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PART 1

1 Functions and requirements of industrial and commercial buildings

AIMS
After studying this chapter you should be able to:

- Appreciate the main physical functions of buildings
- Describe the factors that must be considered in creating an acceptable living and working environment
- Discuss links between these factors and the design of modern commercial and industrial high-rise and long-span buildings
- Recognise the sources and nature of loadings applied to building elements and the ways in which they affect those elements
- Appreciate the influence of the choice of materials and the selection of design features on building performance

This chapter contains the following sections:

1.1 Physical and environmental functions of industrial and commercial buildings
1.2 Forces exerted on and by buildings
1.3 Structural behaviour of elements

INFO POINT
- Building Regulations Approved Document A: Structures (2004 including 2010 amendments)
- BS 648: Schedule of weights of building materials (1964 – withdrawn)
- BS 5250: Code of practice for control of condensation in buildings (2011)
- BS EN ISO 7730: Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria (2005)
- BS ISO 6243: Climatic data for building design (1997)
- BRE Digest 426: Response of structures to dynamic loads (2004)
- Durability of materials and structures in building and civil engineering, WHITTLES (2006)
- http://www.natural-building.co.uk/
1.1 Physical and environmental functions of industrial and commercial buildings

Introduction

- After studying this section you should be aware of the nature of buildings as environmental enclosures.
- You should appreciate the nature of the building user’s need to moderate the environment and understand how buildings have evolved to allow this to be achieved.
- You should also have an awareness of the link between environmental needs and the form of the building fabric.
- You should be able to recognise the key features of building form that affect the internal environment.

Overview

The ways in which the internal environments of buildings are controlled have become very sophisticated as the needs of occupiers have evolved. The extent to which the internal environment can be controlled through the building fabric and building services is immense. However, it is easy to overlook the importance of the external fabric with regard to the internal environment. Most buildings are designed to be aesthetically pleasing and many of the details associated with building styles have evolved in order to satisfy functional requirements. As buildings have developed, the role of building services to control heat, light and ventilation has become more significant, and it is easy to forget that these services rely on an appropriate building envelope in order to achieve required levels of performance. The main functions of the building envelope are therefore to protect occupiers from the elements; to provide a suitable enclosure for building services that will enable a suitable internal environment to be provided; and to be aesthetically pleasing.

The building as an environmental envelope

Historically, people have sought to modify and control the environment in which they live. In prehistoric times caves and other naturally occurring forms of shelter were used as primitive dwellings, providing protection from the external environment. As civilisation has developed, so the nature of human shelter has become more refined and complex, developing from caves and natural forms of shelter to simple artificial enclosures, such as those used throughout history by nomadic peoples worldwide. The way in which the structures created by humans have developed has depended upon the nature of the climate in specific locations and the form of building materials available locally.

The ability to transport building materials over relatively large distances is a recent development. In Britain this was limited prior to the Industrial Revolution by the lack of effective transport networks. Hence vernacular architecture has arisen to cope with specific environmental demands, using the materials available locally. Examples of vernacular architecture are found throughout the world. In areas such as the Middle
Eastern desert regions, where diurnal temperatures vary considerably, being very hot during the day and cool at night, buildings of massive construction are common. Such buildings are referred to as ‘thermally heavy’ structures. The intense heat of the day is partly reflected by the use of white surface finishes. That which is not reflected is absorbed by the building fabric, rather than being transmitted into the occupied space. As a result of the slow thermal reaction of the building, this stored heat is released at the times of day when the external temperatures may be very low, acting as a form of storage heater. The effects of direct solar gain are reduced by the use of a limited number of small window openings. Conversely, in areas where the climate is consistently warm and humid, such as the Far East, a very different approach to building design is required. In such situations, rare breezes may be the only cooling medium which can remove the oppressive heat and humidity of the internal environment. Since this cooling and dehumidifying effect takes place over a short period, the building must be able to react quickly to maximise any potential benefit. Hence a thermally light structure is essential to transmit external changes to the interior with minimal delay. The nature of buildings in such areas reflects these requirements, with lightweight building fabric and many large openings to allow cooling breezes to pass through the building. Figure 1.1 illustrates the differing properties of thermally light buildings, with fast response to external changes, and thermally heavy buildings, which insulate the interior from external changes as a result of slow reaction times.

