CHAPTER 1

Introduction

In the past it was common practice to teach structural analysis and stress analysis, or theory of structures and strength of materials as they were frequently known, as two separate subjects where, generally, structural analysis was concerned with the calculation of internal force systems and stress analysis involved the determination of the corresponding internal stresses and associated strains. Inevitably a degree of overlap occurred. For example, the calculation of shear force and bending moment distributions in beams would be presented in both structural and stress analysis courses, as would the determination of displacements. In fact, a knowledge of methods of determining displacements is essential in the analysis of some statically indeterminate structures. It seems logical, therefore, to unify the two subjects so that the 'story' can be told progressively with one topic following naturally on from another.

In this chapter we shall look at the function of a structure and then the different kinds of loads the structures carry. We shall examine some structural systems and ways in which they are supported. We shall also discuss the difference between statically determinate and indeterminate structures and the role of analysis in the design process. Finally, we shall look at ways in which structures and loads can be idealized to make structures easier to analyse.

1.1 Function of a structure

The basic function of any structure is to carry loads and transmit forces. These arise in a variety of ways and depend, generally, upon the purpose for which the structure has been built. For example, in a steel-framed multistorey building the steel frame supports the roof and floors, the external walls or cladding and also resists the action of wind loads. In turn, the external walls provide protection for the interior of the building and transmit wind loads through the floor slabs to the frame while the roof carries snow and wind loads which are also transmitted to the frame. In addition, the floor slabs carry people, furniture, floor coverings, etc. All these loads are transmitted by the steel frame to the foundations of the building on which the structure rests and which form a structural system in their own right.

Other structures carry other types of load. A bridge structure supports a deck which allows the passage of pedestrians and vehicles, dams hold back large volumes of water, retaining walls prevent the slippage of embankments and offshore structures carry drilling rigs, accommodation for their crews, helicopter pads and resist the action of the sea and the elements. Harbour docks and jetties carry cranes for unloading cargo and must resist the impact of docking ships. Petroleum and gas storage tanks must be able to resist internal pressure and, at the same time, possess the strength and stability to carry wind and snow loads. Television transmitting masts are usually extremely tall and placed in elevated positions where wind and snow loads are the major factors. Other structures, such as ships, aircraft, space vehicles, cars, etc. carry equally complex loading systems but fall outside the realm of structural engineering. However, no matter how simple or

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how complex a structure may be or whether the structure is intended to carry loads or merely act as a protective covering, there will be one load which it will always carry, its own weight.

1.2 Loads

Generally, loads on civil engineering structures fall into two categories. *Dead loads* are loads that act on a structure all the time and include its self-weight, fixtures, such as service ducts and light fittings, suspended ceilings, cladding and floor finishes, etc. Interestingly, machinery and computing equipment are assumed to be movable even though they may be fixed into position. *Live* or *imposed loads* are movable or actually moving loads; these include vehicles crossing a bridge, snow, people, temporary partitions and so on. *Wind loads* are live loads but their effects are considered separately because they are affected by the location, size and shape of a structure. Soil or hydrostatic pressure and dynamic effects produced, for example, by vibrating machinery, wind gusts, wave action or even earthquake action in some parts of the world, are the other types of load.

In most cases Codes of Practice specify values of the above loads which must be used in design. These values, however, are usually multiplied by a *factor of safety* to allow for uncertainties; generally the factors of safety used for live loads tend to be greater than those applied to dead loads because live loads are more difficult to determine accurately.

1.3 Structural systems

The decision as to which type of structural system to use rests with the structural designer whose choice will depend on the purpose for which the structure is required, the materials to be used and any aesthetic considerations that may apply. It is possible that more than one structural system will satisfy the requirements of the problem; the designer must then rely on experience and skill to choose the best solution. On the other hand there may be scope for a new and novel structure which provides savings in cost and improvements in appearance.

Beams

Structural systems are made up of a number of structural elements although it is possible for an element of one structure to be a complete structure in its own right. For example, a simple *beam* may be used to carry a footpath over a stream (Fig. 1.1) or form part of a multistorey frame (Fig. 1.2). Beams are one of the

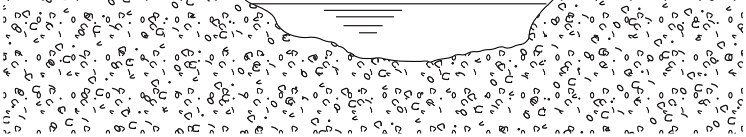


FIGURE 1.1

Beam as a simple bridge.

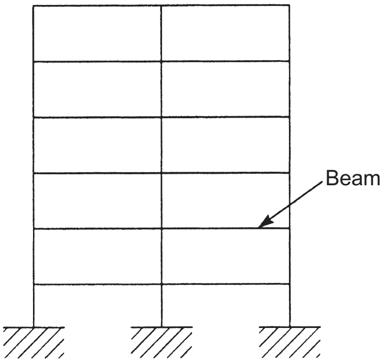


FIGURE 1.2

Beam as a structural element.

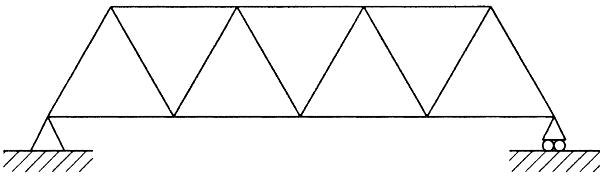


FIGURE 1.3

Warren truss.

commonest structural elements and carry loads by developing shear forces and bending moments along their length as we shall see in Chapter 3.

Trusses

As spans increase the use of beams to support bridge decks becomes uneconomical. For moderately large spans *trusses* are sometimes used. These are arrangements of straight members connected at their ends. They carry loads by developing axial forces in their members but this is only exactly true if the ends of the members are pinned together, the members form a triangulated system and loads are applied only at the joints (see Section 4.2). Their depth, for the same span and load, will be greater than that of a beam but, because of their skeletal construction, a truss will be lighter. The Warren truss shown in Fig. 1.3 is a two-dimensional *plane truss* and is typical of those used to support bridge decks; other forms are shown in Fig. 4.1.

