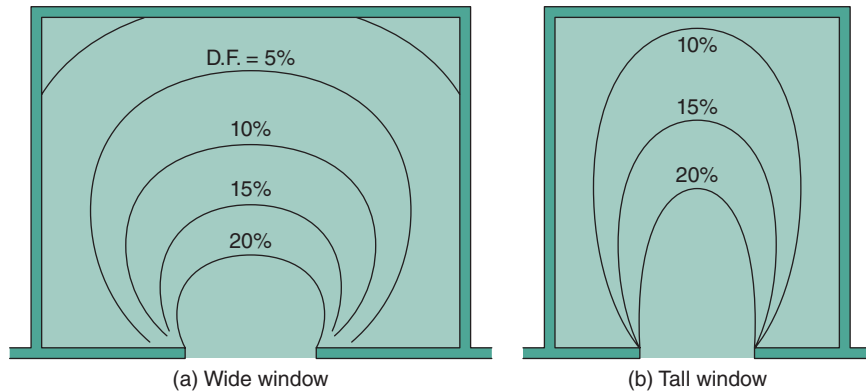


Figure 14.20 Daylight factor contours.

as the distance from a window increases. The internally reflected component, however, remains uniform in the room interior.

The daylight contours, which are lines on a plan joining all points of the same DF, show how the daylight factor reduces away from a window. Compared to wide windows, tall windows provide greater penetration of daylight as shown in Figure 14.20.

14.9.5 Prediction of daylight factors

Several methods are available to predict daylight factor components and total daylight factors:

- i) BRS daylight protractors
- ii) BRS simplified daylight tables
- iii) IRC nomograms/IRC formula
- iv) Pilkington sky dots
- v) Waldram diagrams
- vi) Computer programs

Publications by the Building Research Establishment and other organisations give the detailed description of these methods.

In the early stages of building design, the average daylight factor may be used to assess the adequacy of daylight:

$$\text{Average DF} = \frac{W}{A} \frac{T \theta}{(1-R^2)}$$

where: W is the net glazed area of the windows (m^2)

A is the total area of the internal surfaces (m^2)

T is the glass transmittance corrected for dirt

θ is the visible sky angle in degrees (see Figure 14.21)

R is the average reflectance of area A

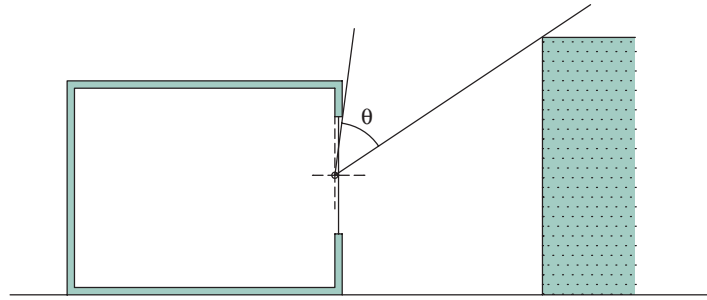


Figure 14.21 Visible sky angle.

The values of W , T and R can be obtained from the BS Daylight Code.

The recommended minimum average daylight factor for dwellings varies between 1 and 2%. This represents an illuminance of between 50 and 100 lx, which is easily exceeded on a bright day.

Exercise 14.1

1. A point source of light has a luminous intensity of 250 cd and radiates in all directions. Calculate the total luminous flux emitted by the source.
2. A street lamp (point source), having a luminous intensity of 1200 cd, is suspended 6 m above the edge of a road. If the road is 8 m wide, calculate the illuminance:
 - a) at point A on the road surface, which is directly under the lamp;
 - b) at a point, on the other edge of the road, directly opposite point A.
3. Calculate the illuminance at A, due to two light sources shown in Figure 14.22.
4. A room measures 7.0 m $\times$ 6.0 m $\times$ 2.8 m high. The lamps are surface mounted on the ceiling and the desks are 0.75 m high. Find the room index.
5. A room measuring 14.0 m $\times$ 10.0 m $\times$ 4.2 m high is provided with Quattro T 610 $\times$ 600 mm recessed modular luminaires with 2 $\times$ 40 W TC-L lamps. The height of the working surface is 0.70 m. Determine the utilisation and maintenance factors if:
 - i) the ceiling, wall and floor reflectance are 50%, 50% and 20% respectively
 - ii) the lamps are changed when they fail; assume operation time = 10 000 hours
 - iii) the lamps, luminaires and room surfaces are cleaned every two years
 - iv) the room environment is clean
6. A room measuring 12.0 m $\times$ 10.0 m $\times$ 4.0 m high is to be used as a seminar room. The required illuminance on the desks is 500 lux. The 610 $\times$ 600 mm recessed Quattro T Body modular luminaires have been specified for use in the room. Use the lumen design method to determine the number of luminaires required, if:
 - i) the ceiling, wall and floor reflectance are 70%, 50% and 20% respectively.

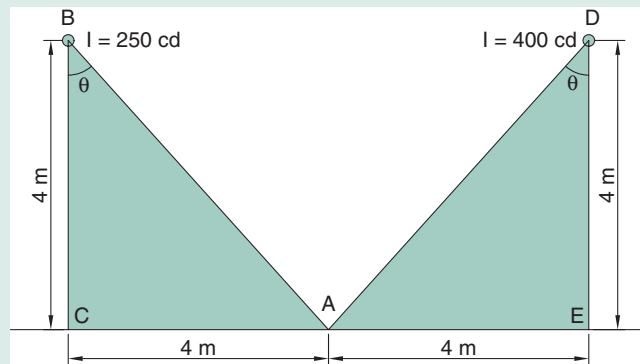


Figure 14.22

- ii) there is a spot replacement programme for replacing lamps; operation time of each lamp is 10000 hours
 - iii) the room environment is clean; the luminaires and the room surfaces are cleaned annually
7. A room measuring $15.0\text{ m} \times 12.0\text{ m} \times 3.5\text{ m}$ high is to be used as an office. The required illuminance on the working plane is 500 lux. Surface-mounted luminaires measuring $1515 \times 217 \times 90\text{ mm}$ have been specified. Each luminaire will house $2 \times 49\text{ W}$ T16 fluorescent lamps, flux of each lamp being 4350 lumens. Use the lumen design method to determine the number of luminaires required, if:
- i) the ceiling, wall and working surface reflectance are 70%, 50% and 20% respectively
 - ii) there is a spot replacement programme for replacing lamps; operation time of each lamp is 10000 hours
 - iii) the room environment is clean; the luminaires and the room surfaces are cleaned annually
8. Calculate the illuminance at a point in a building if a daylight factor of 2.5% is required. Assume that the external illuminance due to an unobstructed standard sky is 5000 lx.

References/Further reading

1. BS EN 12464-1:2002. *Light and Lighting - Lighting of work places. Indoor work places.*
2. CIBSE/The Society of Light and Lighting (2002). *Code for Lighting.*
3. Jones, M., Tingle, M., Petheram, L. and Gadd, K. (2005). *AQA GCSE Science.* London: Harper Collins.
4. Thorn Lighting Company. Website: www.thornlighting.co.uk

15

Human comfort

Learning outcomes:

- 1) Explain the key factors that affect human comfort in buildings.
- 2) Explain what happens when the factors of human comfort deviate from their recommended values.

15.1 Introduction

Human comfort inside a building is important for its inhabitants to carry out their activities in a safe and efficient manner. A number of factors are important to create a comfortable environment within a building; these are:

temperature, air movement, humidity, ventilation, noise and lighting.

15.2 Temperature

A building should be maintained at an appropriate temperature so that the occupants feel comfortable. The food we consume results in the production of heat energy, which is constantly lost through the skin and through bodily functions like breathing. The heat gain and heat loss must be balanced to maintain the inner body temperature at $37 \pm 0.5^\circ\text{C}$. If the temperature of the surroundings in a building is low, heat loss from the human body will be excessive and could cause health problems such as cold, fever, hypothermia etc. It is, therefore, important to maintain the air temperature in a building within reasonable limits.

Despite large variations in the temperature of the external environment, the human body temperature is maintained within a range of values around a set point of 37°C . The process of maintaining constant conditions in the internal environment of the body is known as **homeostasis**, and when applied to temperature it is called **thermoregulation**.

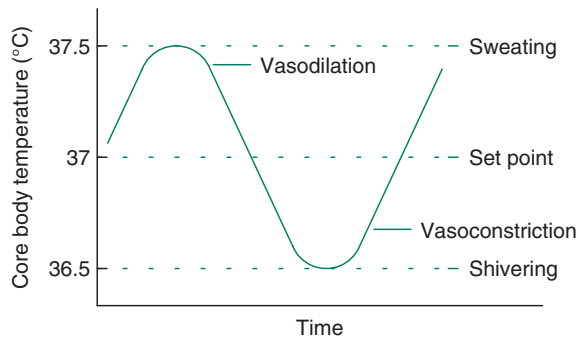


Figure 15.1 Thermoregulation.

There are special sensors in our body that sense the temperature of the blood and send this information to the brain, which knows that the proper temperature should be around $37 \pm 0.5^\circ\text{C}$. If the sensed temperature is significantly higher, signals are sent to the sweat glands of the skin and surface blood vessels. Sweat glands produce sweat, which on evaporation causes cooling. Blood vessels dilate to allow more heat loss through the skin. If the external temperature is low, signals are sent to the muscles to cause shivering (to produce heat), and for the surface blood vessels to constrict (Figure 15.1). The factors that affect thermal comfort in a building are:

air temperature, mean radiant temperature, ventilation and air flow, humidity, activity level and clothing.

15.2.1 Air temperature

Air temperature, or dry bulb temperature, is the temperature of air in a room, which is independent of air movement and heat radiation from the surroundings. Air temperature can be measured by mercury thermometer, digital thermometer, thermocouple and other devices. The thermometer should be shielded to protect it from radiation from the surrounding surfaces.

15.2.2 Mean radiant temperature

The mean radiant temperature (t_r) is the average temperature of the room surfaces. Thermal comfort in a room depends on the exchange of radiation between the human body and the surrounding surfaces. The radiation exchange depends on the size, nature and temperature of the surfaces.

$$t_r = \frac{a_1 t_1 + a_2 t_2 + a_3 t_3 + \dots}{a_1 + a_2 + a_3 + \dots}$$

where t_1, t_2, t_3 are surface temperatures ($^\circ\text{C}$)

a_1, a_2, a_3 are surface areas (m^2)

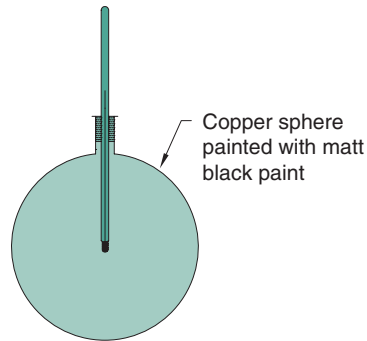


Figure 15.2 Globe thermometer.

A **globe thermometer** may be used to estimate the mean radiant temperature within a room. It consists of a mercury thermometer with its bulb at the centre of a 150 mm diameter blackened copper globe, as shown in Figure 15.2. The globe temperature (t_g) lies between the air temperature and the mean radiant temperature. In still air (velocity, $v = 0$) the globe temperature and the mean radiant temperature are equal.

15.2.3 Environmental temperature

Environmental temperatures are used in the calculation of U-values of building elements. Basically, they are the assumed temperatures, inside and outside a building. The inside temperature t_{ei} is a combination of radiant and air temperatures:

$$t_{ei} = \frac{2}{3}t_r + \frac{1}{3}t_{ai}$$

where t_r is the mean radiant temperature (°C)

t_{ai} is the inside air temperature (°C)

15.2.4 Dry resultant temperature

Dry resultant temperature (t_{res}) has been adopted by CIBSE as a thermal index for moderate thermal environments. Like the environmental temperature, this is also a combination of the inside air temperature and the mean radiant temperature:

$$t_{res} = \frac{t_r + t_{ai}\sqrt{10v}}{1 + \sqrt{10v}}$$

where v is the indoor air speed (m/s)

$$t_{res} = \frac{1}{2}t_r + \frac{1}{2}t_{ai} \text{ when indoor air speed} = 0.1\text{ m/s}$$

Table 15.1 shows the recommended (CIBSE) dry resultant temperatures for some buildings.

Table 15.1 Typical dry resultant temperatures

Building/room type	Dry resultant temperature (°C)
Dwellings:	
Bedrooms	17-19
Kitchens	17-19
Living rooms	22-23
Toilets	19-21
Educational buildings:	
Lecture halls	19-21
Seminar rooms	19-21
Factories:	
Heavy work	11-14
Light work	16-19
Offices	21-23
Shops, supermarkets	19-21

(Reproduced from CIBSE Guide A: Environmental Design)

15.2.5 Activity

The metabolic rate of a person depends on their level of activity. Metabolism may be defined as the sum of all chemical reactions that take place in the human body for converting the food consumed into energy. The metabolic rate, and hence the heat generated by a person, increases as the rate of expenditure of physical energy increases. Thus, a person will be comfortable at a slightly lower resultant temperature. Sedentary people lose body heat at a rate of about 120W at a temperature of 21°C. The rate of body heat loss will increase to about 240W on taking up light physical activity. The room temperature may be reduced slightly to maintain the level of thermal comfort.

15.2.6 Clothing

Clothes provide thermal insulation due to the low thermal conductivity of the clothing material and the air layer trapped between the clothing and the skin. The thermal resistance of clothing is expressed in terms of a unit known as the **clo-value**: 1 clo being the insulation provided by such clothing as a business suit. In winter people wear thicker and heavier clothing to achieve better insulation and hence more comfort. In summer people need to lose more heat from their bodies, therefore, lightweight clothing such as a shirt/blouse and trousers/skirt may provide the necessary comfort. Women, generally, wear lighter clothing than men and hence prefer slightly higher temperatures.

15.3 Air movement

Air movement in a building is usually due to ventilation and draughts. The draughts could be due to gaps around openable parts of doors and single-glazed windows. Air movement creates freshness in a building and is more desirable in summer than in winter. Air movement increases heat loss from the human body and causes chilliness and discomfort in winter. In domestic buildings, an air velocity of 0.1-0.2 m/s is considered to be reasonable. As draught increases and air velocity of 0.2 m/s or more is achieved, an increase in the dry resultant temperature is required to compensate for the cooling effect produced by air movement.

15.4 Humidity

The effect of humidity on human comfort is studied by considering the relative humidity (RH) of air (see Chapter 9 for details on RH). Its effect is considered to be very small when the resultant temperature is close to the recommended value. At temperatures above 25°C (approx.) and from higher activity level, heat is lost from the body by sweating. If the RH of the air is high, i.e. >70%, the evaporation of sweat is very slow so that people feel uncomfortable. The comfortable range of relative humidity is about 40-70%. If the RH of air is below 40%, some people may suffer from a dry throat and dryness of the skin and eyes.

15.5 Ventilation

Ventilation is the process by which clean air is brought into a building to remove the stale air. It is essential in buildings to remove carbon dioxide gas, body odours, bacteria, cooking smells and humidity. In crowded rooms the humidity may increase due to respiration and perspiration of the occupants, and there will also be an increase in the air temperature. Adequate ventilation will bring in fresh air to maintain the supply of oxygen for breathing, remove smells and excess water vapour, and lower the air temperature. A selection of ventilation requirements is shown in Table 15.2.

Table 15.2 Extract ventilation rates

Building/room type	Minimum intermittent extract rate (litres/s)
Dwellings:	
Bathrooms	15
Kitchen	60
Sanitary accommodation	6
Utility room	30
	Whole building ventilation
Offices	10 litres/s per person

(Source: Building Regulations 2000, Approved Document F)

15.6 Noise

Noise can be defined as unwanted sound. Noise in a building may be produced by a multitude of sources like printers, photocopiers, air-conditioning systems, people in a room, and people in adjoining rooms. Whatever the source, noise may interfere with our hearing of speech, distract us from what we are trying to do, or it may just be annoying.

Various criteria have been developed to analyse noise and hence minimise, or avoid, disturbance and speech interference. Two of these criteria, i.e. speech interference criteria and noise criteria, and their curves are explained here.

In the presence of background noise, verbal communication is affected; Figure 15.3 shows the level at which we must speak to be heard clearly. If the distance between the speaker and the listener is small, then higher levels of background noise may be acceptable. As the distance between them increases, the acceptable levels of background noise must decrease for the speaker to be heard clearly.

Noise criterion (NC) curves were developed in the USA for rating indoor noise, e.g. noise from air-conditioning systems. Sound intensity levels that were acceptable to people working in a wide variety of environments were used to produce the NC curves. For a given noise spectrum, the NC rating can be obtained by plotting its octave band levels on the set of NC curves. The NC curve that is just above the noise spectrum determines the noise criterion for the building/space. Figure 15.4a shows the set of NC curves.

Noise rating (NR) curves, shown in Figure 15.4b, are commonly used in Europe for specifying noise levels from mechanical services. NC curves are very similar to the NR curves at middle frequencies.