The use of protective structures or enclosures is not the only method utilised in the moderation of the human environment. Since fire was first discovered and used by primitive people to provide light and heat, the use of energy to aid in environmental moderation has been fundamental. Although the use of built enclosures can moderate the internal environment and reduce the effects of extremes in the external climate, the active control and modification of the internal environment requires the input of energy. The use of buildings to house people, equipment and processes of differing types, exerting differing demands in terms of the internal environment, has resulted in the
development of buildings and associated services capable of moderating the internal conditions within desired parameters with great accuracy.

The nature of people’s perception of comfort within buildings has also developed; the simple exclusion of rain and protection from extreme cold or heat are no longer sufficient to meet human needs. The provision of an acceptable internal condition relies on a number of factors, which may be summarised as follows:

- Thermal insulation and temperature control
- Acoustic insulation
- Provision of light (natural or artificial)
- Control of humidity
- Exclusion of contaminants
- Heat gain due to equipment such as photocopiers and computers.

Figure 1.2 illustrates these requirements and the ways in which they are met in modern construction forms.
Performance requirements of the building fabric

The requirement to provide an acceptable internal environment is simply one of the performance requirements of modern buildings. The level of performance of buildings depends upon several factors, and the emphasis which is placed upon these individual performance requirements varies from situation to situation.

However, minimum standards are set out by statutes and guidelines, such as the Building Regulations, which must be achieved in any instance. The increasing role of the building as an asset has also affected the ways in which buildings have been designed to maximise the long-term value and minimise the maintenance costs of the structure and fabric.

The performance requirements of buildings may be summarised as follows.

Structural stability

In order to satisfactorily fulfil the functions required of it a building must be able to withstand the loadings imposed upon it without suffering deformation or collapse. This necessitates the effective resistance of loadings or their transfer through the structure to the ground.

Durability

The long-term performance of the structure and fabric demands that the component parts of the building are able to withstand the vagaries and hostilities of the environment in which they are placed, without deterioration. The ability of the parts of the building to maintain their integrity and functional ability for the required period of time is fundamental to the ability of the building to perform in the long term. This factor is particularly affected by the occurrence of fires in buildings.

Thermal insulation

The need to maintain internal conditions within fixed parameters and to conserve energy dictate that the external fabric of a given building provides an acceptable standard of resistance to the passage of heat. The level of thermal insulation which is desirable in an individual instance is, of course, dependent upon the use of the building, its location and so on.

Exclusion of moisture and protection from weather

The passage of moisture from the exterior, whether in the form of ground water rising through capillary action, precipitation or other possible sources, should be resisted by the building envelope. The ingress of moisture to the building interior can have several undesirable effects, such as the decay of timber elements, deterioration of surface finishes and decorations and risks to health of occupants, in addition to effects upon certain processes carried out in the building. Hence details must be incorporated to resist the passage of moisture, from all undesirable sources, to the interior of the building. The exclusion of wind and water is essential to the satisfactory performance of any building fabric.
Acoustic insulation

The passage of sound from the exterior to the interior, or between interior spaces, should be considered in building construction. The level of sound transmission which is acceptable in a building will vary considerably, depending upon the nature of the use of the building and its position.

Flexibility

In industrial and commercial buildings in particular, the ability of the building to cope with and respond to changing user needs has become very important. Hence the level of required future flexibility must be taken into account in the initial design of the building; this is reflected, for example, in the trend to create buildings with large open spaces, which may be subdivided by the use of partitions that may be readily removed and relocated.

