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CHAPTER 1

Reinforced concrete: an overview

This chapter introduces the basic ideas of reinforced concrete. It explains terms such as cement, concrete, reinforced concrete and prestressed concrete and goes on to describe how individual reinforced concrete members channel the applied loads to their supports through internal load paths that consist, usually, of compressive forces in the concrete and tensile forces in small amounts of strategically placed reinforcing steel. A low-rise reinforced concrete building is used as an example to show how load paths carry the applied loads through an entire structural system down to the footings and into the foundations. The chapter ends with a discussion of long-term structural effects in reinforced concrete and their relevance in design. Time-dependent processes such as creep, shrinkage, temperature change and foundation settlement are briefly explained and discussed.

1.1 Cement and concrete

The term **cement** is used generically in the construction industry to refer to materials that form a hard, stone-like substance after being mixed with water. **Portland cement** has been widely used in building since the late 18th century, when a process for its manufacture was developed by firing a mixture of clay and limestone at high temperature and then grinding the resulting small stones (clinker) to a fine powder. The name 'portland cement' was given to the material because of its resemblance, in its hardened state, to a natural stone found near Portland in England. It is a hydraulic cement, which means that it is impervious to the action of water and can set under water. Some cementitious materials occur as by-products of modern industrial processes. In particular, **blast furnace slag** is produced during steel making, while **fly ash** is a fine residue from the burning of powdered coal in power plants.

Concrete is made by mixing coarse aggregate and sand with cement and water. After a short period of time, the fresh concrete undergoes an initial set as a result of the reaction of the cement with the water. It then goes through a hardening process that continues over weeks, months and even years. The strength of the concrete increases with time, rapidly at first but at a progressively decreasing rate.

The cement used in modern concrete is a blend of portland cement with fly ash and blast furnace slag. The use of a blend of cements results not only in reduced cost but also in improved properties of the fresh and hardened concrete. The term **binder** is sometimes used for this mix of cementitious materials.

The coarse aggregate in concrete serves as an inert filler. It often takes the form of small pieces of crushed stone or round river gravel, but other materials can be used. For example, special-purpose lightweight aggregate is made from expanded, fired clay and is used to reduce the self-weight of concrete. Crushed concrete from demolished structures has been used as aggregate as a means of recycling building materials.

While the sand also acts as a filler, its prime function is to improve the flow properties of the fresh concrete, thus allowing the mix to be easily transported, placed and compacted. The relative quantities of the ingredients are chosen so that the fresh concrete is a viscous liquid that flows readily and can even be pumped. Another important factor to be considered in choosing the quantities for the mix is that the strength of the hardened concrete depends mainly on the ratio of water to cement: the larger the water content, the lower the strength. The process of choosing appropriate proportions for the ingredients is known as **mix design**.

Various **admixtures** are used to improve the properties of concrete, both in the fresh and the hardened states. In particular, the workability of fresh concrete can be greatly improved by the addition of **superplasticisers**. The flow properties of the fresh concrete are thus improved, so that it is easily pumped and is largely self-compacting. Superplasticisers also allow less water to be used in the mix. Large increases in the strength of the hardened concrete can thus be achieved through the use of superplasticisers. Other special-purpose additives are available and in common use. Information on the manufacture and technology of concrete can be found in the text by Neville and Brooks (2010) and Day et al. (2017).

Fresh concrete is placed in specially prepared **formwork** which provides initial support and hence fixes the outer dimensions of the hardened concrete. The formwork is removed when the concrete has gained sufficient strength to support itself. Through the choice of the formwork geometry, concrete can be used to construct members of almost any required complex shape, as well as those with a conventional rectangular shape.

Mature, hardened concrete has good compressive strength, typically between 30 and 60 MPa, which is comparable to the strength of the timbers that are used in building construction. However, special-purpose concretes are available with strengths up to, and in excess of, 120 MPa. This is nearly one-quarter of the strength of reinforcing steel. Such high strength concretes have various applications, such as to minimise the size of the columns in tall city buildings. Concretes are currently being produced on an experimental basis with even higher compressive strengths, up to several hundred MPa. The properties of common commercial grade concretes produced in Australia are given in Appendix A.

