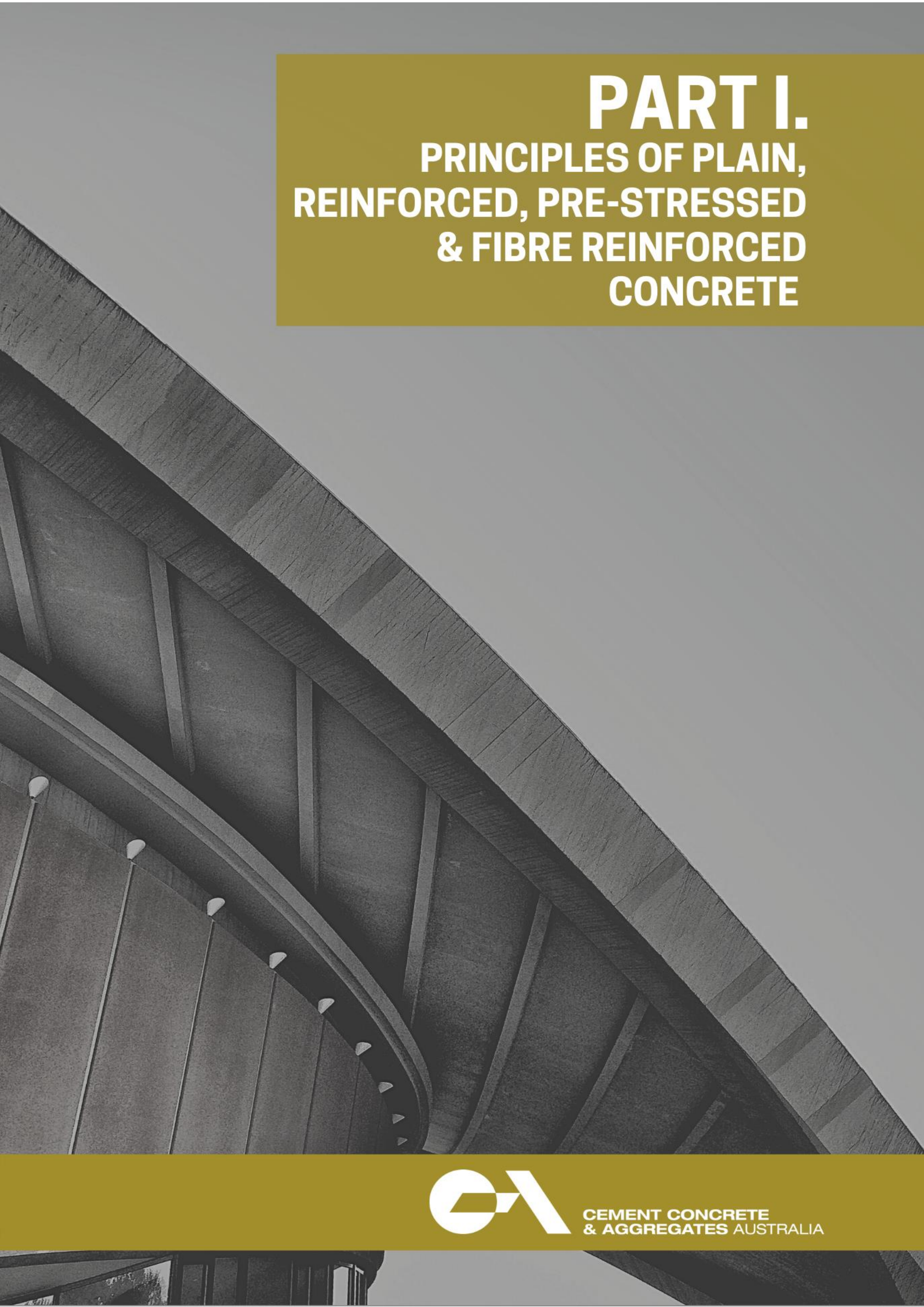
PART I.