Aesthetics

The issue of building aesthetics is subjective. However, it should be noted that in some situations the importance of the building’s aesthetics is minimal, while in others, of course, it is highly important.

For example, the appearance of a unit on an industrial estate is far less important than that of a city centre municipal building. The extent to which aesthetics are pursued will have an inevitable effect on the cost of the building.

This summary is not a definitive list of the performance requirements of all building components in all situations. However, it is indicative of the factors which affect the design and performance of buildings and their component parts (Figure 1.3).

Sustainability

Since the authors wrote the first and second editions of this book, the concept of what sustainability means in the context of construction work has slowly evolved. The basic principles are the same, but how the industry can achieve these principles has become better understood.

There is a wide acceptance that sustainability integrates, at least, three dimensions:

- Social dimension
- Economic dimension
- Environmental dimension.

In order to address sustainability, all three dimensions need to be considered, and most importantly they need to be considered in a local context.

There are a number of different models that are used to illustrate these three dimensions but the authors believe that the three pillars/triple bottom line approach is the easiest to understand and conceptualise in the context of construction.
Figure 1.4 illustrates the concept of sustainability using the three pillars model. It also shows how this links to the triple bottom line view of sustainability. All three pillars and all three aspects of the triple bottom line need to be addressed if a sustainable development is to be achieved, but for the purpose of this book which is about construction technologies, the one that will be discussed predominantly is the ecological pillar and planet bottom line. Construction work affects the environment from an ecological perspective, i.e. it impacts on the environment.
Impact of construction work and buildings on the environment

Construction work and buildings have a major impact on the environment in terms of land use, natural resource usage, carbon dioxide emissions and energy requirements. For example, buildings in use account for about 50 per cent of total energy used in the UK and the construction of buildings accounts for another 5–10 per cent. Figure 1.5 illustrates this graphically.

Figure 1.5
Percentages of total energy use in the UK.

How is all this energy used? Figure 1.6 illustrates how much energy is used for particular activities in occupied buildings.

The highest percentage by far is the 57 per cent used for heating and consequently this is an area where a great deal of research has been undertaken to try to reduce this value, and a number of new technologies have been developed to address energy efficiency. Although good design of the different elements that make up a building can help to improve this figure significantly, even then there can be problems arising from heat loss through the structure of the building and air leakage from the building. It has been estimated that two-thirds of heat loss from a house built to current Building Regulations will be through the structure and one-third from air leakage. In super-insulated buildings the heat loss through the fabric will be much less but the air leakage loss will be about
the same. Ironically, if heat loss from buildings through the structure and air leakage are improved significantly then a different problem may arise, which is overheating. If this occurs, the inclusion of air conditioning in buildings in the UK will increase which requires energy to run and also produces pollutants that can adversely affect the atmosphere. This is a good example of the conundrum of sustainable buildings – you can do something that will improve a particular aspect, but this may increase the demand for a counter system that could be more damaging environmentally in the long term.

Some 5–10 per cent of the total energy is used in the UK during the construction phase. This is a lot of energy and it surprises many people that such a significant amount of energy is used during this phase. This is because of the embodied energy required to manufacture building components. **The embodied energy of a material is the amount of energy required for its manufacture.** Materials such as steel require a huge amount of energy to manufacture and this energy use has to be calculated into the overall energy requirement of a building during construction and in use. However even this does not tell the whole story. In order to gain a greater understanding of the ‘real energy requirement’ you would need also to calculate the energy required to transport the material to its place of installation, the amount of energy required to install it, perhaps also the energy required for the operatives installing the material or system to travel to the site and even maybe the amount of energy used by those operatives powering the water boiler to make their tea!

The other major impact of construction work on the environment is waste. Reducing waste in construction is the intervention that could have the biggest impact on the reduction of mineral extraction and the overuse of materials. The construction industry generates approximately 70 million tonnes of waste annually. At £15 per tonne for disposal this equates to just over £1 billion annually. To put this into context, a reasonably sized and complex hospital would cost around £100 million to build, so £1 billion would build 10 hospitals. Wembley Stadium cost £798 million to build – with the money spent on disposing waste another Wembley could be built with plenty of money to spare.