Trusses are not restricted to two-dimensional systems. Three-dimensional trusses, or *space trusses*, are found where the use of a plane truss would be impracticable. Examples are the bridge deck support system in the Forth Road Bridge and the entrance pyramid of the Louvre in Paris.

Moment frames

Moment frames differ from trusses in that they derive their stability from their joints which are rigid, not pinned. Also their members can carry loads applied along their length which means that internal member forces will generally consist of shear forces and bending moments (see Chapter 3) as well as axial loads although these, in some circumstances, may be negligibly small.

Figure 1.2 shows an example of a two-bay, multistorey moment frame where the horizontal members are beams and the vertical members are called *columns*. Figures 1.4(a) and (b) show examples of *Portal* frames which are used in single storey industrial construction where large, unobstructed working areas are required; for extremely large areas several Portal frames of the type shown in Fig. 1.4(b) are combined to form a multibay system as shown in Fig. 1.5.

Moment frames are comparatively easy to erect since their construction usually involves the connection of steel beams and columns by bolting or welding; for example, the Empire State Building in New York was completed in 18 months.

Arches

The use of trusses to support bridge decks becomes impracticable for longer than moderate spans. In this situation arches are often used. Figure 1.6(a) shows an arch in which the bridge deck is carried by columns supported, in turn, by the arch. Alternatively the bridge deck may be suspended from the arch by hangers, as

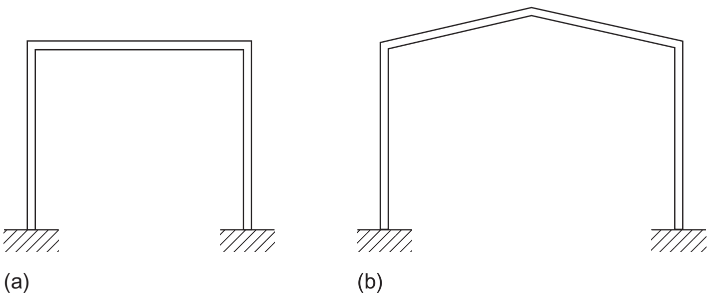


FIGURE 1.4

Portal frames.

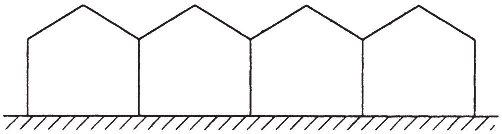


FIGURE 1.5

Multibay single storey building.

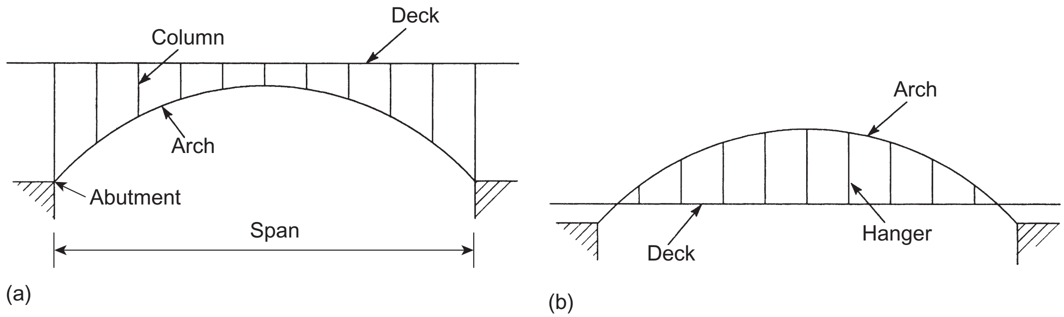


FIGURE 1.6

Arches as bridge deck supports.

shown in Fig. 1.6(b). Arches carry most of their loads by developing compressive stresses within the arch itself and therefore in the past were frequently constructed using materials of high compressive strength and low tensile strength such as masonry. In addition to bridges, arches are used to support roofs. They may be constructed in a variety of geometries; they may be semicircular, parabolic or even linear where the members comprising the arch are straight. The vertical loads on an arch would cause the ends of the arch to *spread*, in other words the arch would flatten, if it were not for the abutments which support its ends in both horizontal and vertical directions. We shall see in Chapter 6 that the effect of this horizontal support is to reduce the bending moment in the arch so that for the same loading and span the cross section of the arch would be much smaller than that of a horizontal beam.

Cables

For exceptionally long-span bridges, and sometimes for short spans, cables are used to support the bridge deck. Generally, the cables pass over saddles on the tops of towers and are fixed at each end within the ground by massive anchor blocks. The cables carry hangers from which the bridge deck is suspended; a typical arrangement is shown in Fig. 1.7.

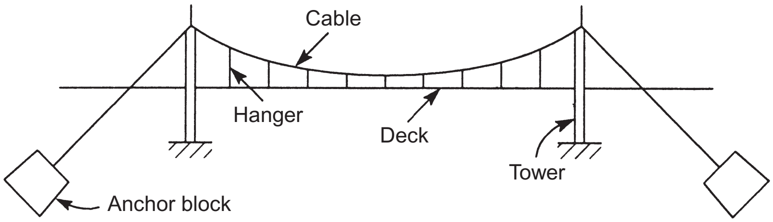


FIGURE 1.7

Suspension bridge.

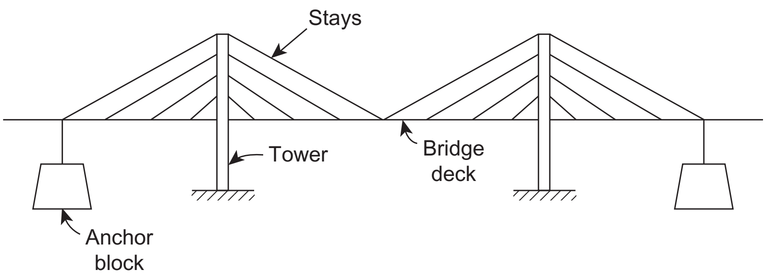


FIGURE 1.8

Cable-stayed bridge.