Table 15.3 shows a selection of the recommended (maximum) values of noise level.

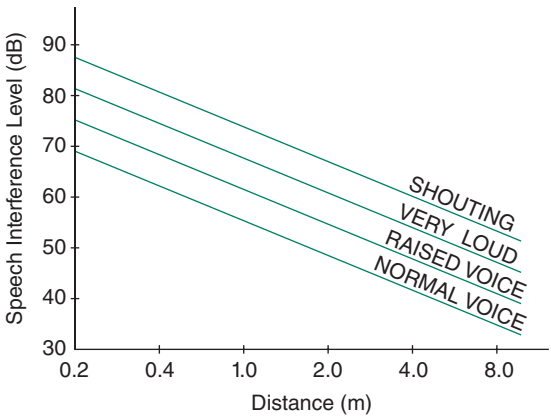


Figure 15.3

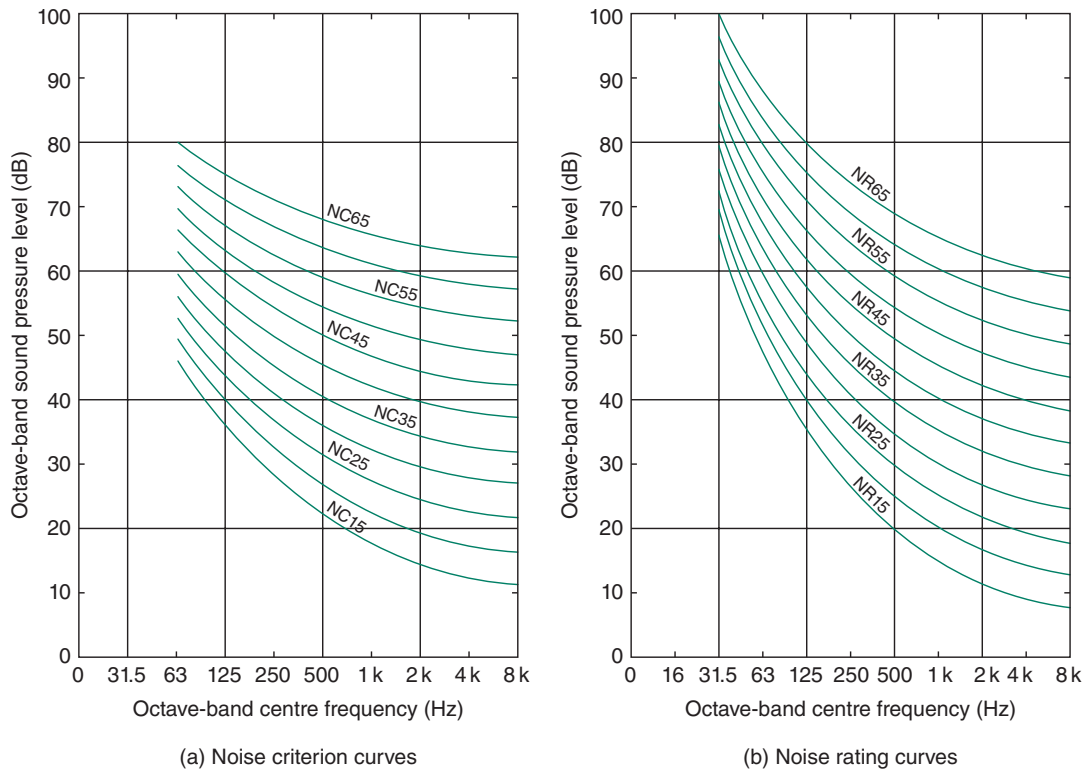


Figure 15.4 a Noise criterion curves.
b Noise rating curves. (Reproduced by permission of CIBSE.)

Table 15.3 Recommended maximum noise levels

Building/space	Noise rating (NR)
Classrooms	25–35
Lecture rooms	25–35
Libraries	30–35
Dwellings: bedrooms	25
living rooms	30
Hospitals	30–35
General offices	35
Supermarkets	40–50

(Reproduced from CIBSE Guide A: Environmental Design)

15.7 Lighting

Light is a form of energy that forms the visible part of the electromagnetic spectrum (see Chapter 14 for details). Lighting in a building should be adequate so that the tasks could be done without any discomfort. In large buildings like office blocks, public libraries and

colleges/universities, the daylight cannot provide an adequate level of illuminance, therefore artificial lighting is used irrespective of the time of day. In dwelling houses, illuminance during the day is provided mainly by daylight.

One of the problems with daylighting is how we can admit enough daylight without creating uncomfortable glare and heat. Direct sunlight can cause discomfort through heating and glare, but is often desirable in winter months. Larger windows, although desirable for letting in more daylight, would cause greater heat loss in winter.

The illuminance requirement in a building depends on the type of work to be done: Table 14.2 (Chapter 14) gives the recommended levels of illuminance for some buildings. Poor lighting does not provide adequate illuminance and hence people will find it difficult to do precise work. For example, in an electronic assembly factory, adequate illuminance is very important for precision. Very bright light, on the other hand, could produce eye strain and glare. **Glare** is a sensation produced by luminaires, windows and other objects, seen directly or by reflection, that are too bright compared with the general brightness to which the eyes have adapted. The usual effects of excessive glare in the office include eye strain, visual fatigue or similar visual discomforts. Glare can be of two types, i.e. disability glare and discomfort glare. Disability glare occurs when in the presence of a very bright object (lamp or reflecting surface); less bright objects cannot be seen properly. Discomfort glare causes visual discomfort without reducing the ability to see the details of an object. Discomfort glare is more likely to occur in a building as compared to disability glare.

The problem of glare can be tackled by reducing the intensity of the light source and by moving the source beyond the line of sight.

References/Further reading

1. CIBSE Guide A (1999). *Environmental Design*. London: Chartered Institution of Building Services Engineers.
2. CIBSE Guide A: *Environmental Design* (2006), Chartered Institution of Building Services Engineers.
3. *The Building Regulations* (2000). *Approved Document F - Means of Ventilation*. London: Department of Communities and Local Government.

16

Construction materials

16.1 Bricks

Bricks have been in use for thousands of years for constructing the substructure and the superstructure of buildings. They were first used as sun-dried bricks but later the Romans found that by firing them their strength could be increased considerably. Although the process has become more mechanised now, the basic method of making bricks has not fundamentally changed. Bricks are now used in building construction internally as well as externally due to their high strength and durability. Bricks, which are made from clay, sand and lime, or from concrete, may be defined as building units that are easy to handle.

16.1.1 Clay bricks

Clay is a natural material formed due to the weathering of rocks and consists mainly of two minerals: silica (SiO_2) and alumina (Al_2O_3). Smaller amounts of iron oxide, magnesium oxide and chalk may also be present. For brick-making, clay must be plastic, have sufficient strength on drying and its particles must fuse together when subjected to a temperature of over 900°C . Clay is extracted from pits and quarries and transported to the works.

16.1.2 Size

The size of clay bricks is $215 \times 102.5 \times 65 \text{ mm}$. Clay usually shrinks on drying and firing, therefore the brick manufacturers allow for this shrinkage by making the bricks originally bigger than the finished size after firing. However, it is not possible to produce bricks of identical size because of variations in the properties of various clay soils. British Standards (BS 3921:1985) suggest the following maximum and minimum sizes based on 24 bricks:

	maximum	minimum
Length (mm)	5235	5085
Width (mm)	2505	2415
Height (mm)	1605	1515

16.1.3 Classification

Clay bricks are classified by British Standards (BS 3921:1985) by considering:

Variety, quality and type

Variety: There are three main varieties: engineering, facing and common. Engineering bricks are the strongest and used where strength of brickwork is very important, for example, the construction of retaining walls, inspection chambers, substructures etc. These are usually red or blue in appearance. Facing bricks, which are available in several colours and textures, are made for appearance and resistance to weather. Common bricks are the least expensive and made for internal work mainly but can be used for external work where rendered.

Quality: Internal quality (to be used internally).

Ordinary quality (bricks are durable enough to be used in constructing external walls).

Special quality (intended for use in harsh and exposed situations).

Type: Solid: Having no holes or cavities or depressions.

Perforated: The volume of holes should be less than 25% of the total brick volume.

Frogged: Having depressions in one or more bed faces, total not exceeding 20% of the total brick volume.

16.1.4 Manufacture

The manufacture of clay bricks starts with the **extraction** of clay (the raw material) from pits and quarries. The raw material is transported to the works where the other processes of manufacture are undertaken. The next stage, called the **preparation** of clay, involves the removal of stones and breaking up of large lumps of clay. Water is added to make the clay-water mixture plastic. The clay-water mixture is then moulded into bricks, the process being known as **forming**. The three main methods of forming bricks are:

Soft mud process, which is done by hand as the higher amount of water in clay makes this possible. The clay is pressed into moulds which are sanded for easy removal of the green brick.

Wire cut process, which is used on moderately stiff clay, involves forcing the clay through a die. The bricks are cut by wire to suitable lengths.

Stiff plastic process, which is used on stiff clay, involves pressing the clay into moulds, mechanically.

The green bricks are allowed to dry out before firing in the kiln. The firing temperature for most bricks is 1000 °C, however, engineering bricks are fired at higher temperatures. After firing, the bricks are allowed to cool before being packaged.

Figure 16.1 shows all stages of brick manufacture.

16.1.5 Properties

The properties of clay bricks are variable even within one delivery to a site. Good clay bricks are generally free from cracks, have a good texture and are well burnt. Some of the main properties and their determination are given here:

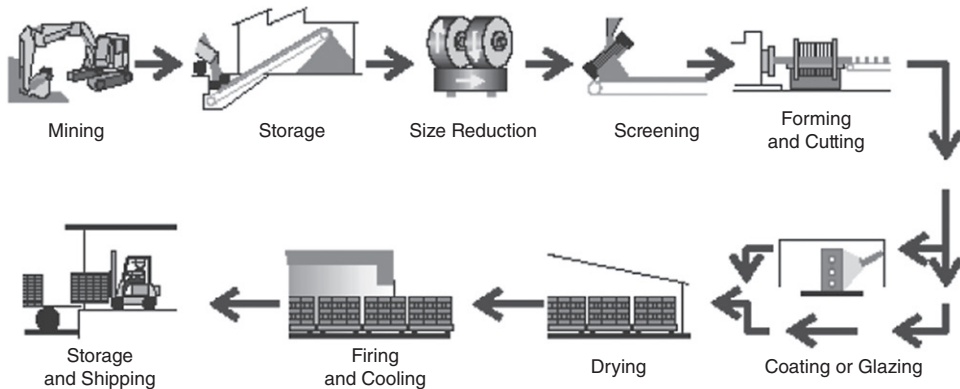


Figure 16.1 Brick manufacturing process. (Reproduced by permission of Brick Industry Association.) (See colour insert.)

a) Appearance

Natural colours of clay bricks include red, white, yellow, brown and blue. The colour darkens as the temperature of firing increases. A light-coloured brick would suggest inadequate firing and hence lower durability and strength, if the normal colour of this brick is known to be dark. Texture results from the method of forming or the surface treatment of green bricks.

b) Strength

Clay bricks may have strengths up to 180N/mm^2 , but considerably lower strengths are adequate for the loads that are usual in small buildings. The Building Regulations require only 2.8N/mm^2 for inner walls of two-storey houses. The compressive strengths of Class A and Class B engineering bricks are at least 70.0 and 50.0N/mm^2 respectively.

c) Water absorption

The absorption of water by bricks may be responsible for several problems that affect their durability. The limits for water absorption for Class A and Class B engineering bricks are 4.5% and 7% respectively.

d) Frost resistance

High strength and/or low water absorption are not the satisfactory indices of frost resistance of bricks. There are three classes of frost resistance:

Class F: These bricks are frost-resistant and should survive 100 cycles of freeze and thaw. These bricks can be used externally in situations of exposure to repeated cycles of freezing and thawing, e.g. garden walls.

Class M: These bricks are moderately frost-resistant and can be used in the construction of external walls of buildings.

Class O: These bricks are not frost-resistant and should be used internally.

e) Thermal conductivity

The thermal conductivity of a material depends on its density. Ordinary clay bricks have high density (typical: 2000kg/m^3) and are poor insulators. In heat-loss calculations, the thermal conductivity of exposed brickwork is usually taken as 0.84W/mK . This, however, varies with the moisture content of brickwork.

f) Fire resistance

During the manufacturing process, clay bricks are fired at a temperature of approximately 1000°C , which is higher than the temperature that may arise normally in fires in buildings. Therefore, clay bricks provide an excellent resistance to fire.

g) Durability

The durability of bricks is much more likely to be a problem than is their strength. Durability problems are mainly associated with water absorption, therefore it is important that bricks are selected according to the exposure conditions.

16.1.6 Deterioration of brickwork

The durability of bricks depends on physical properties like density and porosity, and on the quality of the bricks used in the brickwork. The main cause of deterioration of brickwork is the absorption of water by the bricks.

a) Frost damage

Frost damage is associated with freezing of water below the surface of the bricks. The bricks must be fairly porous in order to admit water. Water expands on freezing, and if the pores within the bricks cannot accommodate this expansion, the surface of the bricks crack and crumble away. This is known as **spalling** (Figure 16.2).

The brickwork should be protected from absorbing large amounts of water by providing a damp proof course (dpc), wherever applicable. The internal pore structure of bricks should be able to accommodate the expansion of water due to freezing.

b) Efflorescence

Some clay bricks may contain salts like sulphates of sodium and calcium. Porous bricks absorb water through their surfaces and the water dissolves these soluble salts. The salt solution moves to the surface of the bricks as they start to dry out in the warmer/dry season. The water evaporates leaving a deposit of unsightly white powder, as shown in Figure 16.3. This is known as **efflorescence**.

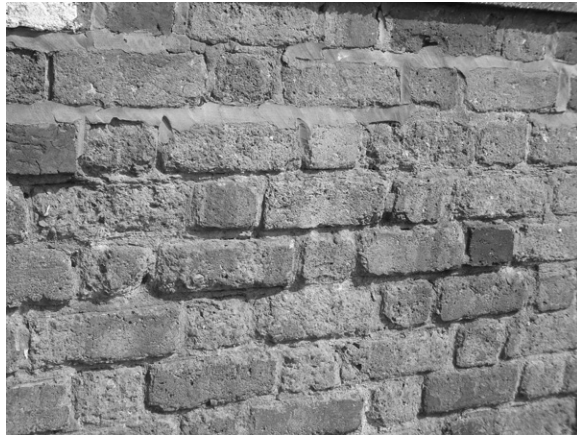


Figure 16.2 Brick spalling. (See colour insert.)

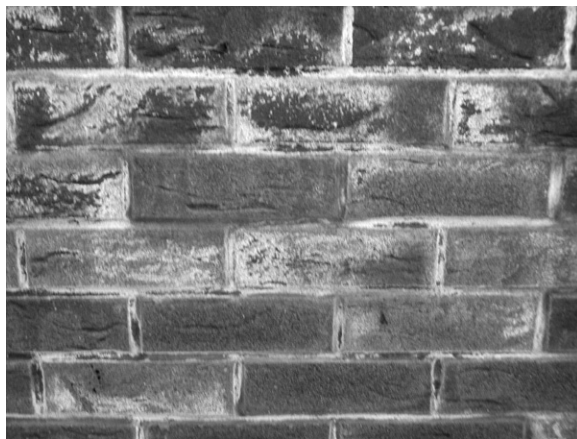


Figure 16.3 Brick efflorescence. (See colour insert.)

The salt deposit on the surface does not cause any damage and it can be removed by brushing the surface of the brickwork. If the efflorescence is heavy and occurs below surfaces, crumbling of under-fired bricks may result.

c) Sulphate attack

Sodium and calcium sulphates in clay bricks can also cause damage to the mortar, which eventually affects the brickwork. Porous bricks absorb water continually and if there are sulphates in the bricks these will be dissolved. If the sulphate solution comes into contact with the mortar, it will react with the cement in the mortar. A new compound (calcium sulpho-aluminate) forms, which has more volume than the original compound (tricalcium aluminate). The mortar expands and causes damage to the brickwork.

Sulphate attack can be prevented by using bricks that have low soluble-salt content or by using sulphate-resisting Portland cement in the mortar.

16.1.7 Environmental implications

An environmentally sustainable material produces only a small impact on the environment due to its manufacture and use in construction projects.

The raw material for clay bricks occurs in abundance, therefore, unlike other raw materials, a shortage of clay is not a concern. There is virtually no wastage of clay in brick manufacture, as any processed clay removed in the forming process before firing is recycled to the production stream. The transportation costs are reduced by siting the brick manufacturing plants near the sources of raw material. Bricks have a long life; this can be confirmed by checking the condition of the bricks used in buildings that are more than 100 years old. Even after demolition of buildings, the old bricks can either be used in construction again or be crushed and used as aggregates or landscaping material.