Waste is generated in different ways:

- **Design waste:** this occurs when designs change during the construction phase and new materials are required. The original materials if already delivered are then redundant.
- **Process waste:** this occurs when materials are ordered but the standard order size means that there will always be waste. For example, timber is ordered in multiple lengths of 300 mm. Therefore if a 2.5 m piece of timber is required, a standard length of 2.7 m will be ordered and 200 mm will be waste. More of this type of waste is generated in wet trades undertaken on-site such as brickwork and plastering, so using system building techniques more frequently could be a major waste saver.
- **Estimating waste:** this occurs when materials are overordered, delivered to site and not used. This accounts for approximately 20 per cent of all construction waste. It needs to be considered whether this waste can be used on other sites rather than being placed in skips.
- **Damage waste:** this occurs when materials are delivered and not stored properly. The materials become damaged and unusable.

Reducing waste is, consequently, viewed as one of the most important factors that needs to be addressed in making construction work more sustainable. In many areas of the UK there are increasing numbers of facilities to sort waste into different categories and then to sell on for recycling. This is a reflection on what is happening with domestic waste which
many Local Authorities require to be sorted into recyclable and non-recyclable bins. The types of materials that are recyclable are growing. However, this needs to be managed carefully on-site as different skips/bins can easily become contaminated if the wrong materials are placed in them. Demolition industry contractors already have an excellent record for recycling waste (over 90 per cent of demolition ‘waste’ was reused or recycled in 2005–06 – NFDC figures). However, to date, the construction industry as a whole has paid less attention to the possibilities of recycling, reuse and reclaiming of materials, but this has to change.

In this third edition of Construction Technology 2, technologies that have been developed to reduce mineral extraction, increase energy and reduce waste are introduced in the relevant chapters. Some of the technologies, such as timber framing for multi-storey buildings to reduce the need for steel and concrete and the use of MMC techniques to reduce waste, were included in the previous editions, but the growing acceptance of these techniques as more ‘sustainable’ practices is emphasised further. In addition, construction technologies that could be badged as ‘green’ are integrated into chapters. The authors believe that by integrating these green technologies as opposed to having a ‘green technologies’ chapter, their choice as potentially realistic solutions will be better evidenced. If these technologies are dealt with separately then potentially they will only be used when a building is required to be show-cased as being green. This approach leads to tokenism rather than a holistic view of the building from a sustainable perspective.

**REFLECTIVE SUMMARY**

With reference to the building as an environmental shelter, remember:

- Heat needs to be preserved, while allowing light into a building.
- Thermally heavy structures tend to be heavy and intercept heat by absorption.
- Aesthetics of buildings are very subjective and will depend very much on the nature and location of a building.
- A large amount of heat is generated by equipment in industrial and commercial buildings, and this needs to be seriously considered in the design of these types of building.
- The increasing recognition of the impact of construction on the environment has led to a recognition of sustainability as a core function of building.

**REVIEW TASK**

- What are the advantages of thermally light buildings and thermally heavy buildings with regard to the performance requirements of multi-storey buildings?
- Visit the companion website at www.palgrave.com/engineering/riley2 to view sample outline answers to the review task.

## 1.2 Forces exerted on and by buildings

### Introduction

- After studying this section you should be aware of the forces that act upon the structure of a building.
You should have developed a knowledge of the origins of these forces and the ways in which they act upon the structural elements of a building.

You should also have an intuitive knowledge of the magnitude of the different forces and be able to distinguish between the forces acting on a building and the forces exerted by it.