1.2 Reinforced concrete and reinforcing steel

While the compressive strength of concrete is quite adequate, its tensile strength is poor, typically between 2 and 10 MPa. This means that plain concrete cannot be used to construct structural members in which significant tensile stresses develop, such as beams, slabs and columns. However, small amounts of **steel reinforcement** can be cast in the concrete in strategic locations to carry the internal tensile forces. The result is **reinforced concrete**, a cheap and effective composite structural material which is almost ideal for the construction of most structural members. The steel reinforcement is much more expensive than the concrete but the volume of steel used is only several per cent of the volume of the concrete, so that a significant cost advantage is maintained.

Modern steel reinforcement is manufactured as **bars** of circular cross-section, typically between 10 mm and 40 mm in diameter and 12 metres long. The bars can be cut to size, or lengthened by splicing or welding, and can be bent to almost any required shape to suit particular applications. In line members, such as beams and columns, the **main reinforcement** consists of straight bars placed close to one or more faces of the member and extending longitudinally over the full member length.

CEMENT AND CONCRETE IN HISTORY

In the civilisations of the Mediterranean and Middle East cementitious materials have been used in building for thousands of years.

In Ancient Rome cement was made from volcanic ash and limestone and this was widely used by engineers to make concrete for the construction of buildings and bridges. Some of these, constructed of stone and concrete, have survived more or less intact to the present day. Examples include the Alcantara bridge over the Tagus river in Spain, the dome of the Pantheon in Rome and the Arena in Verona.

Recent studies of old buildings in China have shown that glutinous rice was used there to make an effective cementitious material.

The idea of reinforcing concrete with small amounts of steel stems from the work of a number of engineers in England and Europe during the 19th century.

Reinforced concrete was a popular building material in Australia from the latter decades of the 19th century. A number of buildings and structures from that time are still in use today. The Gawler Chambers in North Terrace, Adelaide, is a five-storey building with a reinforced concrete internal frame that was designed by Sir John Monash before the First World War. The first substantial cement block building in the southern hemisphere was constructed in 1900 as a department store in Bellingen, in northern NSW. It is a spacious two-storey building of pleasing proportions, still in use and in good condition.

Secondary reinforcement is placed transversely to the main reinforcement, that is, in the directions of the cross-sectional dimensions. The transverse steel serves to tie the longitudinal steel together, but it can also play an important structural role by carrying tensile forces. In beams the transverse reinforcement is referred to as **stirrups**, and in columns as **fitments** or **ligatures**.

In two-dimensional (planar) members, such as slabs and walls, the main reinforcement is arranged as a rectangular grid that extends throughout the plane of the member. For such applications reinforcement is also manufactured in sheets, which are referred to as **mesh**, or fabric. Mesh consists of regularly spaced, small-diameter bars or wires that run longitudinally and another set placed transversely, with factory welding at the intersections. Mesh is used as light reinforcement in slabs, walls and footings. In massive three-dimensional members such as gravity walls and large footings, large diameter reinforcing bars are placed in the three main directions at right angles.

For reinforced concrete to work effectively as a composite material, good **bond** has to be achieved locally between the reinforcement and the adjacent concrete. Indentations or deformations are therefore rolled into the surface of the reinforcement during its manufacture to produce **deformed reinforcement**. The indentations improve the bond by providing an effective means for transferring shear stress across the steel–concrete interface. The deformations thus minimise the slip between the steel and concrete and this ensures that any cracks that form remain narrow. It is also important to achieve sound **end anchorage** of the reinforcement in the concrete, for example by providing bends and hooks at the ends of the bars.

While the main reinforcement is placed as close as practicable to the tensile face of a member, some concrete **cover** to the steel always has to be provided to protect the steel against corrosion and to allow the steel to bond properly with the surrounding concrete.

There is a common misconception that reinforcing steel prevents, or at least delays, the formation of tensile cracks in concrete. This is not so. In fact, the presence of the reinforcing steel can promote cracking because additional tensile stresses are induced in the concrete when it shrinks and shortens over time, relative to the adjacent steel. The main purpose of the reinforcement is to carry the internal tensile forces in regions where the concrete cracks. A secondary function is to prevent excessive widening of any cracks that form.