A weakness of suspension bridges is that, unless carefully designed, the deck is very flexible and can suffer large twisting displacements. A well-known example of this was the Tacoma Narrows suspension bridge in the US in which twisting oscillations were triggered by a wind speed of only 19 m/s. The oscillations increased in amplitude until the bridge collapsed approximately 1 h after the oscillations had begun. To counteract this tendency bridge decks are stiffened. For example, the Forth Road Bridge has its deck stiffened by a space truss while the later Severn Bridge uses an aerodynamic, torsionally stiff, tubular cross-section bridge deck.

An alternative method of supporting a bridge deck of moderate span is the cable-stayed system shown in Fig. 1.8. *Cable-stayed bridges* were developed in Germany after World War II when materials were in short supply and a large number of highway bridges, destroyed by military action, had to be rebuilt. The tension in the stays is maintained by attaching the outer ones to anchor blocks embedded in the ground. The stays can be a single system from towers positioned along the centre of the bridge deck or a double system where the cables are supported by twin sets of towers on both sides of the bridge deck.

Gravity structures

Some structures rely on their weight to resist externally applied loads. Examples of these are dams and retaining walls as shown in Fig. 1.9. A dam resists the horizontal pressure from the water in the reservoir while the retaining wall resists the pressure from soil and possibly rubble. Tall chimneys also come into this category and must be designed to resist wind loads.

Generally, these structures are constructed from concrete or brickwork, which are weak in tension so that at any point the compressive force due to the weight of material above the point must be greater than the tension from the applied loads. We shall consider the design of dams and retaining walls in Chapter 9.

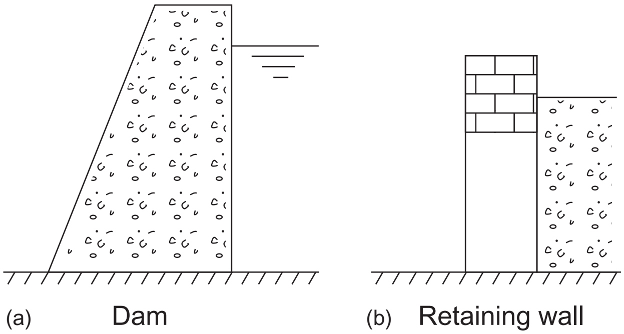


FIGURE 1.9

Gravity Structures.

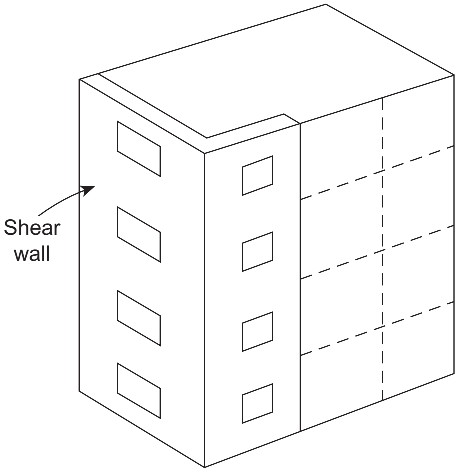


FIGURE 1.10

Shear wall construction.

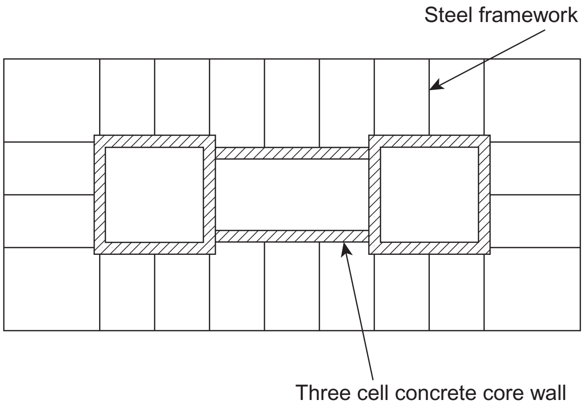


FIGURE 1.11

Sectional plan of core wall and steel structure.

Shear and core walls

Sometimes, particularly in high rise buildings, *shear* or *core walls* are used to resist the horizontal loads produced by wind action. A typical arrangement is shown in Fig. 1.10 where the frame is stiffened in a direction parallel to its shortest horizontal dimension by a shear wall which would normally be of reinforced concrete.

Alternatively a lift shaft or service duct is used as the main horizontal load carrying member; this is known as a core wall. An example of core wall construction in a tower block is shown in cross section in Fig. 1.11. The three cell concrete core supports a suspended steel framework and houses a number of ancillary services in the outer cells while the central cell contains stairs, lifts and a central landing or hall. In this particular case the core wall not only resists horizontal wind loads but also vertical loads due to its self-weight and the suspended steel framework.

A shear or core wall may be analysed as a very large, vertical, cantilever beam (see Fig. 1.16). A problem can arise, however, if there are openings in the walls, say, of a core wall which there would be, of course, if the core was a lift shaft. In such a situation a computer-based method of analysis would probably be used.

Continuum structures

Examples of these are folded plate roofs, shells, floor slabs, etc. An arch dam is a three-dimensional continuum structure as are domed roofs, aircraft fuselages and wings. Generally, continuum structures require computer-based methods of analysis.

1.4 Support systems

The loads applied to a structure are transferred to its foundations by its supports. In practice supports may be rather complicated in which case they are simplified, or *idealized*, into a form that is much easier to analyse. For example, the support shown in Fig. 1.12(a) allows the beam to rotate but prevents translation both horizontally and vertically. For the purpose of analysis it is represented by the idealized form shown in Fig. 1.12(b); this type of support is called a *pinned support.*

A beam that is supported at one end by a pinned support would not necessarily be supported in the same way at the other. One support of this type is sufficient to maintain the horizontal equilibrium of a beam and it may be advantageous to allow horizontal movement of the other end so that, for example, expansion and contraction caused by temperature variations do not cause additional stresses. Such a support may take the form of a composite steel and rubber bearing as shown in Fig. 1.13(a) or consist of a roller sandwiched between steel plates. In an idealized form, this type of support is represented as shown in Fig. 1.13(b) and is called a *roller support.* It is assumed that such a support allows horizontal movement and rotation but prevents movement vertically, up or down.