**Overview**

The forces applied to buildings derive from a variety of sources and act in many different ways. However, a number of basic principles of structural behaviour can be considered to encompass all of these applications and effects. The ways in which the structure and fabric of a building behave will depend upon their ability to cope with the inherent and applied loadings. If the building is able to withstand the loadings imposed upon it, it will remain static – in such a state it is considered to be stable. Any force acting upon a building must be considered as a loading, whether it be from the actions of wind on the building, the positioning of furniture, equipment or people, or simply the effect of the self-weight of the structure.

In order to withstand such forces two basic structural properties must be provided by the building:

- The component parts of the building must possess adequate strength to carry applied loads.
- Applied forces must be balanced, to resist the tendency for the building to move. That is, the structure must be in equilibrium.

The forces, or loadings, applied to buildings can be considered under two generic classifications, *dead loads* and *live loads*. Dead loads would normally include the self-weight of the structure, including floors, walls, roofs, finishes, services and so on. Live loads would include loadings applied to the building in use, such as the weight of people, furniture, machinery and wind loadings. Such loadings are normally considered as acting positively on the building; however, in the case of wind loadings, suction zones may be created, i.e. negative loadings; this effect is often illustrated by the action of roofs being lifted from buildings in high wind conditions. Hence buildings must be designed to cope with forces acting in a variety of ways.

The ability of the materials used in the construction of buildings to withstand these loadings is termed *strength*. In considering whether a building has sufficient strength, the nature of loadings must be considered.

**Stress**

When subjected to forces, all structural elements tend to deform, and this deformation is resisted by stresses, or internal forces within the element. If these stresses do not exceed the level which can be satisfactorily withstood by the material then the building will remain structurally sound.
Types of stress

The formula used to calculate stress is \( W/A \), where \( W = \) load and \( A = \) cross-sectional area, and stress is measured in N/mm\(^2\) or kN/m\(^2\).

Compressive stress

Compressive stress (Figure 1.7) is the internal force set up within a structural element when an external applied force produces a tendency for the member to be compressed. An element is said to be in compression. Some materials, such as concrete, are very good at resisting compressive stress, whereas others, such as steel, are not so good. The amount of stress in a structural member will increase if the load is increased due to an increase in dead loading caused by the weight of the structural elements.

![Figure 1.7 Compressive stress.](image)

Tensile stress

Tensile stress (Figure 1.8) is the internal force induced within an element which resists an external loading that produces a tendency to stretch the component. When such a force is applied the member is said to be in tension.

Steel is very good at withstanding tensile stress, whereas concrete is not. As different materials are better at withstanding the different stresses, the use of two materials to
produce structural elements is common. Reinforced concrete beams (Figure 1.9) are an example of this.

The top of the beam is in compression, so the fibres are being crushed together; the bottom of the beam is in tension, and the fibres are being pulled apart. The cross-section of the beam shows that steel has been placed at the bottom to withstand the tension, whilst the top half of the beam is concrete to withstand the compression. This makes for a very economical beam section, taking advantage of the properties of both materials.

**Shear stress**
Shear stress (Figure 1.10) is the internal force created within a structural element which resists the tendency, induced by an externally applied loading, for one part of the element to slide past another.

**Torsional stress**
Torsional stress (Figure 1.11) is the internal force created within a structural element that resists an externally applied loading which would cause the element to twist.

**Strain**
The effect of a tensile or compressive stress on an element is to induce an increase or decrease in the length of the element. The magnitude of such a change in length depends
upon the length of the unit, the loading applied and the stiffness of the material. The relationship between this change in length and the original length of the component gives a measure of strain ($e$):

$$e = \frac{\delta l}{L}$$

where $\delta l$ = change in length and $L$ = original length.

Strain has no unit.

This effect is also evident in materials subject to shear stress, although the deformation induced in such cases tends to distort the element into a parallelogram shape.

The relationship between stress and strain (subject to loading limits) is directly proportional and is a measure of the material's stiffness. The ratio of stress to strain is known as the Young's modulus of elasticity.