PRINCIPLES OF PLAIN, REINFORCED, PRE-STRESSED & FIBRE REINFORCED CONCRETE



CEMENT CONCRETE
& AGGREGATES AUSTRALIA

CONTENTS

1. OUTLINE

Concrete structures generally incorporate reinforced and/or prestressed members. Many concrete structures do require some form of reinforcement, most commonly steel bars or wires and/or other forms of reinforcement such as steel or synthetic fibres, in order to carry their design loads. However, this is not always the case, and, in some circumstances, structures may contain elements that are formed from plain concrete with no reinforcement required to perform their function. This part provides basic information on the principles and applications for plain (unreinforced) concrete, reinforced concrete, prestressed concrete and fibre reinforced concrete.

Plain concrete (containing no reinforcement) can be used in situations where the tensile strength of the concrete alone is sufficient. Plain concrete members are generally limited to sub-bases and slabs on ground with low loading or in rare cases to industrial slabs with carefully constructed sub-base and designed jointing.

Reinforced concrete is a material that combines concrete and reinforcement into a composite whole. Whilst steel bars, wires and mesh are by far the most widely used forms of reinforcement, other materials are used in special applications, e.g. carbon-filament reinforcement and steel/synthetic fibres. AS 3600 defines reinforcement as 'steel bar, wire, or mesh but not tendons', whereas it defines ‘tendons’ as a coverall for prestressing or post-tensioning tendons, bars or wires.

Prestressed concrete structures use a particular type of reinforcing system that increases the efficiency of the reinforcement. In prestressed concrete members, the concrete is placed in compression before the member is subjected to the applied loads. The compression force is provided by tensioned tendons (high tensile steel wires, strands or bars) before they are bonded to the concrete and then transfer this force to the concrete. Placing the concrete in compression increases its ability to withstand loads.

Reinforcement or prestressing of concrete combines the material properties of steel and concrete to provide a versatile construction material. Plain concrete (unreinforced) has a high compressive strength but a low tensile strength. Steel, on the other hand, has a very high tensile strength and compressive strength, but it is much more expensive to use steel for its compressive strength compared to concrete. By combining steel and concrete into a composite material, it is possible to make use of both the high tensile strength of steel and the compressive strength of concrete cost-effectively.

Aside from strength properties, concrete has other beneficial attributes such as plasticity, which enables it to be moulded readily into different shapes, and relatively high fire resistance, which can be used to protect steel reinforcement embedded in the concrete.

Some advantages to combining steel and concrete are summarised in **Table I.1**.

Table I.1 – Characteristics of Steel and Concrete

Characteristics of concrete	Characteristics of steel
High compressive strength	High compressive strength
Low tensile strength	High tensile strength
Relatively high fire resistance	Relatively low fire resistance
Plastic and mouldable when fresh	Difficult to mould and shape except at high temperatures
Relatively inexpensive	Relatively expensive

The aim of the reinforced concrete designer is to combine the reinforcement with the concrete in an efficient manner. The design requires sufficient of the (relatively expensive) reinforcement to be incorporated to resist the tensile and shear forces which may occur in the structure. The design will also utilise the (comparatively inexpensive) concrete to resist the compressive forces in the structure.

To achieve this aim, the designer needs to determine not only the amount of reinforcement to be used, but also how it is to be distributed and where it is to be positioned. These latter decisions are critical to the successful performance of reinforced concrete and it is imperative that, during construction, reinforcement be positioned exactly as specified by the designer. It is therefore important that both those who supervise the fixing of reinforcement on the jobsite and those who fix it, have a basic appreciation of the principles of reinforced concrete as well as the practices of fixing reinforcement.

Like reinforced concrete, prestressed concrete is a composite material in which the weakness of concrete in tension is compensated by the tensile strength of steel – in this case, steel wires, strands, or bars.

The compressive strength of the concrete is used to advantage in prestressed concrete by applying an external compressive force to the concrete, which either keeps it permanently in compression during its service life loading (fully-prestressed) or limits the value of any tensile stress which arises under load (partial prestressing).

The pre-compressing or prestressing of concrete can be likened to picking up a row of books by pressing the books together **Figure I.1**. If a larger number of books is used (a longer span), the greater the force that has to be applied at either end of the row to prevent the row (the beam) collapsing under its own weight. A load applied to the top of the books would require an even greater force to be applied to prevent collapse.