16.1.8 COSHH

Brick manufacture involves quarrying of clay soil and its transportation to the manufacturing plant. These processes produce fine dust that contains respirable crystalline silica. The particles are so fine that they are deposited into the lungs when they are inhaled by the workers. If this process continues for many years, crystalline silica can cause lung disease known as silicosis. Silicosis takes many years to develop and can cause breathing problems, cough, sputum production and breathlessness. In severe cases it can cause lung cancer and death. HSE (Health and Safety Executive) has set a limit of $0.1\text{mg}/\text{m}^3$ for respirable crystalline silica. The prevention of silicosis can be aided with measures such as improved work practices and respiratory-protection equipment.

16.2 Aerated concrete blocks

Aerated concrete blocks are very light as compared to bricks, stone and dense concrete blocks. They contain numerous tiny air pockets, resulting in smaller mass and other desirable properties. Aerated concrete block is a versatile material that is used in the construction of external walls, internal walls, foundations and suspended concrete floors.

16.2.1 Manufacture

The blocks are manufactured from sand, lime, pulverised fuel ash (PFA) and cement. Aluminium powder is added to the mix, which reacts with cement to form bubbles of hydrogen gas. The mix expands and hardens to form a cake, which is then cut into blocks. The next stage is to steam-cure the blocks, under high pressure, in an autoclave to produce a physically and chemically stable product. The blocks are light-grey in colour and have a texture that is suitable for most types of plastering or rendering.

16.2.2 Sizes

Originally only one or two types of blocks were available, but now a variety of blocks are manufactured, for example, standard, foundation, and floor blocks. The standard size of blocks used in wall construction is 440×215 mm and they are available in several thicknesses, some of which are:

75, 100, 140, 150, 190, 200, 215, 260, 275, 300 mm

For the inner leaf of cavity walls in dwelling houses, 100 mm thick blocks are used. For energy conservation and to satisfy the requirements of Building Regulations, blocks having a compressive strength of 2.9 N/mm^2 and thermal conductivity of 0.11 W/mK are used. The trench blocks are specially made to construct the foundations of a building, and, similarly, floor blocks find their use in the construction of suspended concrete ground floors.

16.2.3 Properties

a) Appearance

The blocks are light-grey in colour and have a rough texture that is suitable for most types of plastering or rendering.

b) Sound insulation and acoustic control

A large number of air voids inside the blocks (micro-cellular structure) offer good sound and thermal insulation. The average sound-reduction index of 100 mm thick blocks with lightweight plaster is 40 decibels (dB). The sound-absorption coefficient depends on the frequency of sound; at a frequency of 500 Hz the sound-absorption coefficient is 0.20.

c) Fire resistance

Aerated concrete blocks are classified as non-combustible. 100 mm thick blocks provide fire resistance of 2 hours and 4 hours for load-bearing and non-load-bearing elements respectively. Blocks thicker than 100 mm will provide longer periods of fire resistance.

d) Durability

Aerated concrete blocks do not rot or decay and are resistant to freeze-thaw cycles. They have good resistance to sulphate attack.

e) Workability

Aerated concrete blocks are lightweight building units that can be safely and repetitively handled by a single person. They can be easily and accurately cut with woodworking tools, minimising the generation of solid waste.

Table 16.1

Property	Insulation blocks	Standard blocks	Foundation blocks
Compressive strength	2.9 N/mm ²	3.6 N/mm ²	3.6, 7.3 and 8.7 N/mm ²
Thermal conductivity	0.11 W/mK	0.15 W/mK	0.15–0.20 W/mK
Average density	460 kg/m ³	600 kg/m ³	600–750 kg/m ³
Vapour resistivity	60 MN s/gm	60 MN s/gm	–
Coefficient of linear expansion	8×10^{-6} /K	8×10^{-6} /K	–

f) Other properties

The strength, thermal conductivity and other properties are summarised in Table 16.1. The blocks are classified according to their compressive strength. Manufacturers in the UK have devised special names for some of these blocks.

16.2.4 Environmental implications

Aerated concrete blocks use up to 80% recycled materials, such as PFA, in their manufacture, and have played a major role in lowering the U-values of external walls of buildings. PFA, a stable material, is a by-product from coal-burning power stations, which would otherwise be used as landfill. Any waste during the manufacturing process is recycled into the next mix or used in other concrete products. Due to their light weight, which is partly due to the micro-cellular structure, less petrol/diesel is used in their transportation. Similarly, the micro-cellular structure of the blocks also results in remarkably high thermal insulation, which lowers energy consumption for the heating of buildings. After their use, aerated concrete blocks can be broken and recycled as aggregates.

16.3 Cement

Cement is one of the most important construction materials and is used in the production of concrete and mortar. The most commonly used type of cement is known as **Portland cement** (previously known as ordinary Portland cement) because the colour of solid cement resembles natural Portland stone.

16.3.1 Raw materials

Portland cement is made from two raw materials: clay (or shale) and limestone (or chalk). Clay may be regarded as a mixture of three substances:

silica (SiO₂), alumina (Al₂O₃) and iron oxide (Fe₂O₃).

Chalk and limestone are carbonates of calcium (CaCO₃). Both are natural materials: chalk occurs as a soft rock whereas limestone occurs as a hard rock.

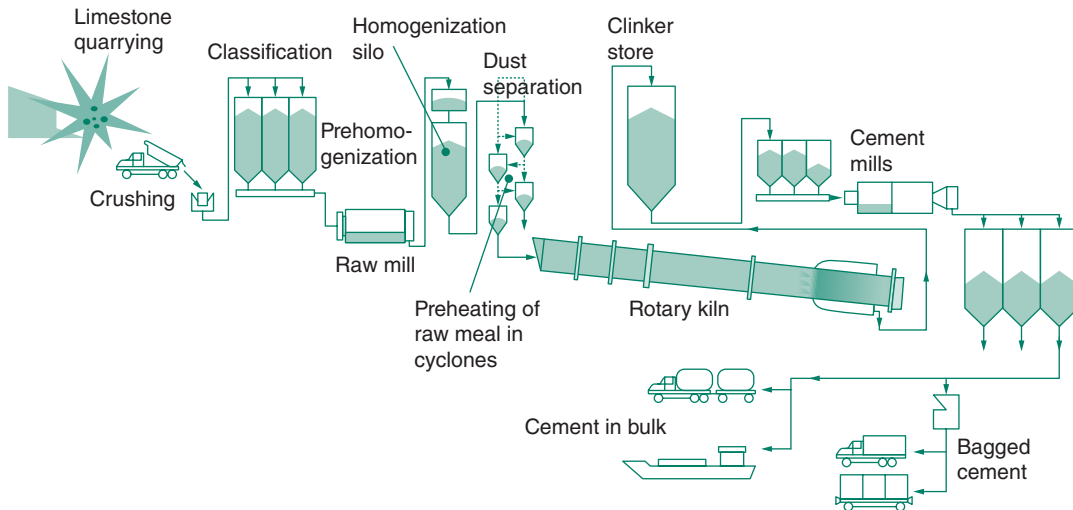


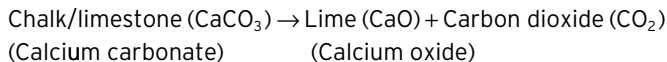
Figure 16.4 Cement manufacturing process. (Reproduced by permission of Kaantee, U.) (See colour insert.)

16.3.2 Manufacture

Cement may be manufactured either by a wet process or by a dry process. The wet process involves crushing of chalk and mixing with clay slurry (clay-water mixture). The mixture is ground further into cement slurry and fed into a rotary kiln for firing.

The raw materials used in the dry process are clay (or shale) and limestone. The raw materials are crushed, mixed and then fed into a ball mill for further grinding. The powdered cement mixture is passed through a screen before feeding into the kiln.

The cement mixture is fed into the upper part of the rotary kiln (see Figure 16.4), which is maintained at a temperature of about 500°C. Water is evaporated from the cement mixture, and the dry mixture is passed into the middle section of the kiln, which is maintained at a temperature of about 900°C. Chalk/limestone is converted into lime at high temperature with the release of carbon dioxide gas.



In the last stage of firing, the ingredients of the cement mixture, i.e. silica and lime, combine to produce nodules of cement, known as cement clinker. The cement clinker is cooled and mixed with about 5% gypsum to retard the setting process.

The wet process requires a large volume of water to make the clay-chalk slurry, which in turn consumes more energy than that of the dry process in evaporating the water. The dry process is therefore the preferred method where feasible.

16.3.3 Setting and hardening of cement

When cement and water are mixed, a chemical reaction known as **hydration** takes place resulting in solid cement. During hydration, water and cement combine to form

Table 16.2 Properties of main constituents of cement

Name	Chemical formula	% in OPC	Properties
Tricalcium silicate	$3\text{CaO} \cdot \text{SiO}_2$	45	Short setting time; high early strength
Dicalcium silicate	$2\text{CaO} \cdot \text{SiO}_2$	28	Long setting time; slow strength development but increases the durability of hardened cement
Tricalcium aluminate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3$	11	Quick setting (delayed by gypsum); attacked by sulphates
Tetracalcium aluminoferrite	$4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$	9	This constituent has no contribution to setting or strength

interlocking calcium silicate hydrate, which gives solid cement its hardness and strength. The heat evolved during the reaction is called the heat of hydration.

Cement powder + water $\rightarrow$ solid cement + heat

Several factors can affect the rate of setting and hardening, temperature being one of them. An increase in temperature will increase the rate of the setting and hardening process. If the temperature falls below 0°C , the setting and hardening process will stop. Similarly, the fineness (particle size) of cement affects the rate of setting and hardening. The rate of setting and hardening of cement increases with an increase in its fineness.

16.3.4 Constituents of portland cement

The raw materials of cement combine chemically in the kiln to produce cement that has properties completely different from their own. The four important constituents and their properties are summarised in Table 16.2.

16.3.5 Types of cement

The classification of cements is based on their main constituents, for example, Portland-fly ash cement and Portland-pozzolana cement. The European Standard EN 197-1:2000 lists five types of cement that have a wide range of permitted constituents:

- CEM I: Portland cement
- CEM II: Portland composite cement
- CEM III: Blastfurnace cement
- CEM IV: Pozzolanic cement
- CEM V: Composite cement

a) Portland cement CEM I

Formerly known as ordinary Portland cement (OPC), CEM I is manufactured to conform to British Standard BS EN 197-1:2000. It is the most commonly used cement in construction work throughout the world. The three strength classes of Portland cement, i.e. 32.5, 42.5 and 52.5, correspond to their lower characteristic strength in MPa ($1\text{ MPa} = 1\text{ N/mm}^2$) at 28 days. Where early strength of concrete is required, Portland cement 32.5R or 42.5R or 52.5R can be used. These cements are more finely ground than 32.5N or 42.5N or 52.5N cements to enable a faster hydration in the early stages.

CEM I cements are easy to procure, and concretes/mortars made using CEM I are versatile and durable. One major disadvantage is that due to a high proportion of cement clinker, this is the least sustainable type of cement.

b) Factory-made composite cements

Factory-made cements (CEM II, CEM III, CEM IV and CEM V) have Portland cement clinker varying from 5% to 94% (by mass) and one or more additional constituents. The additional constituents are selected from materials such as fly ash (PFA), blast-furnace slag, limestone and pozzolanic materials to reduce the environmental impact and promote sustainability. Some of these are described here; for more information, refer to BS EN 197-1:2000 and Lafarge Cement's publications:

i) *Portland-fly ash cement*

Fly ash (PFA) is produced when coal is burnt in coal-fired power stations and furnaces. Fly ash has high silica and alumina content and is added to Portland cement to produce:

- i) CEM II/A-V, which contains 6-20% siliceous fly ash
- ii) CEM II/B-V, which contains 21-35% siliceous fly ash

Calcareous fly ash may also be used to produce CEM II/A-W and CEM II/B-W cements. The use of fly ash in cement increases the strength and durability, improves sulphate resistance, and reduces the heat of hydration, risk of alkali-silica reaction and efflorescence. The use of fly ash has several environmental benefits as well, e.g. recycling a waste by-product of the coal-fired power stations.

ii) *Portland-slag cement*

Blast-furnace slag is a by-product of iron production (see Section 16.5.3). The slag is quenched in water to produce glassy granules that are similar to sand in appearance. Before mixing with Portland cement, the slag is dried and ground to a fineness that is similar to that of cement. There are two types of Portland-slag cement:

- i) CEM II/A-S, which contains 6-20% slag
- ii) CEM II/B-S, which contains 21-35% slag

Table 16.3

Strength class	Compressive strength (MPa)			Maximum strength (MPa)
	2 day	7 day	28 day	28 day
32.5 N	-	≥16.0	≥32.5	52.5
32.5 R	≥10	-	≥32.5	52.5
42.5 N	≥10	-	≥42.5	62.5
42.5 R	≥20	-	≥42.5	62.5
52.5 N	≥20	-	≥52.5	-
52.5 R	≥30	-	≥52.5	-

(extract from BS EN 197-1: 2000)

The use of blast-furnace slag in cement improves the sulphate resistance of concrete, workability and resistance to alkali-silica reaction. As with fly ash, the use of blast-furnace slag reduces the environmental impact by recycling the waste by-product of iron production.

16.3.6 Compressive strength

The samples used for determining the compressive strength measure $40 \times 40 \times 160$ mm, and are made from 1:3 cement-sand mortar with a water-cement ratio of 0.5. The sand used is a standard CEN sand of specified grading with particle size between 1.6 mm and $80 \mu\text{m}$ (BS EN 196-1). The samples are first tested to determine their flexural strength and then broken (if not already) for use in the compression test. A letter is added after the strength: 'N' for normal strength development, 'L' for low, and 'R' for rapid, rates of strength development. Table 16.3 shows the strength classes of Portland cement.

16.3.7 Environmental implications

Cement manufacturing involves the quarrying of raw materials, their transportation to the cement works, firing the raw materials in a kiln and delivery of the finished product. Each stage of cement manufacture has some impact on the environment: i) Extraction of limestone from quarries by blasting produces dust, gases, noise and damage to the landscape. The emission of dust and exhaust gases can be reduced with the use of suitable equipment. The quarrying sites are reintegrated into the countryside after the extraction of the raw materials. ii) Cement manufacturing requires large amounts of energy to heat the kilns and it is responsible for producing large amounts of carbon dioxide (CO_2) emissions. CO_2 is released into the atmosphere if fossil fuels are used to generate the energy. CO_2 is also released directly into the atmosphere when chalk or limestone is heated in the kiln, producing lime and CO_2 . Cement manufacturers use electrostatic precipitators and other measures to reduce the dust created by the kilns.

CEM II cements use by-products like fly ash, blastfurnace slag etc. resulting in less CO_2 emissions and reduced demand for raw materials. Also, the slag and fly ash that would otherwise go to landfill are put to a better use.

16.3.8 COSHH

Cement is highly alkaline and it is important for workers to avoid contact with cement or concrete. Contact with the skin may cause irritation, burns and dermatitis. Cement contains chromium (VI) which may cause allergic reactions.

16.4 Concrete

Concrete is used in the construction of many building elements, and hence is an important building material. It is a composite material made by mixing together cement, aggregates (sand and/or gravel) and water. The proportion of these ingredients affects not just the strength but also the ease with which concrete can be placed and compacted. The function of cement is to act as a binder, i.e. glue the aggregates together. Cement mixes with water to form a paste that coats all aggregates in the mixing process. Although cement is responsible for the strength of concrete, it is not used without the aggregates for the following reasons:

- i) Cement is the most expensive ingredient of concrete. Its volume in concrete is kept to a minimum, as per the mix design.
- ii) Cement shrinks after setting and hardening. This may happen in concretes in which the amount of cement used is far more than what is required. Aggregates help to reduce the cracking in concrete.
- iii) Properly made concrete is likely to be stronger than neat cement.

16.4.1 Raw materials

The raw materials of concrete are:

Cement, which acts as a binder
 Fine aggregate (sand)
 Coarse aggregate (crushed or uncrushed gravel)
 Water

16.4.2 Manufacture of concrete

Concrete is made by mixing the raw materials in correct proportions. A chemical reaction is initiated when cement comes into contact with water. This is known as **hydration**, and is responsible for the setting and hardening of cement. All constituents of cement undergo hydration and contribute to the final product. Most of the early strength of concrete is due to tricalcium silicate, whereas dicalcium silicate, which reacts slowly, is responsible for the development of strength at a later stage.

Concrete is placed in formwork to take the desired shape of the element/component being cast and is vibrated to achieve adequate compaction. **Compaction** of concrete is necessary to remove any air voids formed during mixing and placing.

Cement needs water for setting and hardening, therefore concrete is never allowed to dry out during the first 2 to 3 weeks. This is known as **curing** of concrete.