In the discussion so far we have seen how reinforcement is used to carry the internal tensile forces. However, steel can also assist the concrete to carry compressive force. For example, **compressive reinforcement** is used in columns that have to carry large axial compression forces. The compressive strength of reinforcing steel is about 10 times that of normal concrete so that the column size can be reduced substantially by the use of compressive steel. It is placed near the outer faces of the concrete, where it is also effective in resisting any bending moments that may develop. Reinforcement may also be used in the compression face of beams to reduce the overall section size when space is restricted.

While the tensile reinforcement currently used in reinforced concrete is almost always steel, new materials are increasingly finding specialised uses as reinforcement. Fibre-reinforced plastics and glass are being used increasingly as reinforcement in the repair of existing structures. These and other non-ferrous reinforcing materials will find greater use in construction in the coming decades. In this book, however, we concentrate on reinforced concrete that is made using reinforcing steel. The properties of common commercial grade reinforcing steels produced in Australia are given in Appendix B.

1.3 Load paths in reinforced concrete members

Provided small amounts of tensile reinforcement are properly located in a reinforced concrete member, strong and stable **load paths** (or internal load-carrying mechanisms) develop to transfer the externally applied loads through the member and into its supports. These load paths typically consist of compressive **strut** forces in the concrete and tensile **tie** forces in the reinforcement. The questions of where to place the reinforcement in beams, columns, slabs and other component members, and in what quantities, are of prime importance in design and will be dealt with at length in subsequent chapters of this book. For the present, we shall consider briefly how to locate reinforcement in order to allow the load paths that are needed to carry the external loads to form. Examples of load paths with the corresponding internal tensile and compressive forces are shown in Figures 1.1 to 1.4 for several different members.

The statically determinate beam in Figure 1.1 has two symmetric point loads so that the central region XY is in pure bending, while the end regions WX and YZ are subjected to constant shear force and varying bending moment. The main longitudinal reinforcing steel is placed near the bottom tensile face of the beam, where high tensile concrete stresses develop (because of the bending moment) and where vertical cracking occurs. The reinforcing bars extend over the full length of the beam and are anchored at the supports with hooks. The moment in a cross-section in XY is resisted by an internal couple that consists of a tensile force *T* in the steel and an equal compressive force *C* in the upper fibres of the concrete (Figure 1.1(b)).

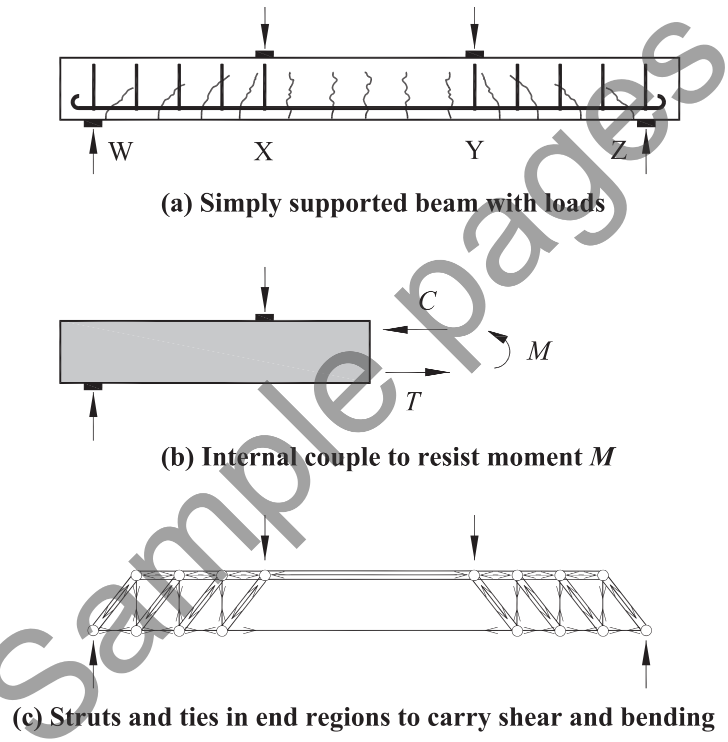
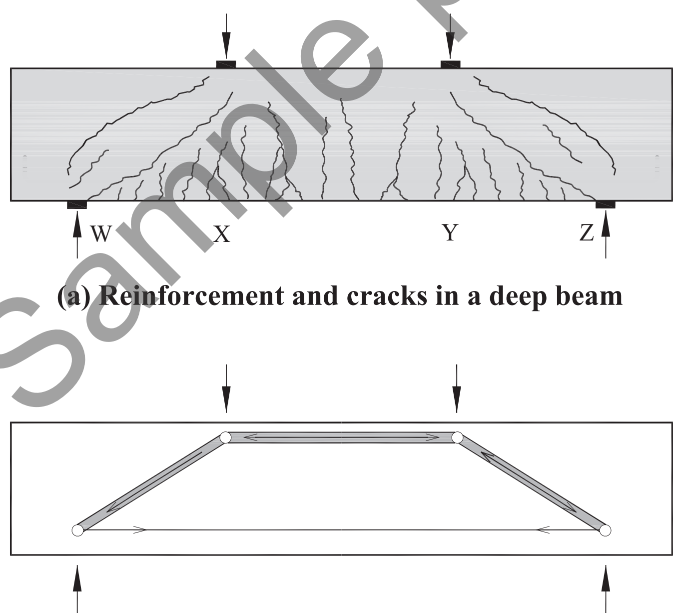