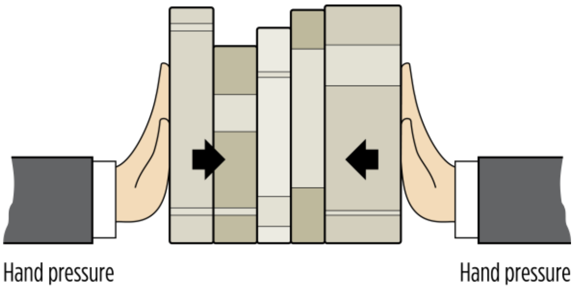


Figure I.1 – Prestressing can be Likened to Picking up a Row of Books

In reinforced concrete, the steel reinforcement carries all of the tensile stresses and in some cases, some of the compressive stresses. In prestressed concrete, the tendons are used primarily to keep the concrete in compression. The tendons are stretched (placing them in tension) and then bonded to the hardened concrete before releasing them. The force in the tendons is transferred to the concrete and so compressing it.

A fully prestressed concrete member is designed to be permanently under compression, effectively eliminating most tensile cracking. In this case, if the member is slightly overloaded, some tension cracks may form but these should close up and disappear once the overload is removed, provided always that the steel has not been strained beyond its elastic limit. In partially prestressed members, some tensile stresses and therefore some cracking, is accepted at the design ultimate load.

In reinforced concrete, the steel is not designed to operate at a high level of stress, as elongation of the steel will lead to cracking of the concrete. In prestressed concrete, the steel does carry very high levels of tensile stress. Whilst it is well able to do this, there are some penalties attached. Firstly, because of the forces involved, considerable care must be exercised in stretching the tendons and securing them. Stressing operations should always be carried out or at least supervised by skilled personnel. Secondly, the structure must be able to compress, otherwise the full, beneficial prestressing forces cannot act on the concrete. The designer must detail the structure so that the necessary movements can occur during stressing operations.

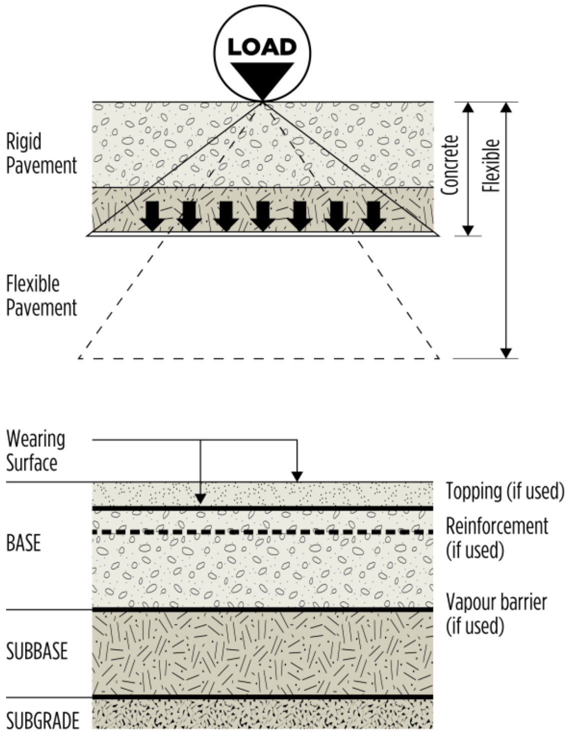
Reinforcement of concrete using steel or synthetic fibres is carried out for a range of beneficial reasons. The quantity and type of fibre used is selected for the benefit that is to be achieved. Fibres are commonly used in conjunction with steel reinforcement but may be used with plain concrete as the only form of reinforcement in some cases. The types of fibres, their benefits and common applications are briefed in the following sub-sections, with more details provided in Part II, Section 7. Also, fibre distribution and testing methods are given in Part V, Section 11.

Information on types and properties of reinforcing and prestressing steel is given in Part II, Section 6. Part V, Section 11 outlines the guidance on handling and fixing of reinforcing steel as well as the techniques used to tension the tendons and to bond it to the concrete. Also, safety precautions which should be observed during reinforcement detailing and stressing operations are provided in Part V, Section 11 and Part IX, Section 28.