16.4.3 Concrete mix

The proportions of aggregates, cement and water for a particular mix depend on the part of the building where it is to be used. It is therefore important to mix the constituents of concrete in the correct proportions so that the final product has the required workability and strength. A typical concrete mix for a strip foundation of a two-storey house is 1 part cement, 3 parts fine aggregates, and 6 parts coarse aggregates; this is written in a shorter form as **1:3:6** concrete. Concrete can also be made by using all-in aggregate (ballast) which is a mixture of fine and coarse aggregate. If we use all-in aggregate, then the equivalent concrete mix is 1:7 (approx.). The quantity of water can be determined from the given water-cement ratio.

There are two methods of determining the quantities of the constituents of concrete:

- i) mixing by volume
- ii) mixing by mass

a) Mixing by volume

The proportions of cement, fine aggregates and coarse aggregates are measured by volume, and the mix thus obtained is known as a **nominal mix**. Typical nominal mixes are:

Mass concrete: mix 1:3:6, for use in narrow strip, and deep strip, foundations of dwelling houses.

Reinforced concrete: mix 1:2:4, 1:1½:3 and 1:1:2, for use in slabs, beams, columns and foundations of buildings, and other structures.

In nominal mixes, the ratio of fine aggregates to coarse aggregates is always 1:2. This will ensure that the volume of fine aggregates is enough to fill the voids between the coarse aggregates and hence result in a dense concrete mix.

Mixing by volume results in poor quality control as the water absorbed by the aggregates is not taken into account.

b) Mixing by mass

The proportions of the constituents of concrete are measured by dry mass. The mixes so obtained are known as prescribed mixes, standard mixes, designated mixes and designed mixes. Details of these are given in BS 5328; a summary is produced here:

i) *Prescribed mixes*

The mix is specified by its constituent materials and the quantities of those constituents to produce a concrete with the required performance. The person requiring the concrete mix must specify the nominal maximum size of aggregates, permitted types of aggregates, the mix proportion by weight and the workability.

ii) *Standard mixes*

Depending on the characteristic compressive strength of concrete, five types of standard mixes can be produced. ST1 is the weakest at 7.5N/mm² and ST5 the strongest at

25 N/mm². The mix is first selected from BS 5328 and reference is made to other tables for selecting the materials and the mix proportions.

iii) *Designated mixes*

Designated mixes are specified by considering the site conditions and then selecting the application (from BS 5328) for which the concrete is to be used. The person requiring the concrete mix specifies:

- i) whether the concrete is reinforced or unreinforced
- ii) the aggregate size, if it is not 20 mm
- iii) whether the concrete is exposed to a chloride-bearing environment, and/or to severe freezing conditions while wet
- iv) the workability

iv) *Designed mixes*

The mix is specified in terms of a strength grade: either compressive strength grades (C7.5 to C60) or flexural strength grades F3 to F5. The specified strength grade is subject to restriction on the maximum or minimum cement content, maximum free water-cement (w/c) ratio, nominal maximum size of aggregate, and any other properties required. An important part of designed mixes is to perform strength testing to check the conformity to the specifications.

16.4.4 Properties of fresh concrete

a) *Workability*

The quantity of water used in making a concrete mix is perhaps the most important factor in influencing the workability of fresh concrete and the strength of matured concrete. The amount of water in a mix is expressed as the w/c ratio. For example, if a concrete mix is made by mixing 50 kg of cement, 300 kg of all-in aggregate and 30 kg of water, then the w/c ratio is:

$$\text{w/c ratio} = \frac{\text{Amount of water}}{\text{Amount of cement}} = \frac{30 \text{ kg}}{50 \text{ kg}} = \mathbf{0.6}$$

The workability of concrete is basically the ease with which it can be placed and compacted, and is proportional to the w/c ratio. The typical range of the w/c ratio is from 0.4 to 0.8. When the w/c ratio is low (e.g. 0.3), the mix is dry and difficult to compact. By increasing the amount of water in concrete, the compaction becomes much easier. Such a mix will have a high w/c ratio and high workability. The strength of solid concrete, however, is inversely proportional to the w/c ratio; maximum strength is achieved at w/c ratio of about 0.3. A large amount of water will produce a highly workable mix, but leaves voids in the solid concrete on evaporation. This will result in a lower strength of concrete.

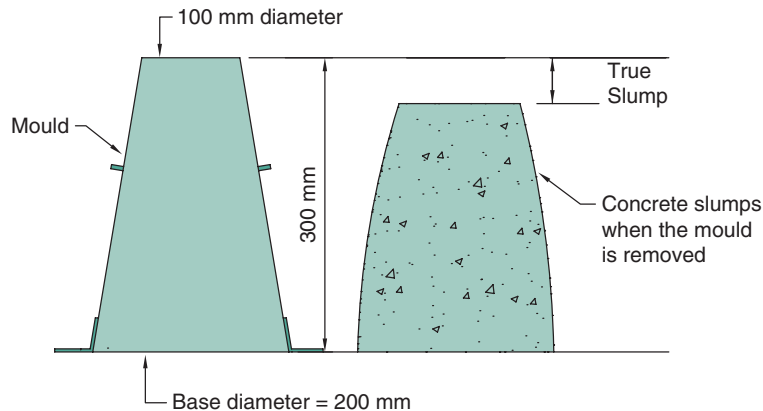


Figure 16.5 Slump test.

Other factors affecting workability are the shape, size and texture of the aggregates. Rounded aggregates produce greater workability whereas angular aggregates produce least workability. As the roughness of the aggregates increases, the workability of the mix decreases. The larger the maximum allowable size of aggregate, the more workable the concrete, because the surface area of bigger aggregates is less than that of smaller aggregates; the cement paste has to coat a smaller area, resulting in more workable concrete.

Tests for workability: The workability of concrete may be determined by performing a slump test, compacting factor test or Vebe consistometer test. Only the **slump test** will be described here as it is the most commonly used site and laboratory method for determining the workability of concrete. The test consists of filling an open-ended conical mould with wet concrete in four equal layers, each being tamped 25 times with the tamping rod. The top of the concrete is levelled off and the cone removed. The drop in the level of concrete, i.e. the slump, is measured as shown in Figure 16.5. A concrete mix of very low w/c ratio may produce zero slump. On the other hand, a concrete mix with a large amount of water may produce a collapse slump. The result must match the specification used in the mix design.

16.4.5 Properties of hardened concrete

a) Density

The density of concrete depends on the type of aggregate used. If dense aggregates are used, then the density will be 2400 kg/m^3 . The use of lightweight aggregate produces concrete with a density less than 2000 kg/m^3 .

b) Modulus of elasticity

The modulus of elasticity of dense concrete ranges between 20700 and 34500 N/mm^2 .

c) Thermal conductivity

Concrete made from lightweight aggregate provides better thermal insulation: its thermal conductivity is approximately 0.6 W/mK . The thermal conductivity of dense concrete is 1.9 W/mK .

d) Strength of concrete

Concrete is very strong in compression but weak in tension. The strength of concrete is affected by several factors, which are explained below:

- i) Voids: The space occupied by coarse aggregate is the sum of the volume of solids and the volume of air voids. In order to obtain dense concrete, the voids must be filled with fine aggregate, which is only possible by proper compaction. Insufficient compaction may not achieve this, resulting in weak concrete.
- ii) Water-cement ratio: The most important factor that affects the strength of concrete is its w/c ratio. If the volume of water used to prepare the mix is more than the optimum requirement, then the excess water remains free while the concrete is still in a semi-fluid state. As the concrete becomes solid, the excess water evaporates leaving voids which make the concrete weaker.
- iii) Fine aggregate: There must be an adequate quantity of fine aggregate in the mix to fill the voids between the coarse aggregate. An insufficient quantity of fine aggregate (a very low fine-coarse aggregate ratio) causes air voids to form, resulting in weaker concrete.
- iv) Shape and texture of aggregates: The shape and texture of aggregates also affect the strength of concrete. The crushed aggregates interlock into one another and produce a higher strength than uncrushed aggregates.

e) Durability of concrete

It is important that the constituent materials of concrete are selected carefully. If concrete is designed, mixed and compacted properly, then it can easily last for several decades. Concrete should be impervious; porous concrete is susceptible to damage from frost and chemicals, as explained in Section 16.4.6.

f) Fire resistance

Concrete is a non-combustible material and reasonably stable up to about 550°C . Because of the low thermal conductivity of concrete, heat is transferred at a very slow rate. It cannot be set on fire and does not emit any toxic fumes if subjected to high temperatures.

16.4.6 Deterioration of concrete

The durability of concrete can be affected by sulphate attack, frost attack, alkali-silica reaction and corrosion of its steel reinforcement.

a) Frost attack

Frost can affect fresh, as well as mature, concrete. If concreting is done in freezing conditions, the water in the mix can freeze and affect the setting and hardening process. Also, water expands on freezing, which can cause damage to concrete. This can be avoided by:

- i) Protecting the concrete from frost by covering the freshly placed concrete with insulation
- ii) Using hot water to accelerate the setting time
- iii) Using rapid-hardening Portland cement

Mature concrete is also likely to be attacked by frost if it is porous. Water is absorbed through pores in the concrete, which expands on freezing, causing damage. Cracking and spalling of the surface of concrete occur due to frost attack. It is important to remember that repeated freeze-thaw cycles are more damaging than steady freezing.

Frost attacks on porous concrete can be avoided by protecting the concrete with a layer of suitable impermeable material.

b) Sulphate attack

Sulphates in soils and in sea water react with the tricalcium aluminate content of cement to form tricalcium sulpho-aluminate. Tricalcium sulpho-aluminate occupies a greater volume than tricalcium aluminate. This has a disruptive effect on concrete, causing cracking and spalling at the surface.

Sulphate attack can be prevented by replacing Portland cement with sulphate-resisting cement in the concrete mix.

c) Alkali-Silica reaction

Alkali-Silica Reaction (ASR), also known as concrete cancer, is a chemical reaction between the alkalis in Portland cement and the reactive forms of silica that are present in some aggregates. Cement (and concrete) contains oxides of sodium, potassium and calcium, which react with water to produce a highly alkaline ($\text{pH} > 13$) pore solution of concrete. Silica, which is a constituent of the aggregates, is acidic and, in the presence of water, reacts with the alkalis to produce viscous alkali silicate gel. The gel forms around, and within, the aggregate and expands on absorbing more water from the cement paste. Eventually the gel may crack the aggregate and the surrounding concrete when the swelling pressure exceeds the strength of the aggregate.

It is quite difficult, if not impossible, to minimise the ASR once it has begun. Although costly, the use of lithium has been found to be effective. The best strategy to minimise ASR is to prevent its occurrence by using appropriate materials in the concrete mix, for example:

- i) Use cement containing low alkali content
- ii) Avoid aggregate that has a reactive form of silica
- iii) Use one or more supplementary cementitious materials, such as PFA and blast-furnace slag, to reduce alkalis in the mix

d) Corrosion of steel reinforcement

Steel bars are used in reinforced concrete to resist the tensile stress that plain concrete cannot resist. The steel is protected from corrosion by the alkaline environment of the concrete. If the alkaline environment is neutralised and the concrete is permeable, water can seep through and cause the corrosion of steel. Corroded steel will lose the bond with concrete that is necessary for transferring tensile stress from concrete to steel.

To protect the steel reinforcement, the concrete must be impermeable to water and must also be free from substances that can chemically attack the steel.

16.4.7 Environmental implications

The main materials required to produce plain concrete are cement and aggregates. Similarly, the main materials required for reinforced concrete are plain concrete and steel. Production of cement and steel requires a number of raw materials, i.e. limestone/chalk, clay/shale, iron ore and coke. These materials, which are extracted from quarries/mines, have a major impact on the environment, as explained in Sections 16.3.7 (cement) and 16.5.6 (steel). The manufacture of steel produces large volumes of waste water, some of which is recycled.

The huge impact that concrete has on the environment can be reduced by replacing Portland cement with CEM II or other cements. For example, Portland-fly ash cement (CEM II/B-W) saves about 35% of limestone and clay.

The impact on the environment can also be reduced if concrete is crushed and recycled as aggregate for new concrete. It must be free from contaminants like plaster and wood. Recycling old concrete saves landfill space and reduces the need for gravel quarries.

16.5 Metals

Metals can be classified into two groups: ferrous and non-ferrous. Ferrous metals contain iron, typical examples being cast iron, wrought iron, and the various types of steel. Non-ferrous metals do not have any iron; typical examples of non-ferrous metals used in buildings are copper, lead, aluminium and zinc. Ferrous metals, mild steel in particular, are used extensively in the construction of buildings, dams, tunnels, bridges and other structures.

16.5.1 Ferrous metals

Ferrous metals and alloys, such as pure iron, cast iron, wrought iron, mild steel etc., contain iron as the parent metal. The word ferrous comes from **ferrum**, which is the Latin name of iron (chemical symbol: **Fe**). In nature, iron is found in minerals formed by its combination with other elements, for example, iron and oxygen combine to produce iron oxides. **Haematite** (Fe_2O_3) and **magnetite** (Fe_3O_4), which are oxides of iron, are the main ores of iron and are mined commercially.

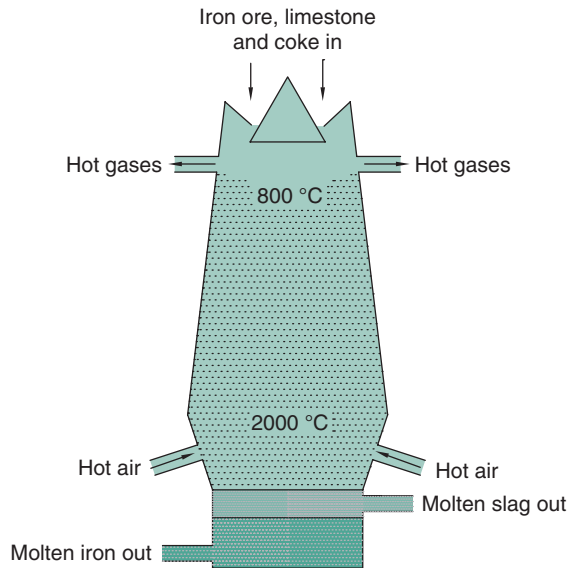


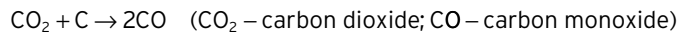
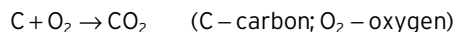
Figure 16.6 Blast furnace.

16.5.2 Raw materials

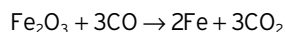
The raw materials used to produce pig iron in a blast furnace are iron ore, coke and limestone. The iron ore is extracted from the ground and partially refined to remove some of the impurities. Coke is made by heating coal; limestone is a carbonate of calcium and occurs naturally. The iron ore is finely divided and roasted with coke and limestone to remove a large amount of the impurities that occur naturally in the ore.

16.5.3 Manufacturing process

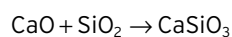
The iron ore is heated in a blast furnace with limestone and coke (impure carbon), where several chemical reactions take place, resulting in molten iron:



Carbon monoxide acts as a reducing agent and reacts with the iron ore to give molten iron, which is collected at the bottom of the furnace (Figure 16.6).



The limestone in the furnace decomposes, forming calcium oxide (CaO). Calcium oxide combines with impurities to make slag (CaSiO_3), which floats on top of the molten iron and can be removed.



The process results in pig iron and slag. Slag is used in cement manufacture and as an aggregate in road construction and other applications. Pig iron contains 4-5% of carbon and other impurities like manganese, silicon, phosphorus and sulphur, which can be removed to give different types of steel.

One of the biggest drawbacks of the blast furnaces is the production of carbon dioxide gas, which is a greenhouse gas. New iron-making processes have been developed, which reduce the emission of CO₂ gas.

All ferrous metals contain carbon. This is due to the use of coke in the blast furnace during the smelting of the ore. Variations in the carbon content of ferrous metals have important influences on their properties. In general, an increase in the carbon content causes a reduction in ductility and ease of welding, but an increase in the hardness. In steel, tensile strength increases with an increase in the carbon content up to about 1.5%.

16.5.4 Iron and its alloys

a) Cast iron

Cast iron is made by re-melting pig iron together with steel and cast iron scrap. Its high carbon content (2.5%-4.5%) makes it free-running and suitable for castings. The tensile strength varies from 155 to 400N/mm². Cast iron was used in the past for drainpipes, guttering and water tanks.

b) Wrought iron

Wrought iron is made by melting pig iron with iron oxide. It is very soft as it contains a very small proportion of carbon, i.e. 0.02%-0.03%. Wrought iron is moderately strong in tension, failing at about 355N/mm², but very tough and resistant to impact loads.

c) Steel

Steel is produced by removing impurities, such as sulphur and phosphorus, from pig iron and adjusting the carbon content. There are many types of steel:

Low carbon steel contains up to 0.15% carbon. It is soft, malleable and ductile, therefore used for wiring and sheets.

Mild steel contains 0.15% to 0.25% carbon and is strong in tension, ductile and suitable for rolling into structural sections, strips and sheets.