It is worth noting that a horizontal beam on two pinned supports would be statically indeterminate for other than purely vertical loads since, as we shall see in Section 2.5, there would be two vertical and two horizontal components of support reaction but only three independent equations of statical equilibrium.

In some instances beams are supported in such a way that both translation and rotation are prevented. In Fig. 1.14(a) the steel I-beam is connected through brackets to the flanges of a steel column and therefore

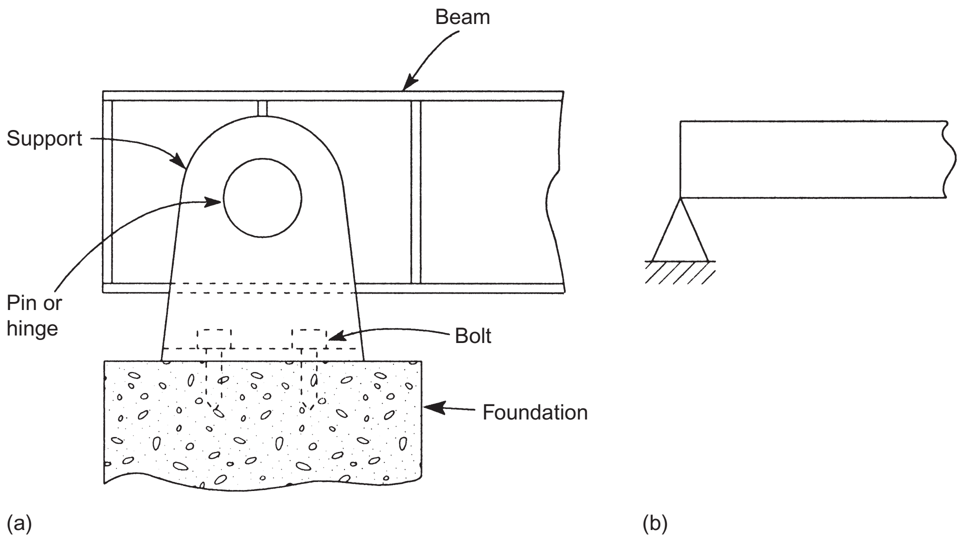
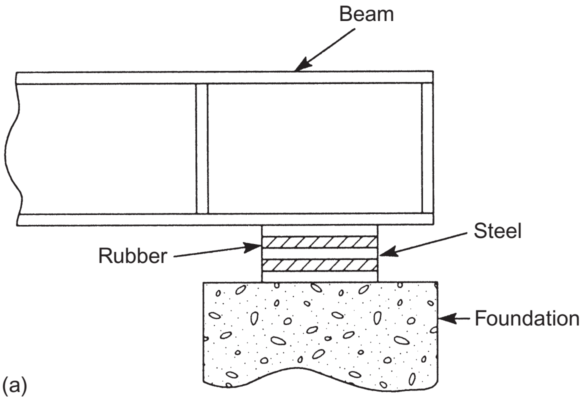
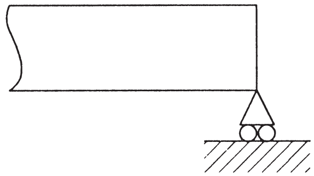


FIGURE 1.12

Idealization of a pinned support.



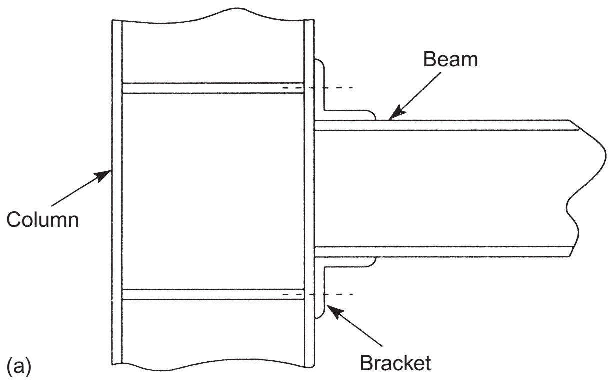
(a)



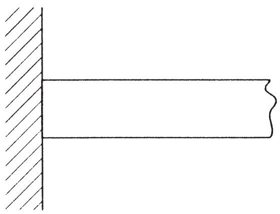
(b)

FIGURE 1.13

Idealization of a sliding or roller support.



(a)



(b)

FIGURE 1.14

Idealization of a built-in support.

cannot rotate or move in any direction; the idealized form of this support is shown in Fig. 1.14(b) and is called a *fixed, built-in* or *encastré support.* A beam that is supported by a pinned support and a roller support as shown in Fig. 1.15(a) is called a *simply supported beam;* note that the supports will not necessarily be positioned at the ends of a beam. A beam supported by combinations of more than two pinned and roller supports (Fig. 1.15(b)) is known as a *continuous beam.* A beam that is built-in at one end and free at the other (Fig. 1.16(a)) is a *cantilever beam* while a beam that is built-in at both ends (Fig. 1.16(b)) is a *fixed, built-in* or *encastré* beam.

When loads are applied to a structure, reactions are produced in the supports and in many structural analysis problems the first step is to calculate their values. It is important, therefore, to identify correctly the type of reaction associated with a particular support. Supports that prevent translation in a particular direction produce a force reaction in that direction while supports that prevent rotation cause moment reactions. For example, in the cantilever beam of Fig. 1.17, the applied load W has horizontal and vertical components which cause horizontal ($R_{A,H}$) and vertical ($R_{A,V}$) reactions of force at the built-in end A, while the rotational effect of W is balanced by the moment reaction M_A. We shall consider the calculation of support reactions in detail in Section 2.5.