2. BASIC PRINCIPLES OF PLAIN CONCRETE

2.1 GENERAL

Plain concrete is designed to be used in a structure without any form of reinforcement other than that required for transfer of loads across joints. Plain concrete is commonly used in 'on-ground' applications such as pavements, including bases, sub-bases or 'blinding layers' as well as wearing surfaces (**Figure I.2**).



Elements of a typical concrete industrial pavement

Figure I.2 – Pavement Construction and Load Transfer

The design of a pavement must include appropriate design of jointing detail and design of the thickness of the concrete base. This should be designed to maintain its integrity while transferring loads on the pavement to the sub-base and subgrade below it (**Figure I.2**).

Concrete used in plain concrete pavement is commonly specified by performance properties including compressive strength grade, flexural tensile strength and maximum drying shrinkage. Other prescriptive properties may be included in the concrete mix design such as maximum size of aggregate and total coarse/fine aggregate grading limits, where the design of the transfer of loads across joints is totally reliant on aggregate interlock.

2.2 TYPES OF STRESSES

The types of stresses that occur in plain concrete are dependent on the structure being designed. In pavements, the key stresses relate to loading. A load on the surface of a plain concrete rigid pavement induces compressive stresses in the top surface as well as tensile stresses in the lower surface if the concrete is placed on a flexible sub-base and sub-grade (see **Figure I.3**). The magnitude of these stresses is dependent, in part, on the thickness of the plain concrete pavement and also on the properties of the sub-base and sub-grade.

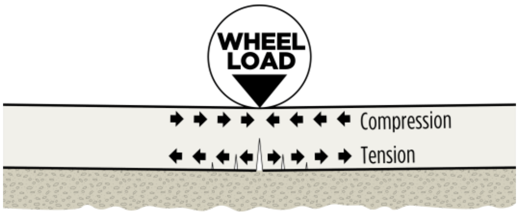


Figure I.3 – Pavement Loading

Much of the strength of a plain concrete pavement is dependent on the properties of sub-base and subgrade supporting the pavement. The principle property of the subgrade and sub-base are their combined elastic modulus (often represented as 'modulus of sub-grade reaction' and used in pavement design). The elastic modulus of subgrade materials is directly related to the modulus of subgrade reaction and is also related to a commonly measured and specified value of the sub-grade known as the California Bearing Ratio (or CBR). A representation of this relationship is indicated in **Figure I.4** [derived from Putri et al].

The other key location where stresses in plain concrete pavements must be considered are at the joints in the pavement base. If the joint is working correctly, it limits differential movement in the vertical direction between jointed slab segments while allowing some limited movement in the horizontal direction. To do this the impact of a vertical load on a slab needs to be restrained by shear force transfer across the joint in the vertical direction (see **Figure I.5**).

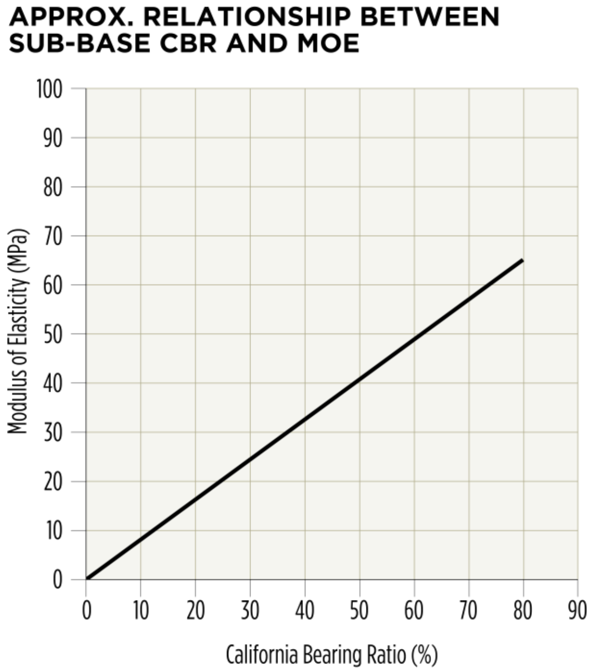


Figure I.4 – The Approximate Relationship between Granular Sub-Grade and Sub-Base CBR with Elastic Modulus