Medium carbon steel contains 0.25% to 0.50% carbon and is suitable for making nuts and bolts.

High carbon steels contain 0.5% to 1.5 % carbon. The carbon content makes these steels both tough and brittle. These are used for making cutting tools, chisels and files.

16.5.5 Properties of steel

a) Malleability and ductility

Malleability is the property of a metal by virtue of which it can be deformed by compression without cracking or rupturing. Ductility is the ability to deform plastically without

fracture under a tensile force. A material is malleable if it is possible to roll it into sheets, and ductile if it can be drawn into wires. On stretching ductile metals, we can see clearly the formation of necking (see Section 10.6.2) before failure, whereas in brittle materials there is no necking. This property (ductility) allows materials to redistribute stresses that may build up at weak points.

Mild steel is both malleable and ductile; it is used in manufacturing tools, tubes, pipes, structural sections, reinforcement bars and other applications.

b) Hardness

The resistance of a material to indentation is known as hardness. The term can also apply to deformation from scratching and cutting. In engineering, the Brinell test is usually performed to determine the hardness of a metal. A hardened metal sphere is placed on the metal to be tested and a force applied. The load divided by the surface area of the indentation on the test sample gives the Brinell hardness number. The hardness of mild steel is 120 HB.

c) Density

Density of steel is 7850 kg/m^3 . This shows that steel is far denser than common building materials like bricks, blocks, cement, concrete and timber.

d) Thermal conductivity

Steel, like other metals, is a good conductor of heat, or a poor insulator. Its coefficient of thermal conductivity (λ -value) is 50 W/mK , which means that the heat loss through steel is about 60 times that in bricks.

e) Thermal movement

The coefficient of linear expansion of steel is $11\text{--}13 \times 10^{-6}/^\circ\text{C}$.

f) Modulus of elasticity

The value of the modulus of elasticity for steel is 210 kN/mm^2 . Young's modulus is a measure of the stiffness of a material, or its resistance to compression or extension. For a comparison, the modulus of elasticity of copper and aluminium is 117 kN/mm^2 and 70 kN/mm^2 respectively. It can be determined by performing a tensile test on the given metal using an apparatus called a 'tensometer'.

g) Electrical conductivity

Steel has a low electrical resistance, or is a good conductor of electricity. Its electrical conductivity is $1.1 \times 10^7/\Omega\text{m}$.

16.5.6 Corrosion of iron/steel

Iron is made from its ores by a reduction process (removal of oxygen). As soon as iron/steel components are manufactured, their corrosion begins if suitable protection is not provided. Corrosion of iron/steel is caused by the following processes:

- i) Oxidation
- ii) Electrolytic action

Oxidation of iron/steel, also known as rusting, causes a lot of damage to unprotected components. The process involves a reaction between oxygen and iron in the presence of water to form ferrous oxide (iron oxide) $\text{Fe}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$ or ferric hydroxide $\text{Fe}(\text{OH})_3$. These products are reddish-brown in colour, commonly known as **rust**. Once rusting starts, the porous oxides formed will allow more air and water to enter, causing more damage. Both air and water are required for the rust to form and, in the absence of one of these, rusting will not occur. This can be shown by performing a simple experiment in which iron nails are put in test tubes and exposed to different types of environments (see Section 5.2 for details).

When two dissimilar metals are in contact, **electrolytic corrosion** occurs in the presence of water. This has been explained in Chapter 5.

Protection of steel from corrosion: Steel can be protected from corrosion by painting, galvanising and other treatments. Refer to Sections 5.4.1 and 5.4.2 for details.

16.5.7 Environmental implications

Steel is one of the main materials used in construction; about 30% of its total production is used in construction. Steel production involves several processes including the mining/quarrying of raw materials, production of coke from coal, and smelting of iron ore in a blast furnace. The mining of iron ore results in some destruction of the landscape, production of dust and gases, and noise from the mining/transportation of raw materials. When mining is over, the sites are used as landfills, which can become a problem if toxic substances are dumped on such sites.

Iron-making requires large amounts of coal to produce coke, which is an important material in making iron by reduction of the iron ore. The coking process emits particulate matter, volatile organic compounds (VOCs), ammonia, methane, phenol, carbon monoxide and sulphur oxides. Most of these by-products are toxic but commercially very useful for many other industrial processes.

About 400 litres of waste water are generated during the production of one tonne of coke. Water is required for the cooling of the coke oven gas and the processing of ammonia, naphthalene, phenol, and light oil. This is only a small fraction of the total water requirement; about 350000 litres of water are required to produce one tonne of steel. The steel-making sector is a very large consumer of energy, therefore a major contributor to greenhouse-gas emission.

Iron and steel are the most recycled materials as it is cheaper to recycle these than to mine iron ore. Recycling reduces piles of old metal and all forms of pollution that are associated with the mining of iron ore. Since the scale of mining is reduced, recycling saves a lot of energy as well.

16.5.8 Non-ferrous metal: aluminium

Non-ferrous metals, such as aluminium, copper, brass, lead and zinc, are used in construction, but in this section only aluminium will be described. Aluminium is a lightweight, malleable, ductile and durable metal that has numerous uses in the construction industry. It is a sustainable material as the physical properties of the metal after recycling are the same as those of the original metal.

16.5.9 Raw materials

Aluminium occurs in the earth's crust as hydrated aluminium silicates and oxides; the usual aluminium ore is **bauxite** which is basically impure aluminium oxide. The traditional smelting methods cannot be used to extract aluminium from bauxite because a very high temperature is needed. Instead, aluminium is extracted from its ore by electrolysis, the details of which are given in Chapter 5. The chemical symbol of aluminium is **Al**.

16.5.10 Properties

The important properties of aluminium include its attractive appearance, light weight, good thermal and electrical conductivities, and high resistance to corrosion. Pure aluminium is comparatively soft and only of moderate tensile strength. However, its alloys with other metals (silicon, copper or magnesium) have considerable strength, making them suitable for use in structural members, scaffolding and ladders. Aluminium is a ductile metal enabling it to be drawn into wires or extruded to structural members, tubes, pipes, gutters and door/window frames. When exposed, a thin layer of aluminium oxide builds up on the surface of fresh aluminium, which protects it from corrosion. This layer can be strengthened further by anodising the aluminium.

Aluminium has a high electrical conductivity and a high thermal conductivity.

a) Hardness

Pure aluminium is very soft, its hardness being 15HB. When aluminium is alloyed with other metals, its hardness increases and ranges between 60 and 100HB.

b) Fire resistance

As with steel, the fire resistance of aluminium is not very high. Its melting point is 660 °C.

c) Durability

Aluminium is a durable metal with high resistance to corrosion. When exposed to the atmosphere, a hard layer of oxides forms on the surface which protects the metal from corrosion.

The properties of aluminium are compared with those of mild steel and copper in Table 16.4.

Table 16.4 Comparison of some properties of mild steel, aluminium and copper

Metal	Density (kg/m ³)	Modulus of elasticity (kN/mm ²)	Coefficient of linear expansion (per °C)	Thermal conductivity (W/mK)	Electrical conductivity (siemens/m)	Tensile strength (kN/mm ²)
Mild Steel	7850	210	$11\text{--}13 \times 10^{-6}$	50–80	1.1×10^7	400
Aluminium	2700	70 (alloys)	23.5×10^{-6}	234	3.7×10^7	100 (pure) 250 (alloy)
Copper	8900	117	16.6×10^{-6}	400	5.85×10^7	250

Note: The tensile strength of a metal depends on its composition

16.5.11 Environmental implications

Bauxite is usually mined by opencast mining and, as with any other mining operation, the landscape and the habitat are destroyed. In opencast mining, the top layer of soil is removed to reach the ore underneath. If the top layer of soil is not reinstated after the mining operation is over, vegetation may not return.

Aluminium can be extracted only by electrolysis, which uses a huge amount of electricity. If fuels are burnt to generate electricity, the carbon dioxide emissions into the atmosphere cause pollution and global warming.

Nowadays, scrap aluminium is collected and recycled to save a large amount of electricity and protect the environment from various types of pollution. The recycling process consumes only about 5% of the energy used to extract the metal from bauxite ore.

16.6 Timber

Timber is one of the main materials used in the construction of low-rise domestic buildings. Its thermal properties, lightness and strength encouraged builders to devise timber-framed house construction in countries with a temperate climate. Timber is an organic material obtained from trees. When a tree reaches maturity, it is felled, and the wood, obtained mainly from the trunk, is cut to suitable sizes. The moisture content of raw wood is reduced by a process known as seasoning. After seasoning, the wood is known as timber and ready for use as a construction material. Timber is divided into two classes: softwood and hardwood; softwood is obtained from evergreen trees, whereas hardwood is obtained from deciduous trees. Deciduous trees have broad leaves which are shed in the autumn. All softwoods are not soft and, similarly, all hardwoods are not hard.

A tree consists of three parts: the roots, the trunk and the crown. The roots spread out in the soil and absorb water and minerals; the solution of these is known as sap. The trunk, which eventually becomes the source of timber, supports the tree and transports the sap to the crown through the sapwood. The leaves, which make the crown, are responsible for producing the sugars and starches needed for the growth of the tree. Leaves absorb

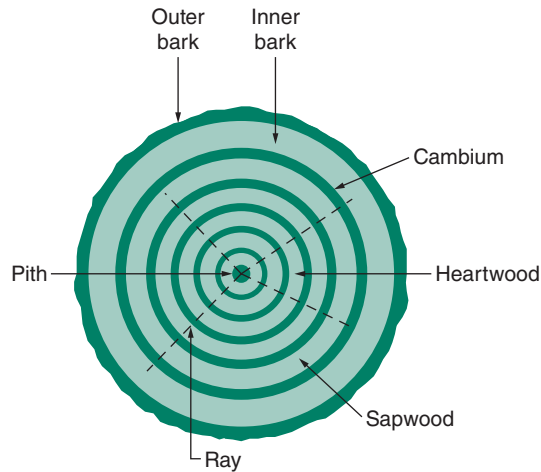


Figure 16.7 Cross-section of a tree trunk.

carbon dioxide from the atmosphere and, in the presence of sunlight and chlorophyll (green substance in the leaves), convert the sap into sugars and starches. Wood tissue is composed of various types of cells, the walls of which are made of cellulose and lignin. Cellulose ($C_6H_{10}O_5$)_n is a long-chain polymeric polysaccharide carbohydrate that forms the primary structural component of green plants. The lignin binds together the cellulose material to give the wood its strength and rigidity.

Figure 16.7 shows a horizontal section of a tree trunk, and illustrates the parts involved in the growth process of a tree.

The trunk and the branches of the tree are covered with **outer bark** which protects the tree. It is formed from the dead inner bark cells.

The **inner bark**, found between the outer bark and the cambium, acts as a food supply line by carrying sap from the leaves to the rest of the tree.

The **cambium** is a very thin layer of growing tissue that produces new cells. Each year a new layer of cells (**sapwood**) is produced, making the cambium layer move further outwards from the centre of the trunk. This layer of sapwood, also known as annular ring, is formed during spring and summer.

As new sapwood layers are formed, the cells in older sapwood layers become inactive and die to form **heartwood**. Heartwood is denser and more durable than sapwood. The central core of the tree is known as **pith**. It decays as the tree becomes older and has no commercial value.

16.6.1 Seasoning

Raw timber is not suitable for immediate use in buildings as it contains a lot of moisture. Seasoning is the process of removing a certain proportion of water from raw timber to make it suitable for use in buildings. Seasoned timber is lighter, stronger, easier to work with and easier to finish with paint/varnish. Seasoning may be natural (air seasoning) or artificial (kiln seasoning).

a) Air seasoning

Timber is protected from sun and rain, and stacked off the ground to allow free circulation of air. The drying process should be slow to protect the timber from excessive shrinkage. Winter is the best time to start air seasoning when the air temperature is low, and the relative humidity of air is high, to ensure slow drying.

b) Kiln seasoning

Air seasoning may take several months, whereas in kiln seasoning an external source of heat energy is used to accelerate the drying process. The timber is stacked inside a chamber in which the temperature and humidity can be controlled to produce best results. Each species requires a different optimum temperature and humidity to produce the desired moisture content.

16.6.2 Properties**a) Appearance**

Timber is available in a variety of colours such as white, light-yellow, orange, light-brown, dark-brown and others. Different species of timber show different colours, which can change with age and by the application of finishes. The texture of a timber depends on the size and arrangement of its cells. Generally, softwoods have fine texture but hardwoods may have fine or coarse texture. The wood grain can also enhance the appearance of timbers.

b) Density

Timber is a light material with the density of different species ranging from 160 to 1250 kg/m³. Although all species of timber are composed of the same substances, the differences in their microstructure affect the values of density. The densities of the most commonly used softwoods in the UK range from 380 to 550 kg/m³.

c) Thermal conductivity (λ)

The thermal conductivity of timber depends on its moisture content and density; light-weight timber has better thermal insulation than dense timber. There are numerous air pockets within the cellular structure of timber that make it a natural insulator. The thermal conductivity values of timber used in buildings range between 0.08 and 0.18 W/mK (approx.).

d) Acoustic properties

The cellular structure of timber has minute interlocking pores which convert the sound energy into heat energy by frictional/viscous resistance achieving sound insulation. The porous structure of timber is also responsible for the absorption of sound. Typical values

of the sound absorption coefficient for wood blocks on a solid floor are: 0.05 at 500 Hz and 0.1 at 2000 Hz.

e) Strength

Timber is a lightweight but strong material with a high strength-weight ratio both in tension and compression. There is a large variation in the strength as there are so many different species of timber. Generally, the strength of timber is directly proportional to its density, and inversely proportional to its moisture content. Defects such as knots can also affect timber strength.

The tensile strength of timber ranges between 2.5 and 13.8 N/mm². The modulus of elasticity of timber ranges between 4600 and 18000 N/mm² (BS 5268-2:1996).

f) Fire resistance

In the case of a fire, the temperature of timber components does not rise quickly as the material is a poor conductor of heat. Timber will ignite at a temperature of about 220–300 °C, but the charring of the timber surface acts as an insulator and provides protection to the inner parts of the components.

g) Hardness

Hardness is an important property to consider when a flooring material is selected. Flooring made of harder timber lasts longer and requires less maintenance than softwood flooring.

16.6.3 Deterioration

Timber is a durable material but can deteriorate if not protected from sunlight, chemicals, fungi, insects and other causes. Because timber is basically cellulose, it is used as a source of food by fungi (plants) and insects. Details of these causes of deterioration and the protection of timber are discussed here.

a) Excessive loading

If the load applied on structural elements is less than the design load, the stresses developed will be within permissible limits. If, due to some reason, the applied loading exceeds the design load, then the stresses developed will be greater than the permissible stresses and may cause unacceptable bending and possibly lead to fracture.

b) Sunlight and rain

The ultraviolet radiation in sunlight causes discoloration; excessive rain causes cracks and growth of moulds and algae.

c) Fire

Timber is a combustible material, and decomposes in high temperatures to produce charcoal and combustible gases like CO and methane. The propagation of fire from the surface of a component to the inside is slow because of the low thermal conductivity of timber. The charred surface of the timber component also acts as an insulator and protects the interior of the section.

d) Fungal attack

Fungi are plants without leaves and branches, which feed on the cellulose of timber. For their growth, they require: moisture, oxygen and a temperature between 20 °C and 30 °C.

The spores (seeds) of fungi are dispersed through the air. They settle on timber to produce fine rootlets called hyphae. Hyphae feed on timber to produce more spores and the cycle continues. The two most common types of fungi are **dry rot** and **wet rot**.

Dry rot is the most common and damaging fungus. It is off-white in colour and spreads over timber like fluffy cotton wool. Once formed, it produces its own moisture. After the attack, the timber darkens in colour and is left with deep cracks along, and across, the grain. The timber loses its strength and crumbles into a powder. Dry rot is often found in places where the moisture content of timber is between 20% and 35% and where there is a lack of ventilation.

Timber affected by dry rot must be removed and replaced with preserved timber. If brickwork has been affected, then it must be burnt with a blowlamp; dry rot cannot survive beyond a temperature of 40 °C. It is also important to provide adequate ventilation so that the damp conditions never occur in the first place.

Compared with dry rot, wet rot is not such a big problem and usually occurs if the moisture content of timber is above 25%. To make timber really wet, there is usually a structural defect, such as leaking gutters or persistent leakage behind baths. The wet rot causes the timber to become dark-brown or black before it splits. Before the affected timber is removed and the adjacent timber treated, it is important to locate the source of moisture and deal with it.

e) Insect attack

As with dry rot and wet rot, insects also feed on timber causing damage, which is less serious than fungal damage. Many types of beetles, termites, wood wasps and other insects can damage timber, not only in timber yards but also in buildings. The life cycle of a beetle starts with the female beetle laying eggs in cracks and crevices of bare timber. The eggs hatch into the larvae which feed on the timber leaving unwanted dust behind. The larvae change into pupae (dormant stage) and, in due course, the pupae change into adult beetles. The adult beetles emerge from the timber through tiny holes known as flight holes, to mate and start the life cycle again. The most common beetles found in the UK are discussed here.