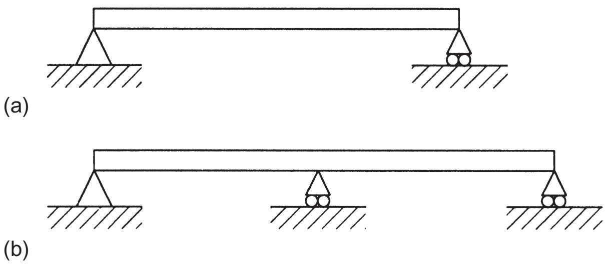


FIGURE 1.15

(a) Simply supported beam and (b) continuous beam.

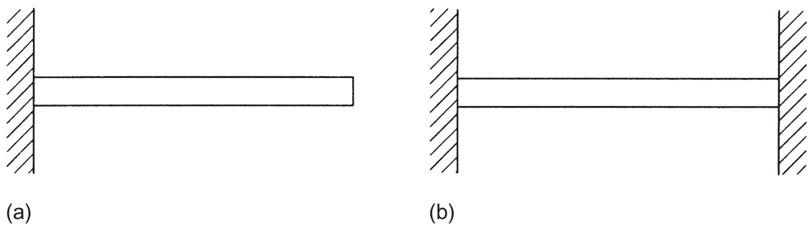


FIGURE 1.16

(a) Cantilever beam and (b) fixed or built-in beam.

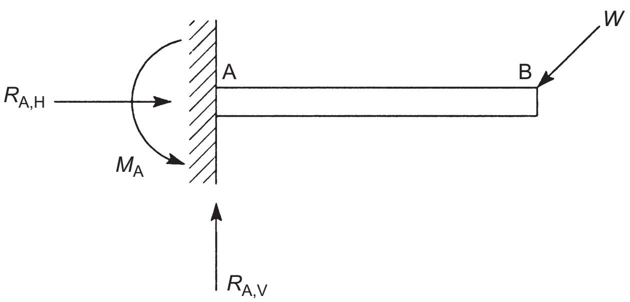


FIGURE 1.17

Support reactions in a cantilever beam subjected to an inclined load at its free end.

1.5 Statically determinate and indeterminate structures

In many structural systems the principles of statical equilibrium (Section 2.4) may be used to determine support reactions and internal force distributions; such systems are called *statically determinate*. Systems for which the principles of statical equilibrium are insufficient to determine support reactions and/or internal force distributions, i.e. there are a greater number of unknowns than the number of equations of statical equilibrium, are known as *statically indeterminate* or *hyperstatic* systems. However, it is possible that even though the support reactions are statically determinate, the internal forces are not, and vice versa. For example, the truss in Fig. 1.18(a) is, as we shall see in Chapter 4, statically determinate both for support reactions and forces in the members whereas the truss shown in Fig. 1.18(b) is statically determinate only as far as the calculation of support reactions is concerned.

Another type of indeterminacy, *kinematic indeterminacy*, is associated with the ability to deform, or the degrees of freedom, of a structure and is discussed in detail in Section 16.3. A degree of freedom is a possible displacement of a joint (or node as it is often called) in a structure. For instance, a joint in a plane truss has

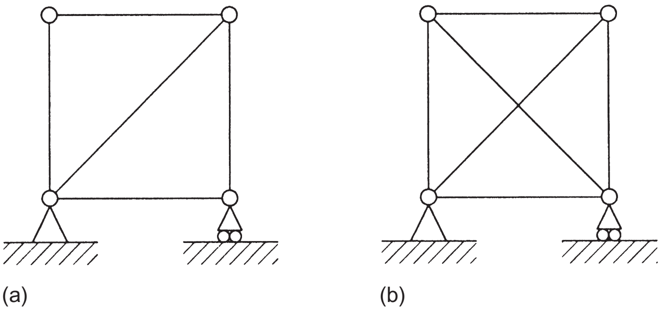


FIGURE 1.18

(a) Statically determinate truss and (b) statically indeterminate truss.

three possible modes of displacement or degrees of freedom, two of translation in two mutually perpendicular directions and one of rotation, all in the plane of the truss. On the other hand a joint in a three-dimensional space truss or frame possesses six degrees of freedom, three of translation in three mutually perpendicular directions and three of rotation about three mutually perpendicular axes.

1.6 Analysis and design

Some students in the early stages of their studies have only a vague idea of the difference between an analytical problem and a design problem. We shall examine the various steps in the design procedure and consider the role of analysis in that procedure.

Initially the structural designer is faced with a requirement for a structure to fulfil a particular role. This may be a bridge of a specific span, a multistorey building of a given floor area, a retaining wall having a required height and so on. At this stage the designer will decide on a possible form for the structure. For example, in the case of a bridge the designer must decide whether to use beams, trusses, arches or cables to support the bridge deck. To some extent, as we have seen, the choice is governed by the span required, although other factors may influence the decision. In Scotland, the Firth of Tay is crossed by a multispan bridge supported on columns, whereas the road bridge crossing the Firth of Forth is a suspension bridge. Very recently, a second road bridge has been constructed using the cable-stayed system. In both road bridges, a large height clearance is required to accommodate shipping. In addition it is possible that the designer may consider different schemes for the same requirement. Further decisions are required as to the materials to be used: steel, reinforced concrete, timber, etc.

Having decided on a particular system the loads on the structure are calculated. We have seen in Section 1.2 that these comprise dead and live loads. Some of these loads, such as a floor load in an office building, are specified in Codes of Practice while a particular Code gives details of how wind loads should be calculated. Of course the self-weight of the structure is calculated by the designer.

When the loads have been determined, the structure is *analysed*, i.e. the external and internal forces and moments are calculated, from which are obtained the internal stress distributions and also the strains and displacements. The structure is then checked for *safety*, i.e. that it possesses sufficient strength to resist loads without danger of collapse, and for *serviceability*, which determines its ability to carry loads without excessive deformation or local distress; Codes of Practice are used in this procedure. It is possible that this check may show that the structure is underdesigned (unsafe and/or unserviceable) or overdesigned (uneconomic) so that adjustments must be made to the arrangement and/or the sizes of the members; the analysis and design check are then repeated.