Figure 1.1 Reinforcement and internal forces in a simple beam

In the end regions WX and YZ, where both shear and moment exist, the situation is rather more complicated. Cracks still form in the bottom fibres as a result of the moment but they tend subsequently to become inclined in the manner shown in Figure 1.1(a) because of the presence of the shear. The bending moment is also resisted here by tension in the longitudinal steel and compression in the upper fibres of the concrete, but the shear force is resisted by inclined compressive forces in concrete struts that form between the inclined cracks. These inclined compressive forces are equilibrated at each joint or **node** by the tensile force in the vertical stirrup and a change in the longitudinal force (either tension in the bottom steel or compression in the upper concrete). The result is a truss-like arrangement of the tensile and compressive forces, as shown in Figure 1.1(c).

The deep beam in Figure 1.2 also has two symmetric point loads but in this case the shear spans (the end regions WX and YZ) are relatively short and comparable in size to the depth of the member. In such a situation there is no room for successive parallel inclined cracks to form, as was the case in the beam in Figure 1.1. The arrangement of internal forces now consists of the following: a tensile tie force, carried by the steel bars near the bottom face and running the full length of the beam between the supports; a horizontal compressive strut in the upper fibres in the central region XY; and two adjoining inclined struts, one in each end region above the main inclined crack.



(a) Reinforcement and cracks in a deep beam

(b) Struts and main tensile tie

Figure 1.2 Internal forces in a deep beam

In Figure 1.3 the load paths are shown for the case of a horizontal load pushing against a squat wall. The tensile steel is vertical and located near the face adjacent to the load. This allows an inclined compressive strut to form in the concrete to equilibrate the load and the tensile tie force.

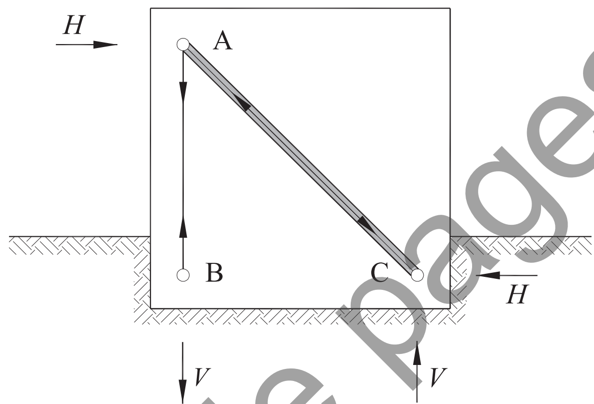
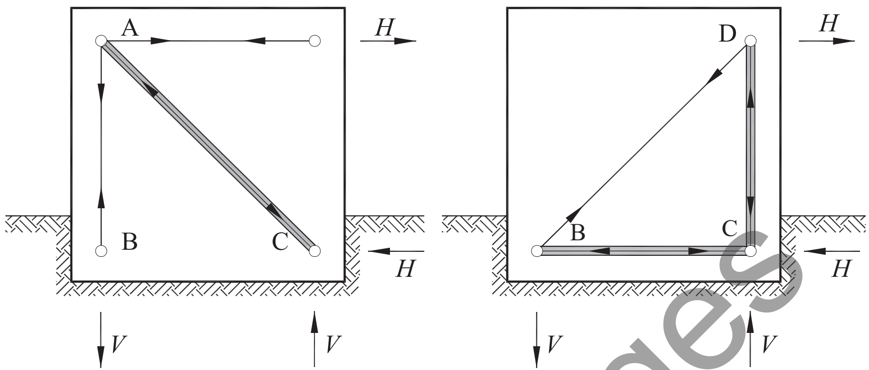