The common furniture beetle is 2-5mm long and is dark-reddish in colour. It attacks both hardwoods and softwoods, particularly their sapwoods. It is most often found in furniture and joinery. The flight holes are circular with a diameter of about 2mm.

The house longhorn beetle is black and 10-20 mm long. It attacks the sapwood of softwoods only. The flight holes are oval and 5-10 mm in diameter.

The death-watch beetle is brown and 8 mm long. It attacks hardwoods, particularly old oak that has high moisture content.

The powder post beetle attacks the sapwood of most hardwoods and is found particularly in timber yards and sawmills. Softwoods are not attacked by this beetle. The beetle is reddish-brown, 4-5 mm long and leaves a flight hole of 2 mm (approx.) in diameter.

16.6.4 Preservation

Fungi and insects use timber as a source of food making it unsuitable for structural purposes. The best way to control this damage is to treat timber with chemicals that are poisonous to fungi and insects, but not to humans. Three types of preservatives are available: creosote substitutes, water-borne preservatives (copper-chrome-arsenate) and organic solvent preservatives (chlornaphthalenes, metallic naphthanates, pentachlorophenol).

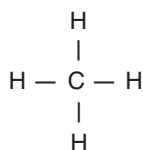
16.6.5 Environmental implications

The environmental impact of the use of timber is the least of all building materials. Timber is a renewable source as the forests can be managed to grow trees on a sustained continuous basis. Trees absorb carbon dioxide from the atmosphere as part of the photosynthesis process. Waste timber, in good condition, can be processed to manufacture products like chipboard.

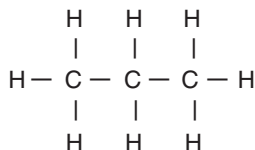
16.7 Plastics

Plastics are relatively new materials as compared to timber, steel and other construction materials, and they have replaced the traditional materials in several applications. Typical examples where plastics have gained more popularity than the traditional materials are drainpipes, windows, external doors, fascias, soffit boards and cladding.

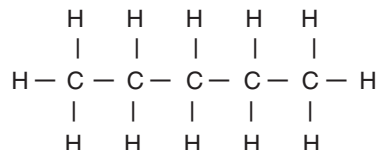
Plastics contain carbon combined with elements like hydrogen, oxygen, chlorine and nitrogen. Organic substances containing only the elements carbon and hydrogen are known as hydrocarbons; typical examples are methane, ethane, propane, butane and pentane. The formulae of a selection of hydrocarbons are shown here:



(a) Methane (CH_4)



(b) Propane ($\text{C}_3 \text{H}_8$)



(c) Pentane ($\text{C}_5 \text{H}_{12}$)

As the chain becomes longer, or the molecule becomes larger, the hydrocarbons change from gas to liquid. Later in the series, the viscosity of the liquid hydrocarbons increases and they become solid. The substitution of other elements in place of one or more hydrogen atoms will produce further homologous series. For example, replacing one atom of methane and ethane with a chlorine atom produces methyl chloride and ethyl chloride respectively.

16.7.1 Raw materials and manufacture

Plastics are made from **monomers** which are obtained from the fractional distillation of coal or petroleum. Fractional distillation of petroleum yields many substances: methane, ethane, propane, butane, hexane etc. are some of them. They are all mixed together initially but separated in the refineries for use in making different types of plastics. Similarly, between 200°C and 250°C, naphthalene and phenol are obtained due to the fractional distillation of coal. Phenol is further used in the production of plastics.

In the next stage of manufacturing, the monomers are subjected to high temperatures and pressures in the presence of catalysts. The monomers are converted into polymers which consist of a large number of monomers. The polymer is compressed into plastic pellets which are further mixed with additives such as pigments, antioxidants, plasticisers, flame retardants, ultraviolet stabilisers etc. to achieve the desired properties in the end product. The mixture is used in the appropriate manufacturing process (extrusion, injection moulding or blow moulding) to produce the desired product.

16.7.2 Classification

Plastics can be classified into two types: thermoplastics and thermosetting plastics.

a) Thermoplastics

Thermoplastics can be repeatedly melted down by heating, and they harden on cooling without any change in properties. Thermoplastics can be remoulded several times into any desired shape. Typical examples are: polyethylene, polystyrene, PVC etc.

Thermoplastics have good weathering properties, but may discolour in sunlight. They show creep characteristics and are usually inflammable at high temperatures.

b) Thermosetting plastics

Thermosetting plastics harden on the application of heat. Once set in the moulded stage, they cannot be melted and remoulded. Typical examples are: bakelite and urea-formaldehyde.

Thermosetting plastics are hard-wearing, stronger than thermoplastics, and resistant to abrasion. The disadvantages are that they are brittle, inflammable and not very flexible.

16.7.3 Properties and uses

a) Polyethylene

The scientific name is poly(ethane) but it is more commonly known as polythene which is ICI's trade name. Polyethylene can be produced by following different methods of polymerisation, hence its properties vary as well. Two common forms of this polymer are low-density polyethylene (LDPE) and high-density polyethylene (HDPE). In LDPE the chains do not lie close together, resulting in a weaker plastic. It has lower density (910 to 940 kg/m^3) and a lower melting point (110°C). LDPE is more flexible than HDPE, and is used in making moisture-barrier films.

In HDPE the molecules lie close together, resulting in higher density (941 to 970 kg/m^3), higher melting point (135°C) than LDPE and higher strength. HDPE is used in manufacturing water pipes and cable insulation. Polyethylene is a poor conductor of heat, having thermal conductivity between 0.30 and 0.40 W/mK . The coefficient of thermal expansion ranges between 2×10^{-5} to 20×10^{-5} per K.

Both plastics show good resistance to vegetable oils, acids and alkalis.

b) Polyvinyl chloride

Polyvinyl chloride (PVC) is a thermoplastic and the most widely used plastic in the construction industry. It is available as plasticised polyvinyl chloride as well as unplasticised polyvinyl chloride (PVCu) and used in a variety of constructional and non-constructional applications. PVCu is strong (at normal temperatures), durable, lightweight and flame retardant. PVCu is also resistant to dilute acids, dilute alkalis and domestic chemicals, but has poor resistance to aromatic hydrocarbons like naphthalene. Due to these properties, PVCu is extensively used in making window and door frames, pipes and pipe fittings, rainwater gutters, fascias and soffit boards, cladding and conservatories.

PVC is combustible, giving off toxic hydrogen chloride fumes, however, PVCu tends to burn only with difficulty. Typical values of density for PVC and PVCu are 1300 kg/m^3 and 1400 kg/m^3 . PVC and PVCu are good thermal insulators having thermal conductivity values of 0.15 W/mK and 0.20 W/mK respectively. A typical value of the coefficient of thermal expansion is 6×10^{-5} per K.

Pure PVC is a tough material with good resistance to weather and chemicals. Its resistance to heat and light is comparatively poor and, as a result, chlorine is lost when it is exposed to heat and UV light. The loss of chlorine is avoided by adding stabilisers, which are salts of heavy metals like lead and cadmium.

Lead and cadmium compounds used in PVC are toxic and dangerous to the environment. Some cadmium compounds are classified as carcinogens. The use of lead and cadmium stabilisers is safe during the use phase, but contamination of the environment can take place during production and waste treatment. Measures should be taken to eliminate, or to reduce to a minimum, the exposure of workers to these toxic substances.

PVC, which is originally rigid, is made flexible by the addition of substances known as plasticisers and is used in manufacturing upholstery, flooring, roofing membranes and insulation for electrical cables. Naphthalates, especially diethylhexyl phthalate (DEHP),

are quite commonly used for this purpose. Some organisations have raised concerns over the toxicity of naphthalates, and some countries have banned their use in children's plastic toys.

c) Polytetrafluoroethylene (PTFE)

PTFE is a thermoplastic, consisting of carbon and fluorine; it is resistant to high temperature, chemical reaction and corrosion, and has a very low coefficient of friction (0.05 to 0.1). These properties make it useful in several applications. It was developed by DuPont in 1938, and marketed as Teflon. Because of its resistance to high temperature and its non-stick properties, its initial use was to make non-stick kitchen utensils. Due to its resistance to chemicals, it is used for machinery parts that could be susceptible to corrosion, and due to its very low coefficient of friction, it is used in bridge bearings to allow expansion or contraction of bridge decks. PTFE tape is used by plumbers to seal threaded connections as the tape performs a lubricating action. PTFE is white with a density of 2150 to 2200 kg/m³. Typical values of thermal conductivity and the coefficient of thermal expansion are 0.25 W/mK and 12×10^{-5} per K.

d) Melamine formaldehyde (MF)

Melamine formaldehyde is a thermosetting plastic, made from the polymerisation of formaldehyde with melamine. MF is odour-free, can be easily coloured, and is resistant to heat, light, fire, chemicals and abrasion. MF is used as an adhesive in manufacturing particle board (chipboard) and plywood. Particles of cheap wood, sawdust and paper are glued with melamine formaldehyde and compressed under high pressure to produce particle board. Melamine formaldehyde is also used as a protective covering in laminated boards that are used in furniture, flooring and worktops. The density and the tensile strength are 1400 kg/m³ and 60 N/mm² respectively. The coefficient of linear expansion is 35×10^{-6} per K.

Melamine formaldehyde is affected by alkalis and concentrated acids.

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17

Assignments

17.1 Assignments for Level 2 courses

17.1.1 Assignment No. 1

Task 1

- Explain, briefly, the effects of gravitational force on the structural elements (walls, floors, roof, beams and columns) of a building.
- Explain the effect of gravitational forces on the shape of structural elements like walls, columns and beams.
- Explain how the structural elements of a building may fail as a result of overloading.
- A 6.0m long concrete beam that is 200mm $\times$ 400mm in cross-section is resting on two walls. Calculate the dead load of the beam if the density of concrete is 2400kg/m³.
- Calculate reactions R_1 and R_2 for the beam shown in Figure 17.1.

17.1.2 Assignment No. 2

Task 1

- Describe, briefly, what happens to plastic guttering and PVCu windows when the air temperature rises during the day and drops during the night.
- Describe, briefly, what happens to water when:
 - its temperature is lowered to -3°C .
 - its temperature is raised to 100°C .
- Explain the effect of temperature change, in terms of latent heat and sensible heat, on the physical changes in the state of water.
- A 5.0m length of steel tube is heated from 10°C to 40°C . Calculate the thermal movement if the coefficient of linear expansion of steel is 0.000012.
 - A 4.0m length of steel tube is cooled from 45°C to 20°C . Calculate the thermal movement if the coefficient of linear contraction of steel is 0.000012.

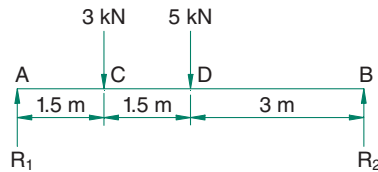


Figure 17.1

17.1.3 Assignment No. 3

Task 1

Explain how sub-zero temperatures can affect porous materials like bricks, concrete blocks and roof tiles saturated or partially saturated with water. How are these materials affected by repeated freeze-thaw cycles?

Task 2

- Select two materials and evaluate the effect of forces and temperature changes on their properties.
- Justify the use of the two materials in the construction of a dwelling house.

17.2 Assignments for Level 3/4 courses

17.2.1 Assignment No. 1

Introduction

Midlands Institute of Engineering and Technology has proposed to construct a single-storey conference centre as an extension to the main building. The size of the extension and other details are given in the data sheet. Although the main use of this extension will be for conferences and seminars, it may also be used for other events like lectures, open days etc.

The choice of materials, components and construction techniques should ensure that the new construction conserves energy and creates a comfortable environment in the conference room. The constructional details of the extension are:

Roof: RC slab

Ground floor: Solid concrete floor

Walls: Cavity construction using bricks and dense concrete blocks

Your assignment, as a trainee technician, is to complete the following tasks and present your findings in the form of a written report/PowerPoint presentation. Use tables, images, graphs, wherever appropriate.

Task 1

- a) Identify and describe the factors (temperature, humidity, ventilation, acoustic environment and visual environment) that could affect human comfort in the conference room.
- b) Describe, with diagrams of appropriate instruments, how each factor is measured and state the acceptable values of each identified factor.

Task 2

- a) Use the information given in the data sheet and calculate the fabric heat loss and the heat loss due to ventilation from the conference room.
- b) Three vehicles, parked in the car park, started at the same time and produced noise levels of 76dB, 80dB and 83dB. Use either the analytical method or the graphical method to calculate the overall noise level.
- c) A street lamp (point source), having a luminous intensity of 1200cd, is suspended 6m above the edge of the road leading to the car park. If the road is 8m wide, calculate:
 - i) the illuminance at point A on the road surface that is directly under the lamp.
 - ii) the illuminance at a point, on the other edge of the road, directly opposite point A.

Task 3

- a) Explain how the human thermoregulatory system is affected by air temperature, air movement, humidity, clothing and level of activity. Give acceptable values of these factors for the conference room.
- b) Discuss how the NC/NR curves and the speech interference criteria may be utilised to analyse noise and achieve acoustic comfort in the conference room.
- c) Discuss the reasons why designing for high levels of daylight in the conference room may impact upon levels of visual and thermal comfort. Give acceptable values of illuminance for the conference room.

Data sheet

Plan area of the extension (internal): 20.0m × 15.0m
 Height of the building: 4.5m (floor to ceiling)
 Number of 1.5m × 1.2m high double-glazed windows: 12
 Number of 2.0m × 2.0m high doors: 3
 Internal temperature and humidity: 21°C and 60% respectively
 External temperature and humidity: 0°C and 100% respectively
 Number of air changes: 2 per hour
U-values (W/m² K)
 Floor: 0.50; Roof: 0.50; Windows: 1.70; Doors: 2.0
 (Refer to Chapter 9 for any other information)

17.2.2 Assignment No. 2

Task 1

- a) The conference centre will be affected by different types of forces when the construction is over. Explain the following forces:
 - (i) point load and uniformly distributed load
 - (ii) dead load, imposed load and wind load
 - (iii) concurrent, non-concurrent and coplanar forces
- b) Explain and differentiate between compressive, tensile, shear and bending stresses.
- c) Explain how the above stresses change the shape of elements/members they act upon.
- d) Describe, briefly, how excessive stresses may lead to the failure of elements/members.

Task 2

- a) Explain how the forces acting on beams, joists, floors etc. can cause compressive stress, tensile stress and shear stress at the same time.
- b) Explain how forces can cause the following in simply supported beams, and cantilevers:
 - (i) positive and/or negative bending
 - (ii) positive and negative shear

Task 3

- a) Find reactions for the beams shown in Figure 17.2:
- b) A metal rod of 10 mm diameter had an initial length of 1.0 m. After a tensile force of 12 kN was applied to the rod, its length increased to 1.002 m. Calculate the modulus of elasticity of the metal.
- c) Figure 17.3 shows two rods A and B supporting a load of 400 N. Find the nature and magnitude of forces in the two rods.

17.2.3 Assignment No. 3

Introduction

Several materials will be used in the construction of the conference room. These are: cement, concrete, bricks, concrete blocks, timber, plastic, steel, gypsum plaster, glass, copper and others. Select any THREE that are relevant to your course/profession and answer the following tasks. You can present your findings either in the shape of a word-processed report or PowerPoint presentation. Use tables, images, graphs, wherever appropriate.

Task 1

- a) Describe the process for producing/manufacturing your selected materials. In each case, comment on the amount of energy consumed in the production/manufacturing process.

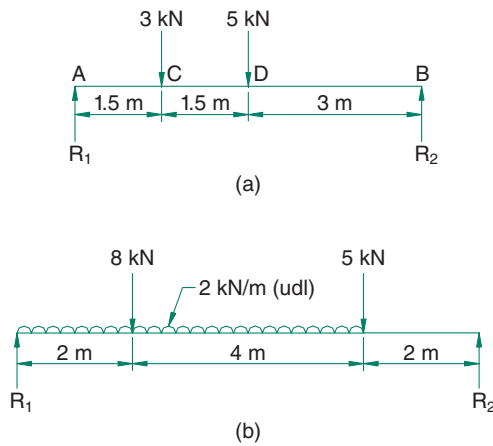


Figure 17.2

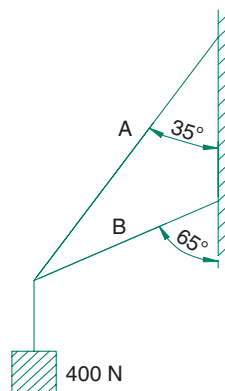


Figure 17.3

- Describe in detail the main properties (e.g. strength, elasticity, thermal movement etc.) of the selected materials.
- Describe the processes that may cause the deterioration/failure of the selected materials, after their use in the conference centre.
- Explain the preventative and remedial techniques used to prevent deterioration of construction materials, and compare their effectiveness.