Analysis, as can be seen from the above discussion, forms only part of the complete design process and is concerned with a given structure subjected to given loads. Generally, there is a unique solution to an analytical problem whereas there may be one, two or more perfectly acceptable solutions to a design problem.

1.7 Structural and load idealization

Generally, structures are complex and must be *idealized* or simplified into a form that can be analysed. This idealization depends upon factors such as the degree of accuracy required from the analysis because, usually, the more sophisticated the method of analysis employed the more time consuming, and therefore the more costly, it is. A preliminary evaluation of two or more possible design solutions would not require the same degree of accuracy as the check on the finalized design. Other factors affecting the idealization include the type of load being applied, since it is possible that a structure will require different idealizations under different loads.

We have seen in Section 1.4 how actual supports are idealized. An example of structural idealization is shown in Fig. 1.19 where the simple roof truss of Fig. 1.19(a) is supported on columns and forms one of a series comprising a roof structure. The roof cladding is attached to the truss through purlins which connect each truss, and the truss members are connected to each other by gusset plates which may be riveted or welded to the members forming rigid joints. This structure possesses a high degree of statical indeterminacy and its analysis would probably require a computer-based approach. However, the assumption of a simple support system, the replacement of the rigid joints by pinned or hinged joints and the assumption that the forces in the members are purely axial, result, as we shall see in Chapter 4, in a statically determinate structure (Fig. 1.19(b)). Such an idealization might appear extreme but, so long as the loads are applied at the joints and the truss is supported at joints, the forces in the members are predominantly axial and bending moments and shear forces are negligibly small.

At the other extreme a continuum structure, such as a folded plate roof, would be idealized into a large number of *finite elements* connected at *nodes* and analysed using a computer; the *finite element method* is, in fact, an exclusively computer-based technique. A large range of elements is available in finite element

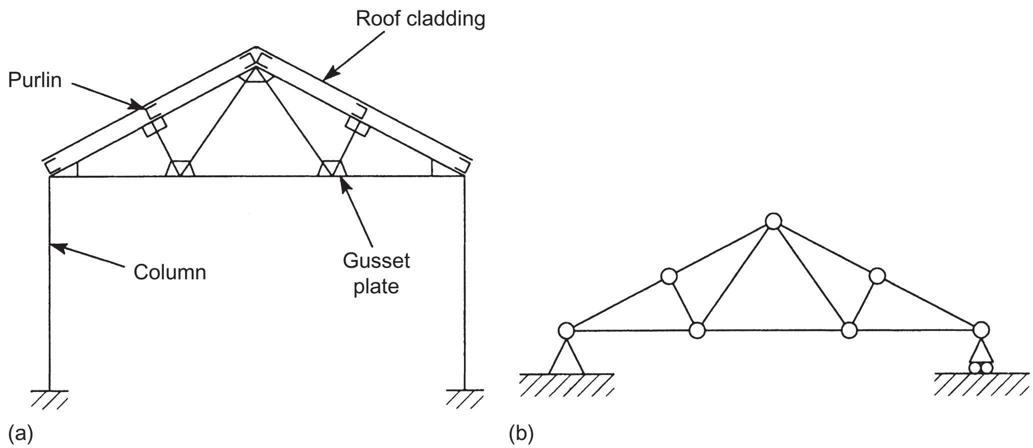


FIGURE 1.19

(a) Actual truss and (b) idealized truss.

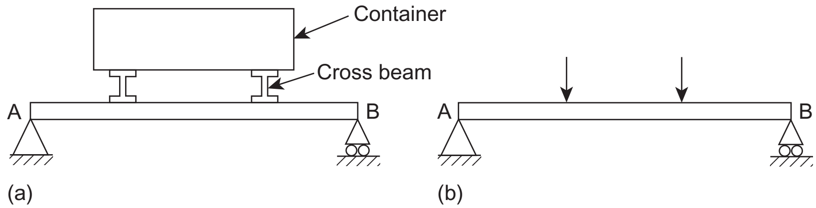


FIGURE 1.20

Idealization of a load system.

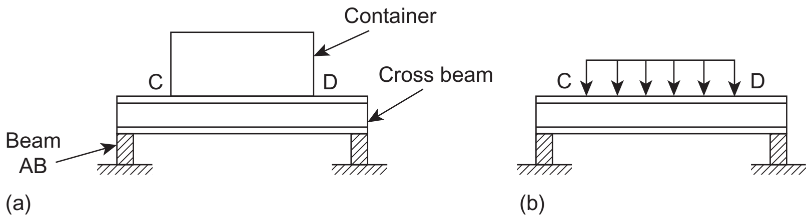


FIGURE 1.21

Idealization of a load system: uniformly distributed.

packages including simple beam elements, plate elements, which can model both in-plane and out-of-plane effects, and three-dimensional 'brick' elements for the idealization of solid three-dimensional structures.

In addition to the idealization of the structure, loads also, generally, need to be idealized. In Fig. 1.20(a) the beam AB supports two cross beams on which rests a container. There would, of course, be a second beam parallel to AB to support the other end of each cross beam. The flange of each cross beam applies a *distributed load* to the beam AB but if the flange width is small in relation to the span of the beam they may be regarded as *concentrated loads* as shown in Fig. 1.20(b). In practice there is no such thing as a concentrated load since, apart from the practical difficulties of applying one, a load acting on zero area means that the stress (see Chapter 7) would be infinite and localized failure would occur.

The load carried by the cross beams, i.e. the container, would probably be applied along a considerable portion of their length as shown in Fig. 1.21(a). In this case the load is said to be *uniformly distributed* over the length CD of the cross beam and is represented as shown in Fig. 1.21(b).

Distributed loads need not necessarily be uniform but can be trapezoidal or, in more complicated cases, be described by a mathematical function. Note that all the beams in Figs. 1.20 and 1.21 carry a uniformly distributed load, their self-weight.