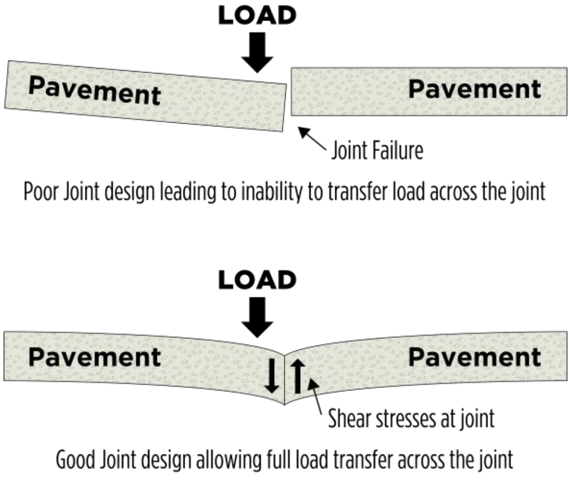
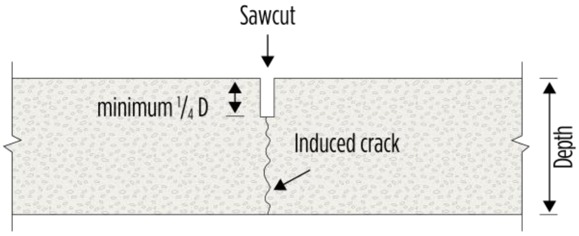


Figure I.5 – Shear Stresses are Controlled at the Joint to Prevent Failure

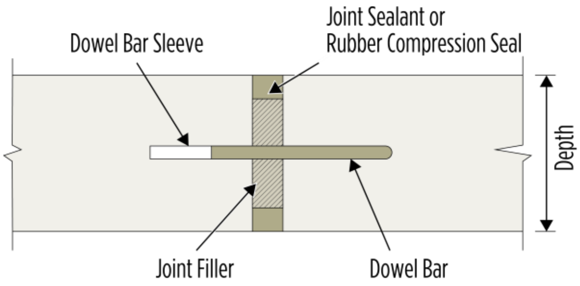
Figure I.5 shows the idealised load transfer between jointed segments of an unreinforced pavement. Joints should allow for concrete dimensional change caused by shrinkage and thermal expansion/contraction without allowing differential vertical movement between two pavement segments under applied loads. There are various methods used to allow joints to perform the function and some of the common joint designs include:

- Saw cut and tooled contraction joints;
- Dowel joints;
- Key joints.

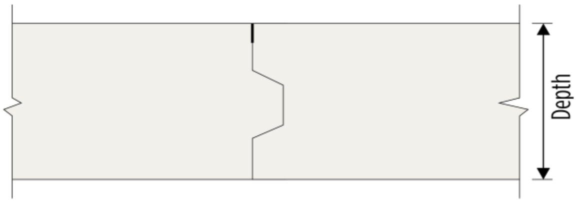
These three common joint methods are described in **Figure I.6**. Other less common methods are not discussed here, but are detailed in Part V, Section 17 of this Guide.



SAWED CONTRACTION JOINT



DOWEL JOINT



KEY JOINT

Figure I.6 – Common Pavement Joint Details

Saw Cut Joints – The purpose of saw cut joints is to restrain differential vertical and horizontal movements in the same direction as the joint but allow limited horizontal movement perpendicular to the plane of the joint. Saw cut joints rely on aggregate interlock in the cracked section below the saw cut (cut to a minimum of one quarter of the slab depth) to transfer load across the joint. The effectiveness of this form of joint is dependent on the joint opening, maximum aggregate size and distribution of coarse aggregate in the concrete mix. If the joint opening is too great, the load transfer may become ineffective leading to failure of the joint. This type of joint is common in lightly loaded pavements such as footpaths. With careful design and construction, sawn joints can be used in road and aircraft pavements.

Dowel Joints – The purpose of dowel joints is to restrain differential vertical and horizontal movements in the same direction as the joint but allow horizontal movement perpendicular to the plane of the joint. Dowel joints are often used for interior industrial pavements and commonly in conjunction with key joints. In this case dowel joints may be used in the longer direction of a jointed segment and key joints in the narrower direction. It is critical that dowels are placed accurately and perpendicular to the joint direction.