Task 2

Justify the use of your selected materials in the construction of the conference centre.

Appendix 1: Formulae for Example 9.2

The screenshot shows a Microsoft Excel spreadsheet titled 'spreadsheet example 9.2'. The spreadsheet is organized into columns A through G. Column A lists materials and layers, Column B lists thermal conductivity (λ), Column C lists thickness (d), Column D lists thermal resistance (R), and Column E lists the U-value. The formula for U-value is given as $U = \frac{1}{R_{total}}$. The spreadsheet shows calculations for various materials including Inside Surface, Lightweight plaster, Aer. Conc. Blocks, Mineral wool, Bricks, and Outside surface. The total thermal resistance (R_{total}) is calculated as the sum of individual resistances (D2:D7), and the U-value is calculated as 1 divided by the total resistance (D8).

	A	B	C	D	E	F	G
	Material/ layer	Thermal conductivity, λ	Thickness, d (m)	Thermal resistance, R (m ² K/ W)	U-value $U = \frac{1}{R_{total}}$ (W/m ² K)		
1							
2	Inside Surface			0.12			
3	Lightweight plaster	0.16	0.012	=C3/B3			
4	Aer. Conc. Blocks	0.11	0.1	=C4/B4			
5	Mineral wool	0.04	0.1	=C5/B5			
6	Bricks	0.84	0.103	=C6/B6			
7	Outside surface			0.06			
8			R _{total}	=SUM(D2:D7)	=1/D8		
9							
10							
11							
12							

Example 9.2

This spreadsheet shows how the formulae are entered to calculate the thermal resistance of plaster, bricks and other materials. The syntax for adding a number of values is also shown.

Appendix 2: Solutions for Example 13.10

Microsoft Excel - Example 13.10

Type a question for help

Reply with Changes... Egd Review...

	A	B	C	D	E	F	G	H	I	J
1	Example 13.10									
2										
3	Surface	Area (m ²)	500 Hz		2000 Hz					
4			Abs. Coeff.	Absorption units	Abs. Coeff.	Absorption units				
5	Walls	618	0.02	12.36	0.04	24.72				
6	Floor	375	0.2	75	0.3	112.5				
7	Ceiling	750	0.05	37.5	0.07	52.5				
8	Windows	30	0.1	3	0.05	1.5				
9	Doors	12	0.08	0.96	0.1	1.2				
10	Audience (No. of people)	500	0.46	230	0.51	255				
11	Air (Volume in m ³)	4500			0.007	31.5				
12										
13	Total 'A'			358.82		478.92				
14										
15										
16										
17										

Sheet1 / Sheet2 / Sheet3

Ready

Start | Welcome to South Bl... | South Birmingham C... | Removable Disk (F:) | Microsoft Excel - ... | 09:58

Microsoft Excel - Example 13.10

Type a question for help

File Edit View Insert Format Tools Data Window Help

Reply with Changes... Egd Review...

F30

	A	B	C	D	E	F	G
1	Example 13.10						
2							
3	Surface	Area (m ²)	500 Hz		2000 Hz		
			Abs. Coeff.	Absorption units	Abs. Coeff.	Absorption units	
4							
5	Walls	618	0.02	=B5*C5	0.04	=B5*E5	
6	Floor	375	0.2	=B6*C6	0.3	=B6*E6	
7	Ceiling	750	0.05	=B7*C7	0.07	=B7*E7	
8	Windows	30	0.1	=B8*C8	0.05	=B8*E8	
9	Doors	12	0.08	=B9*C9	0.1	=B9*E9	
10	Audience (No. of people)	500	0.46	=B10*C10	0.51	=B10*E10	
11	Air (Volume in m ³)	4500			0.007	=B11*E11	
12							
13	Total 'A'			=SUM(D5:D12)		=SUM(F5:F12)	
14							
15							
16							
17							
18							
19							

Sheet1 Sheet2 Sheet3

Ready

Start Welcome to So... South Birmingham... Removable Dis... Microsoft Ex... Document1 - ... 10:01

Appendix 3: Answers to Exercises

Answers to Exercise 1.1

1. 19.43
2. 41.82
3. 8.836
4. 9.229
5. 543.25
6. a) 61.02 b) 22.523 c) 1.447
7. a) 4.5 b) 7 c) 10.802
8. a) 4.813 b) 2818.383
9. a) 474.609 b) 31.25
10. 36.478
11. a) 1.97 b) 1.743
12. a) 57°8'24.43" b) 40°32'8.89" c) 34°36'20.43"
13. a) 0.796 b) 0.739 c) 3.777
14. 1.004

Answers to Exercise 2.1

1. a) 0.075m b) 0.335m c) 780cm d) 1066.8mm
e) 54.864m f) 0.381m g) 7.62m h) 11 feet
2. a) 60g b) 22.5 tonnes c) 26.276oz
3. a) 40.785lbs b) 440.924lbs c) 6.804kg
4. a) 105.8cm² b) 0.695m² c) 3650000mm² d) 92900cm²
5. a) 0.006545m³ b) 12.545cm³ c) 960000mm³
6. a) 14.760 litres b) 1665cl c) 2.35 litres d) 60 litres e) 7.699 gallons

Answers to Exercise 3.1

1. a) 98.1N b) 588.9N
2. 27.6kg

3. Mass = 3024 kg; Weight = 29665.44 N
4. 12 m/s^2
5. 188.89 N
6. a) 2707.56 N b) 40613.4 J
- 7.

Height (m)	$v^2 = 2as + u^2$	Kinetic energy (KE)	Potential energy (PE)	Total energy = PE + KE
9	0	0 J	706320 J	706320 J
6	58.86	235440	470880	706320
3	117.72	470880	235440	706320
0	176.58	706320	0	706320

8. a) 245250 J; b) 20437.5 W

Answers to Exercise 4.1

1. See Section 4.3
2. See Table 4.3
3. i) CaCl_2 ii) CaSO_4 iii) MgCl_2
4. a) and b) See Section 4.5.1
5. a) See Section 4.5.2
 b) NaOH
 c) Chemical reaction between the two occurs which produces hydrogen gas and a salt. The strength and the texture of marble are affected.
 d) Marble + dilute sulphuric acid $\rightarrow$ calcium sulphate + water + carbon dioxide gas
6. i) Sodium + dilute hydrochloric acid $\rightarrow$ sodium chloride + hydrogen gas
 ii) Sodium + dilute sulphuric acid $\rightarrow$ sodium sulphate + hydrogen gas
 iii) Iron + dilute hydrochloric acid $\rightarrow$ ferrous chloride + hydrogen gas
 iv) Iron + dilute sulphuric acid $\rightarrow$ ferrous sulphate + hydrogen gas
 v) Aluminium + hydrochloric acid $\rightarrow$ aluminium chloride + hydrogen gas
 vi) Sulphuric acid + sodium hydroxide $\rightarrow$ sodium sulphate + water

Answers to Exercise 6.1

1. 400 V
2. p.d. across 4Ω resistor = 16 V; p.d. across 8Ω resistor = 32 V
 Supply voltage = 48 V
3. 2Ω
4. a) 3Ω b) 4 A c) Current through 4Ω resistor = 3 A; Current through 12Ω resistor = 1 A
5. a) 6Ω b) Current in 2Ω resistor = 2 A; Current in 4Ω resistor = 1.5 A
 Current in 12Ω resistor = 0.5 A
6. a) 55 b) 4.78 A

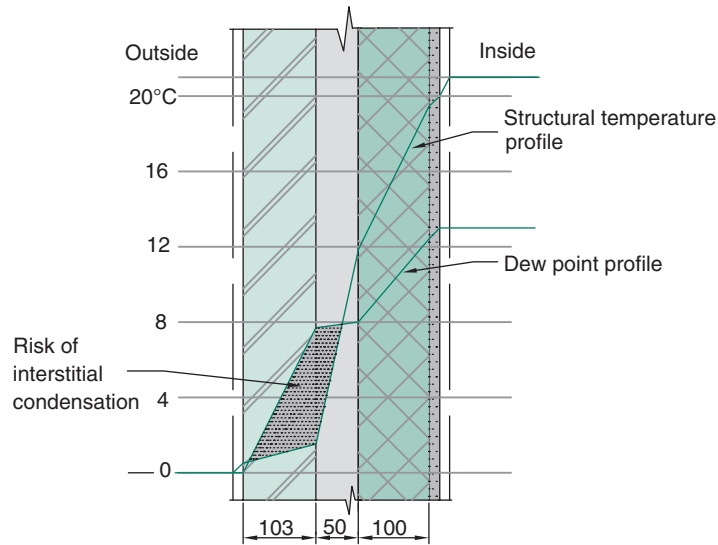


Figure A9.1-1

Answers to Exercise 8.1

1. a) 283 K b) 303 K c) 223 K
2. a) 22 °C b) 42 °C c) 70 °C
3. 22.8×10^{-6} per °C
4. 1.8 mm

Answers to Exercise 9.1

1. $1.81 \text{ W/m}^2\text{K}$
2. a) $2.16 \text{ W/m}^2\text{K}$ b) 78 mm
3. a) $0.68 \text{ W/m}^2\text{K}$ b) $0.39 \text{ W/m}^2\text{K}$
4. 2835.73 W
5. See Figure A9.1-1

Answers to Exercise 10.1

1. 0.04 kN/mm^2
2. 0.00133 or 0.133%
3. 95.49 kN/mm^2
4. See Figure A10.1-1
5. 1.67 mm
6. a) 25.75 mm b) 2.13 mm

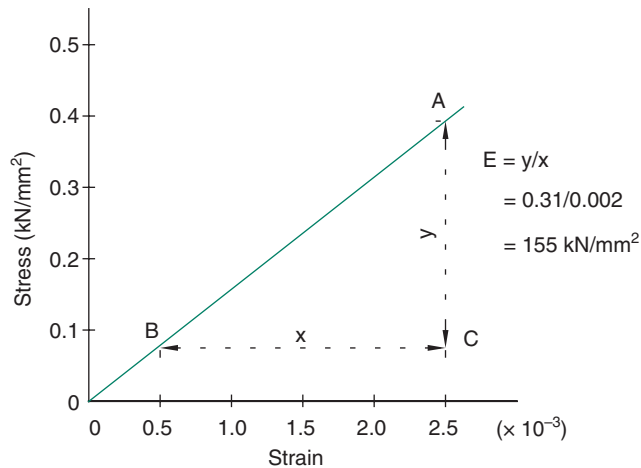


Figure A10.1-1

Answers to Exercise 11.1

1. a) 24.5 kNm b) 11.25 kNm
2. a) About B: CW moment = ACW moment = 19.25 kNm
About A: CW moment = ACW moment = 8.25 kNm
b) About B: CW moment = ACW moment = 21 kNm
About A: CW moment = ACW moment = 28 kNm
3. a) $R_1 = 3.43 \text{ kN}$, $R_2 = 4.57 \text{ kN}$
b) $R_1 = 4.75 \text{ kN}$, $R_2 = 3.25 \text{ kN}$
c) $R_1 = 6.67 \text{ kN}$, $R_2 = 3.33 \text{ kN}$
d) $R_1 = 14.75 \text{ kN}$, $R_2 = 10.25 \text{ kN}$
4. a) See Figure A11.1-1
b) See Figure A11.1-2
c) See Figure A11.1-3
d) See Figure A11.1-4
5. Force in string A = 19.4 N (Tension)
Force in string B = 23.0 N (Tension)
6. a) Force in rod A = 600 N (Tension)
Force in rod B = 412 N (Compression)
b) Force in rod A = 205 N (Tension)
Force in rod B = 300 N (Tension)
c) Force in rod A = 728 N (Tension)
Force in rod B = 460 N (Compression)
7. a) See Figure A11.1-5
b) See Figure A11.1-6