**Moments**

The application of a force can in certain instances induce a tendency for the element to rotate. The term given to such a tendency is moment (Figure 1.12). The magnitude of such a moment depends on the extent of the force applied and the perpendicular distance between the point of rotation and the point at which the loading is applied. As a result

$$LM = IR$$
of the effects of leverage, relatively small loadings applied at considerable distances from
the point of action can induce rotational forces. Moments upon structures must be in
equilibrium in order for the structure to remain stable, i.e. clockwise moments (+) must
be equalled by anticlockwise moments (−). The magnitude of a moment is the product
of the force applied and the distance from the point of action at which it is applied (the
lever arm) and is expressed in newton millimetres.

It is necessary to calculate the maximum bending moment that will be created in a
structural element by the predicted loadings in order for the element and its supports
to be designed.

REFLECTIVE SUMMARY

- Loads derive from a variety of sources including:
  - Dead and live loads
  - Horizontal, vertical and oblique directions
  - Point loads, axial loads and uniformly distributed loads.
- There is a relationship between loads, area and pressure.
- Possible stresses induced in structural elements are: compressive, tensile, torsional
  and shear.
- Some materials withstand the different stresses induced better than others.
- Concrete is very good at withstanding compressive stress, whereas steel is very
good at withstanding tensile stress.

REVIEW TASKS

- Identify the differences between compressive, tensile, torsional and shear stresses.
- Attempt to identify where these stresses may occur in a typical framed building.
- Visit the companion website at www.palgrave.com/engineering/riley2 to view
  sample outline answers to the review tasks.

1.3 Structural behaviour of elements

Introduction

- After studying this section you should be aware of the implications of loads applied
to structural building elements.
- You should understand the terminology associated with the structural behaviour of
buildings and the elements within them.
- In addition you should appreciate the implications of the structural performance upon
the selection of materials.

Included in this section are:

- The nature of forces acting on buildings
- The nature of building components
Overview

The effects of the types of loadings or forces exerted on a building depend on the way in which those forces are applied. Maintaining the integrity and structural stability of a building relies on its ability to withstand inherent and applied loadings without suffering movement or deformation, although it is possible to allow for a limited amount of movement or deformation within the building design, as is common in mining areas, for example. Resistance to movement and deformation results from effective initial design of the structure as a unit and the ability of materials used for individual components to perform adequately.

Limited movement, of certain types, is inevitable in all structures and must be accommodated to prevent the occurrence of serious structural defects. The effects of thermal and moisture-induced changes in building materials can be substantial, producing cyclical variations in the size of components. This dictates the inclusion of specific movement accommodation details, particularly when dealing with elements of great size, such as solid floors of large area. Additionally, the period shortly following the erection of a building often results in the minor consolidation of the ground upon which it is located; this will generally be very minor in nature however. These forms of movement and deformation are acceptable but other forms must be avoided, their nature and extent depending upon the nature and direction of the applied forces. Three main categories of applied forces combine to give rise to all types of building movement.

The nature of forces acting on buildings

Vertical forces

Vertically applied forces, such as the dead loading of the building structure and some live loadings, act to give rise to a tendency for the structure to move in a downward direction, i.e. to sink into the ground. The extent of any such movement depends upon the ability of the building to spread the building loads over a sufficient area to ensure stability on ground of a given loadbearing capacity. The loadbearing capacities of different soil types vary considerably, and the function of foundations to buildings is to ensure that the bearing capacity of the ground is not exceeded by the loading of the structure. In most instances the bearing capacity of the ground, normally expressed in kN/m², is very much less than the pressures likely to be exerted by the building structure if placed directly onto the ground. The pressure is reduced by utilising foundations to increase the interface area between the building and the ground (foundation design), thus reducing the pressure applied to the ground (Figure 1.13).