Key Joints – The purpose of key joints is to restrain differential vertical movements in the same direction as the joint but allow horizontal movement perpendicular to the plane of the joint as well as allowing horizontal movement in the plane of the joint. Key joint effectiveness diminishes as the joint opens. Care is required in design using key joints where a greater joint opening is expected (higher shrinkage or thermal movement).

2.3 PROPERTIES OF PLAIN CONCRETE

The key properties of un-reinforced (plain) concrete are noted in **Table I.1**. These are relatively high compressive strength, low tensile strength and relatively high fire resistance. It should be noted that concrete has low shear strength in comparison to steel but has a moderately high abrasion resistance depending on its compressive strength grade. This supports a view that plain concrete is best suited for purposes where it is not required to rely heavily on its tensile or shear strength and uses such as concrete pavements are a good fit for these properties provided that the sub-grade and sub-base are sufficiently high modulus of elasticity to provide support to the concrete pavement. In addition to this, the pavement joint spacing needs to be sufficiently low (a maximum of 25 to 30 times the pavement thickness is recommended) to aid control of early cracking between joints and the concrete strength and pavement depth sufficiently high to ensure that tensile stress levels are under the specified maximum tensile strength of the concrete.

2.4 APPLICATIONS OF PLAIN CONCRETE

The quantity of concrete used in plain concrete structures is quite high but is still economical in certain applications. Some common applications are listed below:

- Concrete road pavements;
- Aircraft pavements;
- Industrial pavements (interior);
- ‘Blinding Layers’ over subgrade as a working platform for further concrete pavement construction;
- Sub-base for unreinforced concrete highway construction;
- High or low strength fill where washout resistance greater than that of granular road-base is required;
- Gravity dam construction and roller compacted concrete construction more generally.

3. BASIC PRINCIPLES OF REINFORCED CONCRETE

3.1 GENERAL

Whilst the behaviour of reinforced concrete is actually quite complex, for practical purposes we can assume that steel and concrete can combine to act compositely for the following reasons:

- Upon hardening, concrete bonds firmly to steel reinforcement so that, when loads are applied, the two act as though they are one. The tensile forces are carried by the reinforcement and the tensile contribution from the concrete is ignored;
- When subjected to changes in temperature, concrete and steel expand or contract by similar amounts. They therefore remain firmly bonded and continue to act compositely;
- Concrete, having a relatively high resistance to fire, and a relatively low thermal conductivity, protects the embedded steel reinforcement with low fire resistance, thereby substantially increasing the time taken for the temperature of the reinforcement to rise to a level where there is a substantial loss of strength;
- Concrete provides an alkaline environment for steel embedded in it. This protects the steel from corrosion and, because concrete is relatively inert to chemicals other than acids, it continues to do so for long periods of time in all but very hostile environments.

The key aims of a designer of reinforced concrete are:

- To be able to determine the amount and the location of reinforcement so that it resists the stresses which develop in the concrete under load;
- To ensure that the steel has a sufficient layer of an appropriate quality of concrete covering it to protect it from the environment to which it might otherwise be exposed;
- To ensure that the steel has a sufficient layer of the appropriate quality of concrete around it to protect it against fire.

3.2 TYPES OF STRESSES

The principal types of stresses that develop in structural elements or members, illustrated in **Figure I.7**, are:

- Compressive stresses – those which tend to cause the member to compact and crush;
- Tensile stresses – those which tend to cause the member to stretch and crack; and
- Shear stresses – those which tend to cause adjacent portions of the member

to slide across each other.

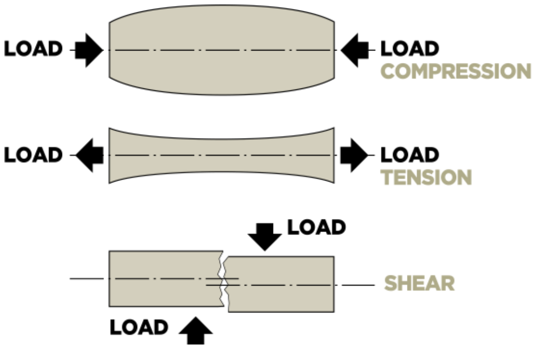


Figure I.7 – Types of Stresses

It is very rare that there is only one of these types of stresses found in a structural member. Generally, some combination of compressive, tensile and shear stresses will be encountered, and it is the job of the designer to determine these and locate the appropriate amount of reinforcement necessary to resist this combination of stresses.