1.8 Structural elements

Structures are made up of structural elements. For example, in frames these are beams and columns. The cross sections of these structural elements vary in shape and depend on what is required in terms of the forces to which they are subjected. Some common sections are shown in Fig. 1.22.

The solid square (or rectangular) and circular sections are not particularly efficient structurally. Generally they would only be used in situations where they would be subjected to tensile axial forces (stretching forces acting along their length). In cases where the axial forces are compressive (shortening) then angle sections, channel sections, Tee-sections or I-sections would be preferred.

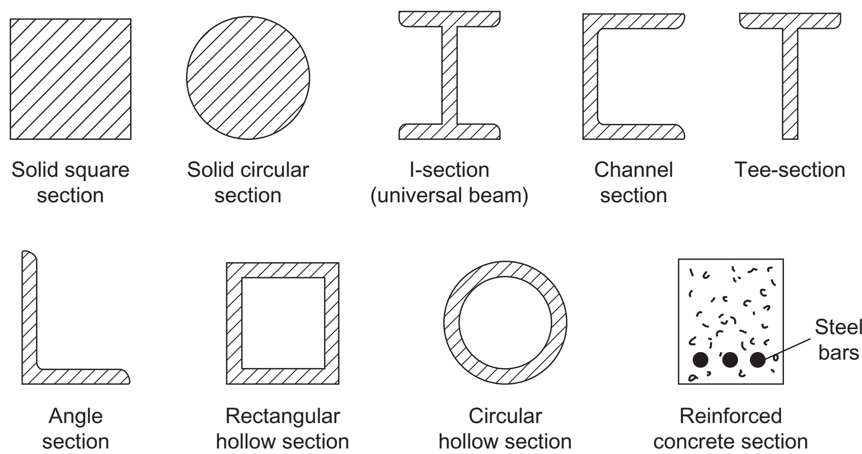


FIGURE 1.22

Structural elements.

I-section and channel section beams are particularly efficient in carrying bending moments and shear forces (the latter are forces applied in the plane of a beam's cross section) as we shall see later.

The rectangular hollow (or square) section beam is also efficient in resisting bending and shear but is also used, as is the circular hollow section, as a column. A Universal Column has a similar cross section to that of the Universal Beam except that the flange width is greater in relation to the web depth.

Concrete, which is strong in compression but weak in tension, must be reinforced by steel bars on its tension side when subjected to bending moments. In many situations concrete beams are reinforced in both tension and compression zones and also carry shear force reinforcement.

Other types of structural element include box girder beams which are fabricated from steel plates to form tubular sections; the plates are stiffened along their length and across their width to prevent them buckling under compressive loads. Plate girders, once popular in railway bridge construction, have the same cross-sectional shape as a Universal Beam but are made up of stiffened plates and have a much greater depth than the largest standard Universal Beam. Reinforced concrete beams are sometimes cast integrally with floor slabs whereas in other situations a concrete floor slab may be attached to the flange of a Universal Beam to form a composite section. Timber beams are used as floor joists, roof trusses and, in laminated form, in arch construction and so on.

1.9 Materials of construction

A knowledge of the properties and behaviour of the materials used in structural engineering is essential if safe and long-lasting structures are to be built. Later we shall examine in some detail the properties of the more common construction materials but for the moment we shall review the materials available.

Steel

Steel is one of the most commonly used materials and is manufactured from iron ore which is first converted to molten pig iron. The impurities are then removed and carefully controlled proportions of carbon, silicon, manganese, etc. added, the amounts depending on the particular steel being manufactured.

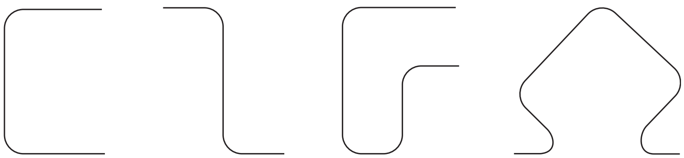


FIGURE 1.23

Examples of cold-formed sections.

Mild steel is the commonest type of steel and has a low carbon content. It is relatively strong, cheap to produce and is widely used for the sections shown in Fig. 1.22. It is a *ductile* material (see Chapter 8), is easily welded and because its composition is carefully controlled its properties are known with reasonable accuracy. *High carbon steels* possess greater strength than mild steel but are less ductile whereas *high yield steel* is stronger than mild steel but has a similar stiffness. High yield steel, as well as mild steel, is used for reinforcing bars in concrete construction and very high strength steel is used for the wires in prestressed concrete beams.

Low carbon steels possessing sufficient ductility to be bent cold are used in the manufacture of *cold-formed* sections. In this process unheated thin steel strip passes through a series of rolls which gradually bend it into the required section contour. Simple profiles, such as a channel section, may be produced in as few as six stages whereas more complex sections may require 15 or more. Cold-formed sections are used as lightweight roof purlins, stiffeners for the covers and sides of box beams and so on. Some typical sections are shown in Fig. 1.23.

Other special purpose steels are produced by adding different elements. For example, chromium is added to produce stainless steel although this is too expensive for general structural use.

Concrete

Concrete is produced by mixing cement, the commonest type being *ordinary Portland cement*, fine aggregate (sand), coarse aggregate (gravel, chippings) with water. A typical mix would have the ratio of cement/sand/coarse aggregate to be 1 : 2 : 4 but this can be varied depending on the required strength.

The tensile strength of concrete is roughly only 10% of its compressive strength and therefore, as we have already noted, requires reinforcing in its weak tension zones and sometimes in its compression zones.

Timber

Timber falls into two categories, *hardwoods* and *softwoods.* Included in hardwoods are oak, beech, ash, mahogany, teak, etc. while softwoods come from coniferous trees, such as spruce, pine and Douglas fir. Hardwoods generally possess a short grain and are not necessarily hard. For example, balsa is classed as a hardwood because of its short grain but is very soft. On the other hand some of the long-grained softwoods, such as pitch pine, are relatively hard.