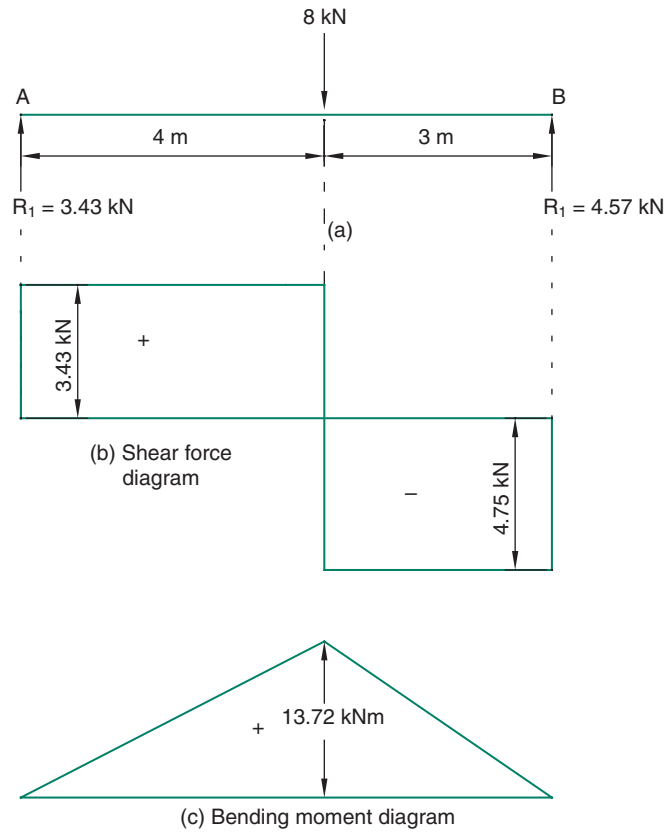


Figure A11.1-1

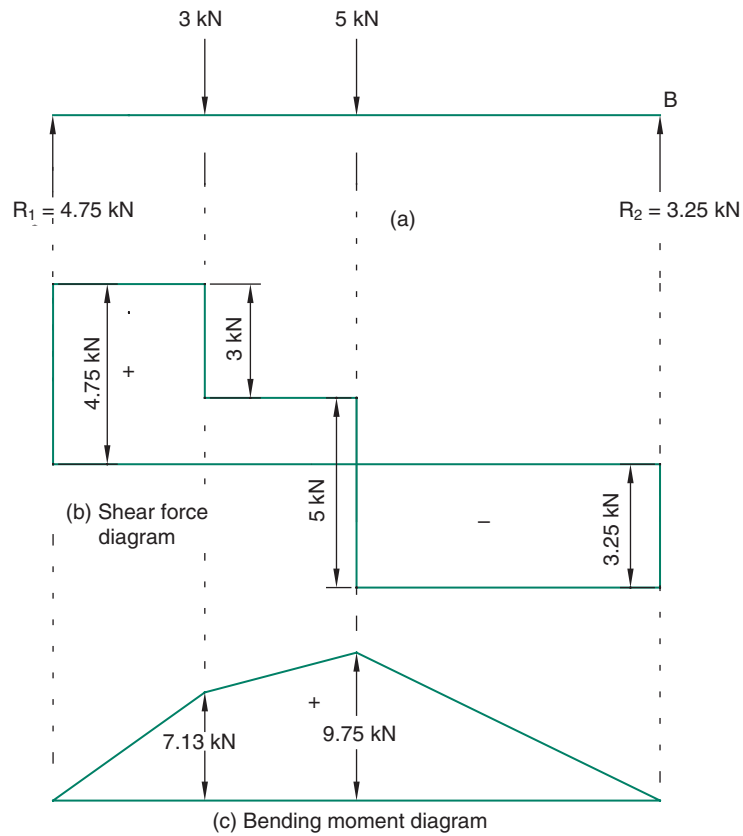


Figure A11.1-2

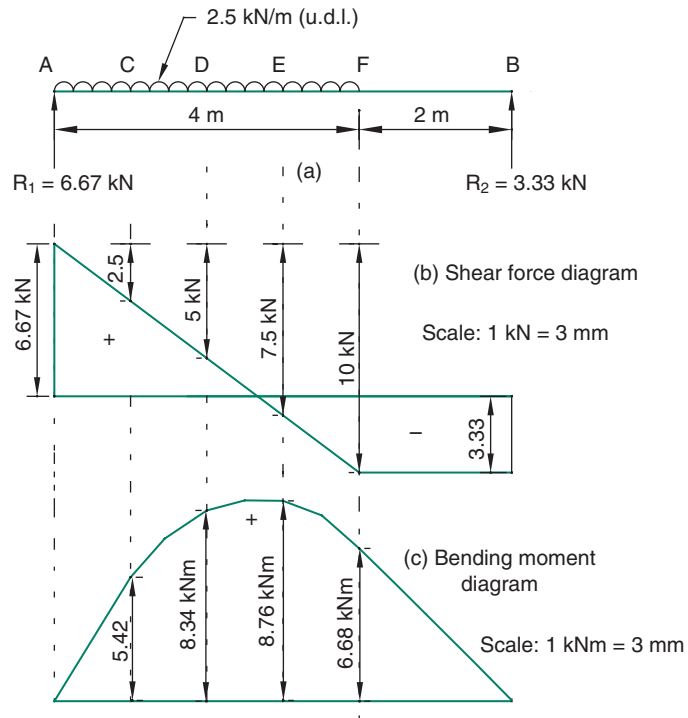


Figure A11.1-3

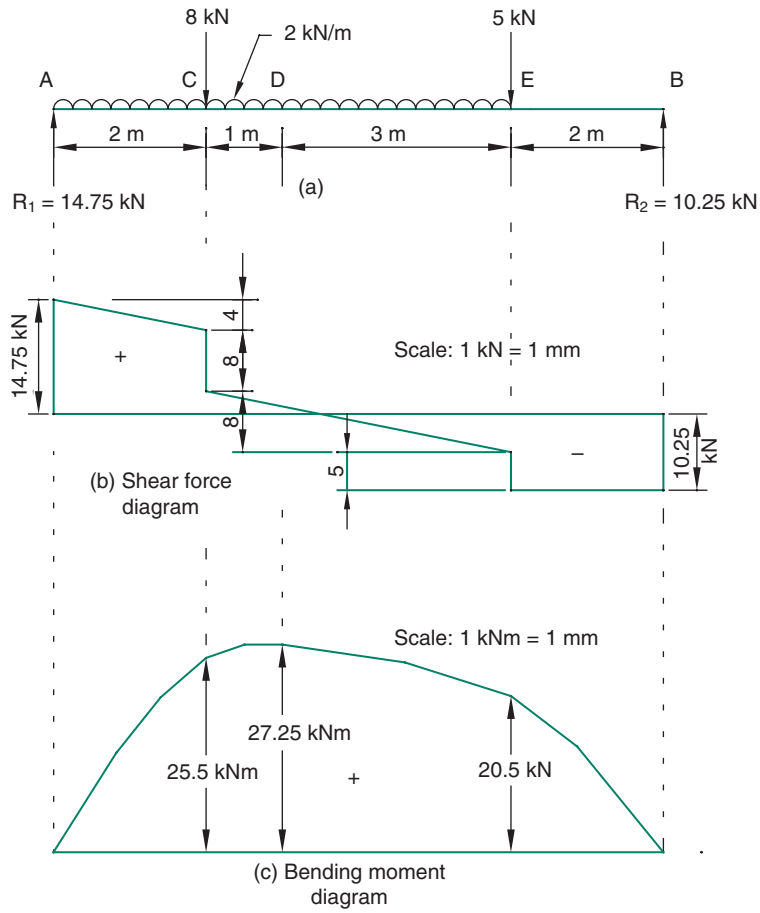
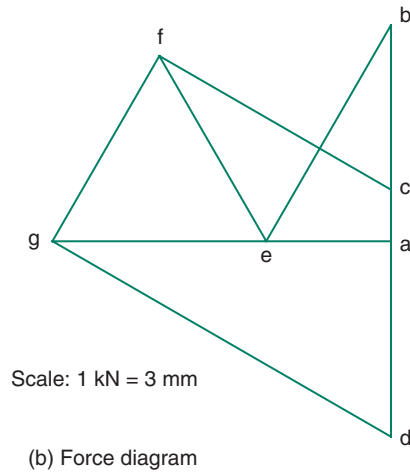
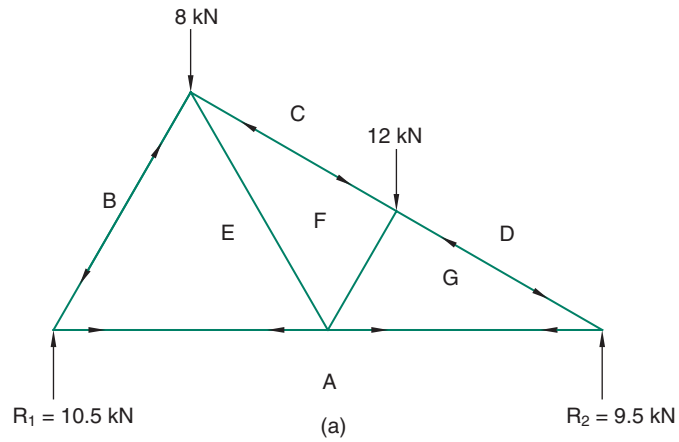


Figure A11.1-4

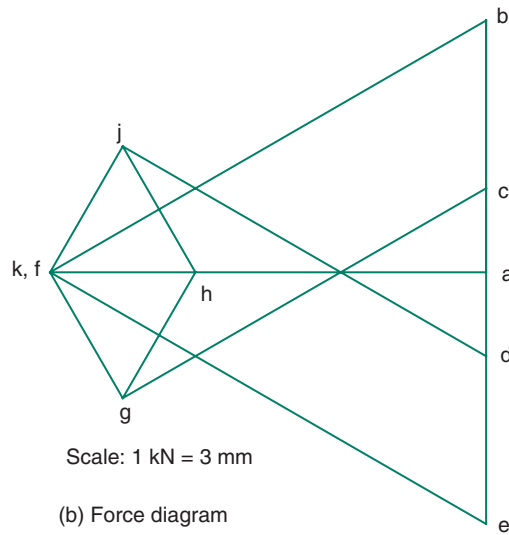
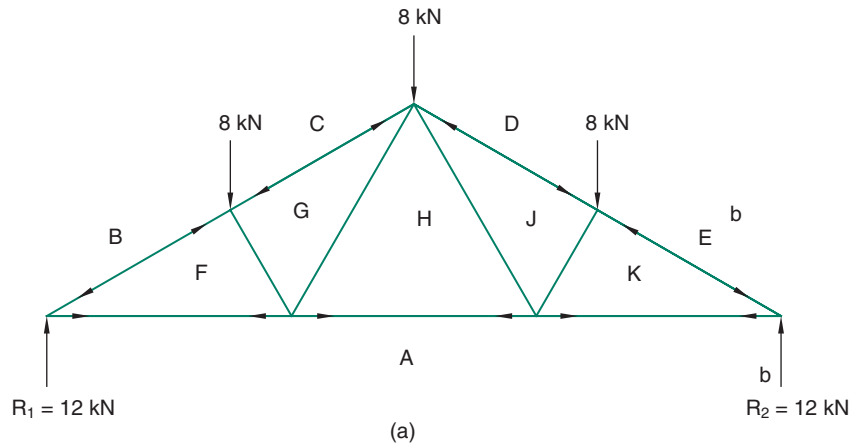


$$R_1 \times 8 = 8 \times 6 + 12 \times 3;$$

$$R_1 = 10.5 \text{ kN}; \quad R_2 = 9.5 \text{ kN}$$

Member	Compression (kN)	Tension (kN)
BE	12.1	
CF	13.0	
FE		10.4
EA		6.1
DG	19.0	
GF	10.4	
GA		16.5

Figure A11.1-5


 $R_1 = 12 \text{ kN};$
 $R_2 = 12 \text{ kN}$

Member	Compression (kN)	Tension (kN)
BF, EK	24.0	
CG, DJ	20.0	
FA, KA		20.8
GF, KJ	6.9	
HG, JH		6.9
HA		13.9

Figure A11.1-6

Answers to Exercise 12.1

1. a) Base: 88.290 kN; 3 m side: 33.109 kN; 2 m side: 22.073 kN
b) 0.5 m
2. a) 847.584 MN b) 8 m
3. a) 3310.875 kN b) 2.1 m
4. 7691.04 N
5. 1.273 m/s and 2.264 m/s
6. 313.67 kN/m²
7. 0.0334 m³/s
8. a) 2.816 m/s b) 4.747 m/s

Answers to Exercise 13.1

1. 345.6 m/s
2. $v = 333.33 \text{ m/s}$; $\lambda = 0.651 \text{ m}$
3. 5073 m/s
4. 56.532 dB
5. 133.06 dB
6. 99.55 dB
7. 105.4 dB (approximate); 105.34 (from analytical method)
8. 27.96 dB
9. a) 3.78 s (at 500 Hz); 2.57 s (at 2000 Hz) b) 1.34 s c) 1.67 s
10. 4.34 s (at 500 Hz); 2.86 s (at 2000 Hz)

Answers to Exercise 14.1

1. 3141.6 lx
2. a) 33.3 lx b) 7.2 lx
3. 14.36 lx
4. 1.58
5. UF = 0.65; MF = 0.65
6. 24 luminaires (610 × 600 mm recessed modular luminaires, Quattro T body - 2 × 34 W TC-L lamps)
7. 24 luminaires
8. 125 lx

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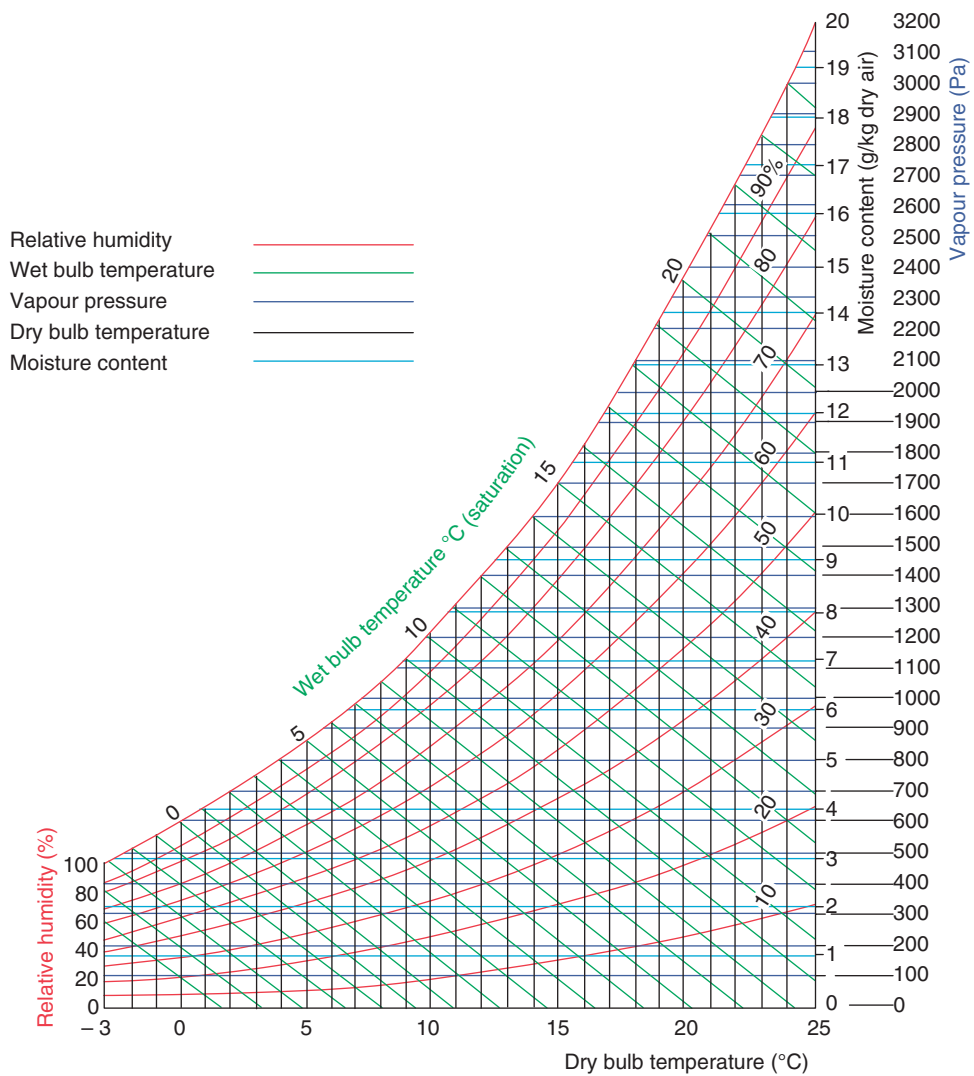


Figure 9.11 The psychrometric chart.

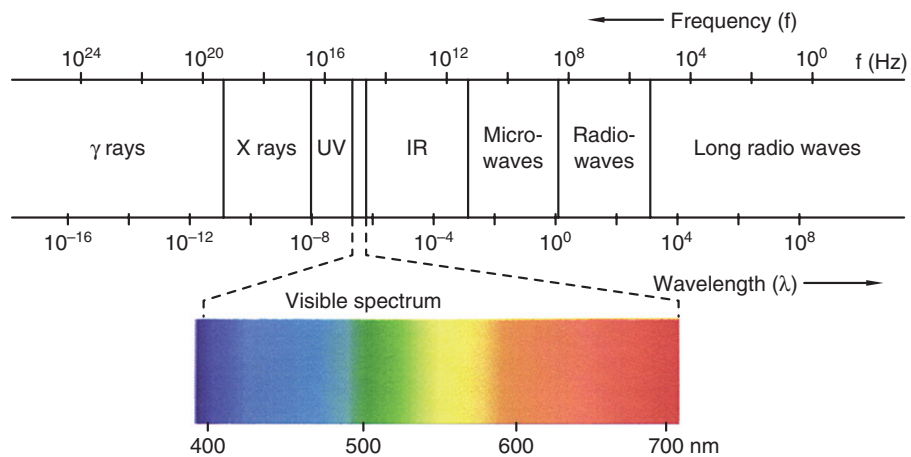


Figure 14.1 Electromagnetic spectrum.

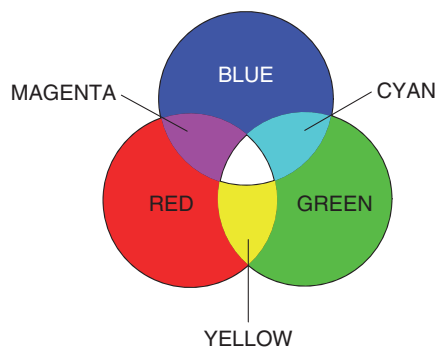


Figure 14.3



Figure 14.12 Lamps and luminaires.

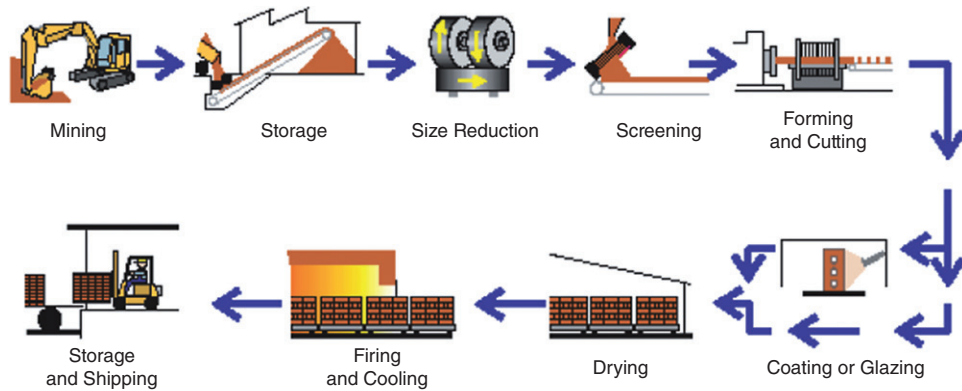


Figure 16.1 Brick manufacturing process. (Reproduced by permission of Brick Industry Association.)



Figure 16.2 Brick spalling.



Figure 16.3 Brick efflorescence.

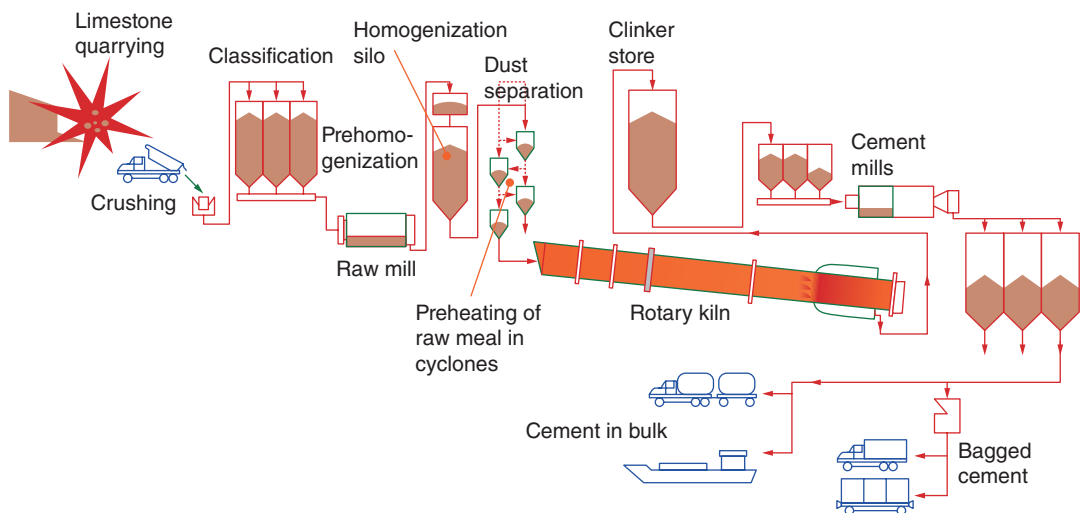


Figure 16.4 Cement manufacturing process.