Whilst shear stresses can be quite complex in the way in which they act and react, two principal types can be distinguished – vertical and horizontal.

Vertical shear stresses occur, for example, near the end supports of beams but are less near the centre of the beam where the vertical shear forces are more in balance **Figure I.8**.

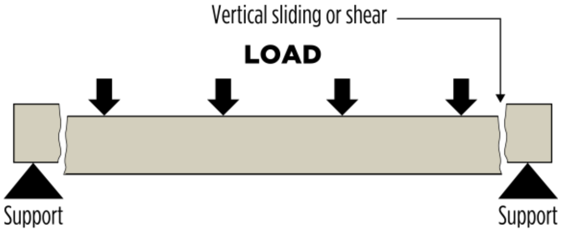


Figure I.8 – Vertical Shear Stresses

Horizontal shear stresses occur as the beam bends and the (imaginary) horizontal layers within it will try to slide over one another **Figure I.9**.

When vertical and horizontal shear stresses react with one another, they produce what is known as diagonal tension which, in turn, tends to produce diagonal cracking. This is illustrated in **Figure I.10** and commonly occurs near the ends of heavily loaded beams.

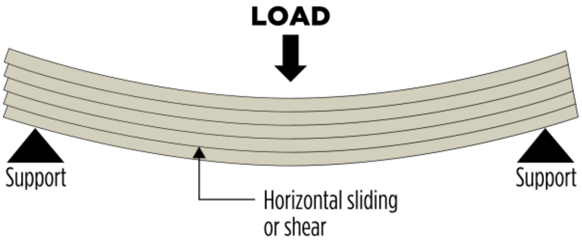


Figure I.9 Horizontal Shear Stresses

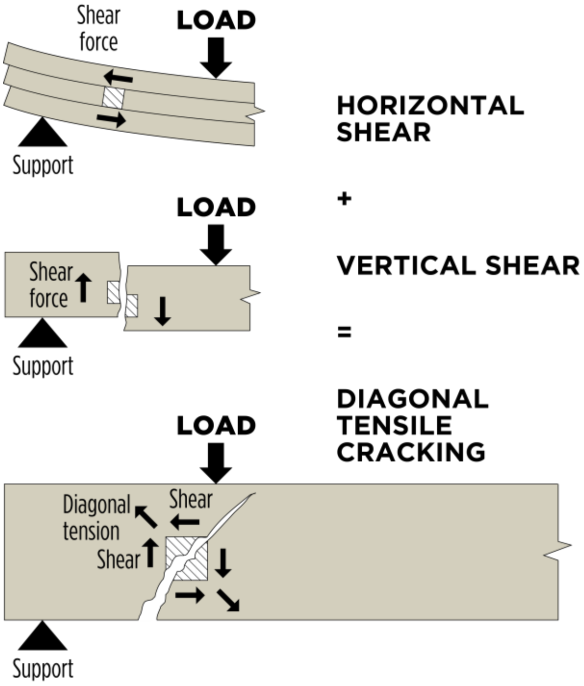


Figure I.10 – Diagonal Tension Cracks

To resist such cracking, reinforcement must be provided. This is done commonly by providing stirrups or, on occasions, cranking the horizontal reinforcement **Figure I.11**. The spacing between stirrups is closer near the supports and increases as the distance from the end of the beam increases.

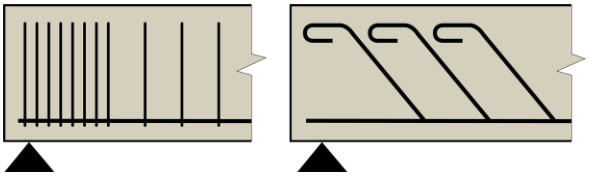


Figure I.11 – Reinforcement to Resist Diagonal Tension

3.3 STRESSES FOUND IN STRUCTURAL MEMBERS

Simply-Supported Beams and Slabs – A simply-supported reinforced concrete beam under load is shown in **Figure 1.12**. When such a beam is loaded, either by a central point load or a uniformly distributed load along its length, it tends to sag or deflect downwards. This causes the top of the beam to compress and the bottom of the beam to stretch and go into tension. Reinforcement is placed in the bottom of the beam to resist the tensile stresses. Compressive reinforcement will not normally be required in the top of the beam due to high compressive strength of the concrete. The tensile stresses in the bottom of the beam induce tension in the reinforcement and cracking in the concrete. Overloads will cause the reinforcement to elongate further and further cracking to occur, until, under severe overload, the beam will fail.