Figure 1.3 Internal forces in a wall with a horizontal load

Clearly, the internal forces shown in Figures 1.1 to 1.3 can only develop if the reinforcement is actually placed in the locations shown. However, alternative arrangements of the internal forces can often be found to carry the applied loads. Various alternative load paths may thus prove to be satisfactory for design, provided the steel is located appropriately. An example of alternative load paths in a wall is given in Figure 1.4. The wall is similar to that in Figure 1.3 but the load is now applied on the leeward side and pulls away from the wall instead of pushing against it. The previous arrangement of internal resisting forces in Figure 1.3 can be retained if an additional horizontal tensile tie is included near the top of the wall. This effectively transfers the load to the left-hand side. The result is as shown in Figure 1.4(a). However, other load paths are possible. For example, a diagonal tensile tie force can be used instead of the diagonal compressive strut. This is shown in Figure 1.4(b) where the tie is equilibrated by two internal compressive struts, one horizontal and one vertical.



(a) Load path with a diagonal strut

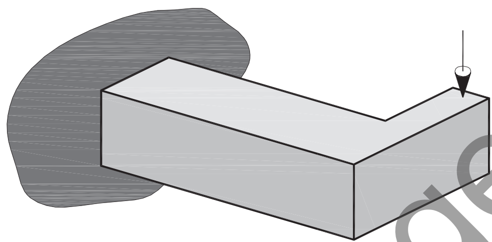
(b) Load path with a diagonal tie

Figure 1.4 Alternative load paths in a wall

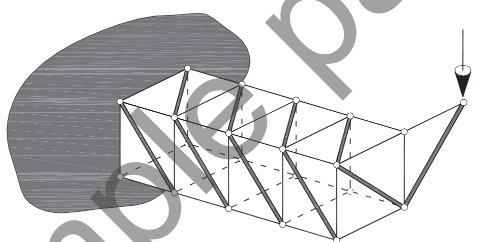
The point of application of the horizontal applied load in Figure 1.4(a) provides a good example of the importance of proper **detailing**. A special external steel fitment is needed to pick up the load and tie it to the horizontal tensile steel, for example by welding. Such detailing is an important aspect of design and guidance on detailing is given in Chapter 8 of this text.

The pattern of compressive concrete struts and tensile steel ties in a member may become considerably more complex than those already shown. For example, in a beam subjected to significant torsion as well as bending and shear, the arrangement is like a space truss. The example shown in Figure 1.5 is a cantilever with an eccentric end load. In this case the inclined struts extend around the member in the form of helices. In Figure 1.5(b) the inclined struts on the upper and nearer faces are shown. Figure 1.5(c) shows one helix of struts on all faces, passing around the cantilever. The additional strut in the vertical end face of the cantilever is needed for equilibrium of forces in the plane in which the load acts.

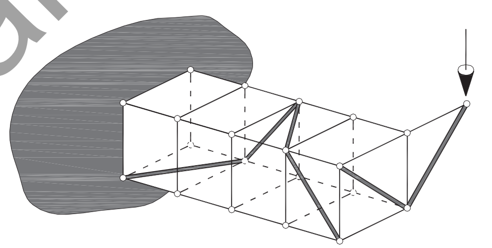
In Figures 1.1 to 1.5 small circles have been used to show the **nodes** where the internal tensile and compressive forces meet. In reality the local stresses in these joint regions can become very complex and careful attention has to be paid to the detailing of these regions. We have already seen how good anchorage of the tensile steel is necessary to allow the load paths to develop properly. The anchorage of the steel bars usually has to be achieved in and around the joint regions.



(a) Cantilever with eccentric end load



(b) Struts and ties



(c) Spiral arrangement of struts

Figure 1.5 Load paths in a cantilevered beam with torsion

If the shear is small in a flexural member, such as a thin slab supported on all sides, the flexural cracks do not incline but remain essentially vertical. The transverse steel can then be omitted and it is only necessary to include longi-