The need to withstand such vertical loadings is not exclusive to the lower elements of the building structure, although such loadings are greater in magnitude at the lower sections due to the effects of accumulated loadings from the structure. All structural components must be of sufficient size and strength to carry loadings imposed upon them without failure or deformation. Columns and walls, often carrying the loads of floors, roofs and so on from above, must resist the tendency to buckle or to be crushed by the forces exerted (Figure 1.14). The way in which columns and walls perform under the effects of vertical loadings depends on the slenderness ratio of the component. In simple terms, long, slender units will tend to buckle easily, whilst short, broad units will
resist such tendencies. In long, thin components the risk of buckling can be greatly reduced by incorporating bracing to prevent sideways movement; this is termed lateral restraint.

If overloaded significantly, even short, broad sections may be subject to failure; in such instances the mode of failure tends to be crushing of the unit, although this is comparatively rare.

Horizontal components, such as floors and beams, must also be capable of performing effectively while withstanding vertically applied loadings (Figure 1.15). This is ensured by the use of materials of sufficient strength, designed in an appropriate manner, with sufficient support to maintain stability. Heavy loadings on such components may give rise to deflection resulting from the establishment of moments, or in extreme cases puncturing of the component resulting from excessive shear at a specific point. When subjected to deflection, beam and floor sections are forced into compression at the upper regions and tension at the lower regions. This may limit the design feasibility of some materials, such as concrete, which performs well in compression but not in tension. Hence the use of composite units is common, such as concrete reinforced in the tension zones with steel.

Vertical forces applied to buildings may also be in an upward direction. These must be resisted, usually by making the best use of the mass of the building. Upward loadings may be generated from the ground, as in zones of shrinkable clay or soils that are prone to expansion due to frost, for example. The upward force exerted by the ground in such cases is termed heave.
Horizontal forces

Horizontal forces acting on buildings derive from many sources and it is difficult to generalise about their origins and effects. Typically, however, such loadings may be exerted by sub-soil pressure, as in the case of basement walls, or by wind or physical loading on the building. The effects of such forces are normally manifested in one of two ways:

- Overturning, or rotation of the building or its components
- Horizontal movement, or sliding of the structure.

These forms of movement are highly undesirable and must be avoided by careful building design. The nature of the foundations and the level of lateral restraint or
buttressing incorporated into the building design are fundamental to the prevention of such modes of failure. Additionally, particularly in framed structures, the use of bracing to prevent progressive deformation or collapse is essential (Figure 1.16); this could be described as resistance of the ‘domino effect’.

**Oblique forces**

In some areas of building structures the application of forces at an inclination is common (Figure 1.17). This is generally the case where pitched roofs are supported on walls. The effects of such forces produce a combination of vertically and horizontally applied load-
ings at the point of support. These effects are resisted by the incorporation of buttressing and/or lateral restraint details. The horizontal effects of these loadings are sometimes ignored, with disastrous effects.

The nature of building components

The most common materials used for the construction of the supporting structure for multi-storey or large-span industrial and commercial buildings are:

- Reinforced concrete
- Structural steel
- Timber (this is a relatively recent development).

The properties of each of these systems, with regard to withstanding tensile and compressive stresses, have been discussed previously and can be summarised as follows:

- Structural steel as a material is excellent at withstanding tensile stresses, but may need to be overdesigned to withstand compressive stresses.
- Timber is an excellent material at withstanding tensile and compressive stresses but, because it is a natural material and defects can be 'hidden' within a section, the section sizes used may need to be increased.
Reinforced concrete combines the compressive strength of concrete and the tensile strength of steel to allow for efficient and cost-effective frame design.

Although reinforced concrete is very efficient, the section sizes required can be very large, especially for massive structures. There are methods, however, that allow for smaller section sizes whilst retaining strength. These are known as pre-tensioning and post-tensioning of concrete.

The development of the use of this type of concrete started in the 1940s because of the shortage of steel that occurred during redevelopment after the Second World War. Using these methods, one tonne of prestressing can result in a structural element taking up to 15 times the load that one tonne of structural steel can take.