Timber is a *naturally* produced material and its properties can vary widely due to varying quality and significant defects. It has, though, been in use as a structural material for hundreds of years as a visit to any of the many cathedrals and churches built in the Middle Ages will confirm. Some of timber's disadvantages, such as warping and twisting, can be eliminated by using it in laminated form. *Plywood* is built up from several thin sheets glued together but with adjacent sheets having their grains running at 90° to each other. Large span roof arches are sometimes made in laminated form from timber strips. Its susceptibility to the fungal attacks of wet and dry rot can be prevented by treatment as can the potential ravages of woodworm and death watch beetle.

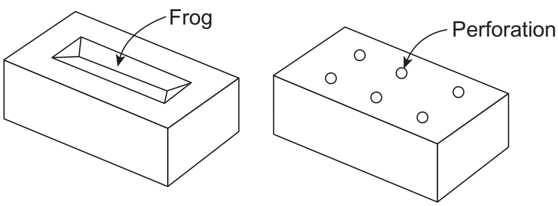


FIGURE 1.24

Types of brick.

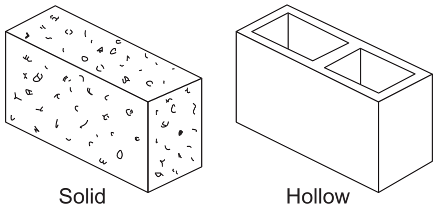


FIGURE 1.25

Concrete blocks.

Masonry

Masonry in structural engineering includes bricks, concrete blocks and stone. These are brittle materials, weak in tension, and are therefore used in situations where they are only subjected to compressive loads.

Bricks are made from clay shale which is ground up and mixed with water to form a stiff paste. This is pressed into moulds to form the individual bricks and then fired in a kiln until hard. An alternative to using individual moulds is the *extrusion process* in which the paste is squeezed through a rectangular-shaped die and then chopped into brick lengths before being fired.

Figure 1.24 shows two types of brick. One has indentations, called *frogs*, in its larger faces while the other, called a *perforated* brick, has holes passing completely through it; both these modifications assist the *bond* between the brick and the mortar and help to distribute the heat during the firing process. The holes in perforated bricks also allow a wall, for example, to be reinforced vertically by steel bars passing through the holes and into the foundations.

Engineering bricks are generally used as the main load bearing components in a masonry structure and have a minimum guaranteed crushing strength whereas *facing* bricks have a wide range of strengths but have, as the name implies, a better appearance. In a masonry structure the individual elements are the bricks while the complete structure, including the *mortar* between the joints, is known as *brickwork*.

Mortar commonly consists of a mixture of sand and cement the proportions of which can vary from 3:1 to 8:1 depending on the strength required; the lower the amount of sand the stronger the mortar. However, the strength of the mortar must not be greater than the strength of the masonry units otherwise cracking can occur.

Concrete blocks, can be solid or hollow as shown in Fig. 1.25, are cheap to produce and are made from special lightweight aggregates. They are rough in appearance when used for, say, insulation purposes and are usually covered by plaster for interiors or cement rendering for exteriors. Much finer facing blocks are also manufactured for exterior use and are not covered.

Stone, like timber, is a natural material and is, therefore, liable to have the same wide, and generally unpredictable, variation in its properties. It is expensive since it must be quarried, transported and then, if necessary, 'dressed' and cut to size. However, as with most natural materials, it can provide very attractive structures.

Aluminium

Pure aluminium is obtained from bauxite, is relatively expensive to produce, and is too soft and weak to act as a structural material. To overcome its low strength it is alloyed with elements such as magnesium. Many different alloys exist and have found their primary use in the aircraft industry where their relatively high strength/low weight ratio is a marked advantage; aluminium is also a ductile material. In structural engineering aluminium sections are used for fabricating lightweight roof structures, window frames, etc.

It can be extruded into complicated sections but the sections are generally smaller in size than the range available in steel.

Cast iron, wrought iron

These are no longer used in modern construction although many old, existing structures contain them. Cast iron is a brittle material, strong in compression but weak in tension and contains a number of impurities which have a significant effect on its properties.

Wrought iron has a much less carbon content than cast iron, is more ductile but possesses a relatively low strength.

Composite materials

Some use is now being made of fibre reinforced polymers or *composites* as they are called. These are light-weight, high strength materials and have been used for a number of years in the aircraft, automobile and boat building industries. They are, however, expensive to produce and their properties are not fully understood.

Strong fibres, such as glass or carbon, are set in a matrix of plastic or epoxy resin which is then mechanically and chemically protective. The fibres may be continuous or discontinuous and are generally arranged so that their directions match those of the major loads. In sheet form two or more layers are sandwiched together to form a *lay-up*.

In the early days of composite materials glass fibres were used in a plastic matrix, this is known as glass reinforced plastic (GRP). More modern composites are carbon fibre reinforced plastics (CFRP). Other composites use boron and Kevlar fibres for reinforcement.

Structural sections, as opposed to sheets, are manufactured using the *pultrusion* process in which fibres are pulled through a bath of resin and then through a heated die which causes the resin to harden; the sections, like those of aluminium alloy, are small compared to the range of standard steel sections available.

1.10 The use of computers

In modern-day design offices most of the structural analyses are carried out using computer programs. A wide variety of packages is available and range from relatively simple plane frame (two-dimensional) programs to more complex *finite element* programs which are used in the analysis of continuum structures. The algorithms on which these programs are based are derived from fundamental structural theory written in matrix form so that they are amenable to computer-based solutions. However, rather than simply supplying data to the computer, structural engineers should have an understanding of the fundamental theory for without this basic knowledge it would be impossible for them to make an assessment of the limitations of the particular program being used. Unfortunately there is a tendency, particularly amongst students, to believe without question results in a computer printout. Only with an understanding of how structures behave can the validity of these results be mentally checked.

The first few chapters of this book, therefore, concentrate on basic structural theory although, where appropriate, computer-based applications will be discussed. In later chapters computer methods, i.e. matrix and finite element methods, are presented in detail.