**Principles**

Stressed concrete can be defined as compressed concrete. A compressive stress is put into a concrete member before it is incorporated into a building structure and positioned where tensile stresses will develop under loading conditions. The compressive stresses, introduced into areas where tensile stresses usually develop under load, will resist these tensile stresses – for example at the bottom of a beam section, as has been discussed previously. The concrete will then behave as if it had a high tensile strength of its own. The most commonly used method for the pre-compression of concrete is through the use of tensioned steel tendons, incorporated permanently into a member. The tendons are usually in the form of high-strength wires or bars, used singly or made into cables known as tendons. The two basic methods used are pre-tensioning and post-tensioning.
Pre-tensioning

In pre-tensioning (Figure 1.18), the steel tendons are tensioned usually through a ‘pulling’ mechanism and the concrete placed in formwork around them. When the concrete has reached sufficient compressive strength, the steel is released. The force of the release is then transferred to the concrete. Pre-tensioning is usually carried out off-site in factory conditions. The formwork is manufactured to the correct size, and the tendons are positioned and then threaded through stop ends and anchor plates before being fixed to a jack. The correct amount of stress is then induced, the tendons anchored off and the jack released. The concrete is then poured. The bond between the concrete and the steel is vitally important and the steel must be kept perfectly clean to ensure the quality of this bond. When the concrete has cured, any temporary supports are removed and replaced with jacks that are slowly released. As the tensioned steel tries to return to
its original shape the bond between the concrete and steel will resist this and the concrete is placed in compression.

**Post-tensioning**

In post-tensioning (Figure 1.19), the concrete is cast into the formwork and allowed to harden before the stress is applied. The steel tendons are positioned in the correct position in the formwork, in a sheath to prevent the concrete and steel from bonding. The concrete is then placed and allowed to cure. The tendons are then tensioned by anchoring one end of the tendon and jacking against the face of the fixed steel at the other end, or alternatively by jacking or pulling the steel from both ends. When the desired load has been reached the tendon can be anchored off and the jacks released. When all the tendons have been stressed the ducts are filled with a cement grout under

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**Figure 1.19**
Post-tensioning of concrete beams.
pressure. This grout prevents steel corrosion and creates a bond between the concrete and the tendon.

The curved profile of the steel permits the effective distribution of prestress within the member at positions in the member where the greatest tensile stresses are expected. Post-tensioning may be used in factory production both on- and off-site, but there are quality assurance issues relating to the production of post-stressed concrete on-site. Figure 1.20 shows reinforcing tendons in place in a concreted slab awaiting stretching.

In Figure 1.21 the tendons have been tensioned and the concrete made good. Propping is required until the concrete is fully cured.

As can be seen, the process of post-tensioning is undertaken on-site. As with all on-site activity, ensuring quality of processes is of paramount importance.

From a sustainability point of view, pre- or post-tensioning of concrete can be deemed to be positive actions. Tensioning the steel effectively means it is stronger and therefore less of it is needed to create a structural element that will carry the same loads. Therefore the amounts of new materials that are needed are also less. Also, if pre-tensioning techniques are used, they are done under factory conditions. This inevitably leads not only to higher quality but also to reduced waste.

**REFLECTIVE SUMMARY**

When considering the structural behaviour of building elements, remember:

- The direction of the applied loading is important in dictating the effect upon the building element.
- Failure of building elements can occur in a variety of ways such as:
  - buckling of slender columns
  - bending of beams and slabs
  - shear at support points
  - crushing of localised areas.
- Individual structural elements can act together to create a stronger form.
Some deflection of elements is essential and acceptable, but if an element is allowed to reach its elastic limit due to overloading, the structural element may fail. Prestressing of concrete can increase its strength by up to a factor of fifteen.

**REVIEW TASKS**

- Briefly explain how vertical, horizontal and oblique forces evolve, and how the effects of these forces can be minimised in industrial and commercial building forms.
- Explain the principles of pre- and post-tensioning of concrete, and the advantages of these techniques.
- Visit the companion website at www.palgrave.com/engineering/riley2 to view sample outline answers to the review tasks.
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