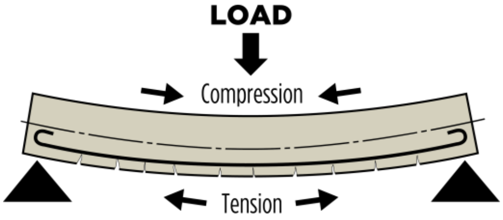


Figure I.12 – Simply Supported Beams or Slabs

Simple Cantilevers – When a simple cantilever beam or slab is loaded, it tends to droop or deflect as shown in **Figure I.13**. Tensile stresses occur in the top of the beam or slab and compressive stresses in the bottom. In this case, therefore, the reinforcement is placed in the top of the beam.

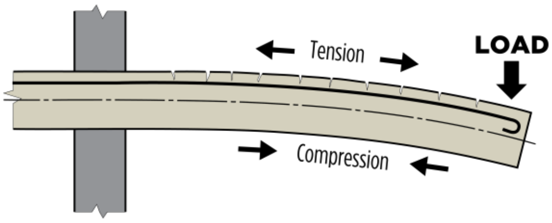


Figure I.13 – Simple Cantilever Beams or Slabs

Fixed-Ended Beams – When a beam which is fixed at both ends is loaded it tends to bend as illustrated in **Figure I.14**. Tension will again occur in the bottom of the beam and in this case also in the top of the beam close to the supports. Reinforcement must be placed in the top near the supports and in the bottom across the centre.

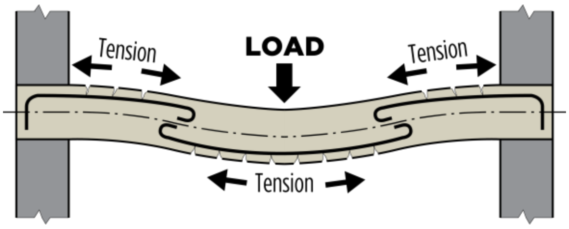


Figure I.14 – Fixed-Ended Beams or Slabs

Multi-Span Beams and Slabs – As may be seen in **Figure I.15**, beams which span between more than two supports tend to flex or bend over the intermediate supports, necessitating reinforcement in the top of the beam at these points. They sag or deflect between supports, necessitating bottom reinforcement in the beam at these points.

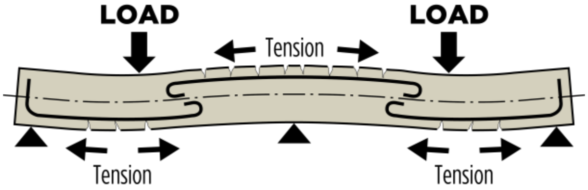


Figure I.15 – Multi-Span Beams or Slabs

Retaining Walls – Retaining walls may be likened to a vertical beam which is fixed at one end. The earth, or other material being retained, then causes the wall to act as a cantilever. However, in this case, the footing of the wall is also involved and it tends to bend or distort as load is applied. The resultant stresses are illustrated in **Figure I.16** which also shows how the reinforcement would be distributed to resist these stresses.

Columns – Whilst columns are designed primarily to support axial loads, bending moments are invariably introduced by uneven or eccentric distribution of the loads. Columns also tend to buckle, this tendency being a function of their slenderness. Tall, thin columns are more prone to this than are short, stocky columns.

All columns will require some reinforcement to resist these tendencies. Since, in practice, the load distribution on a column may change during its service life, it is normal to provide this reinforcement on all faces of a column to ensure that it remains safe (i.e. able to carry its loads), no matter how the distribution of the loads may change. This reinforcement also contributes to the ability of the column to carry axial compression loads.

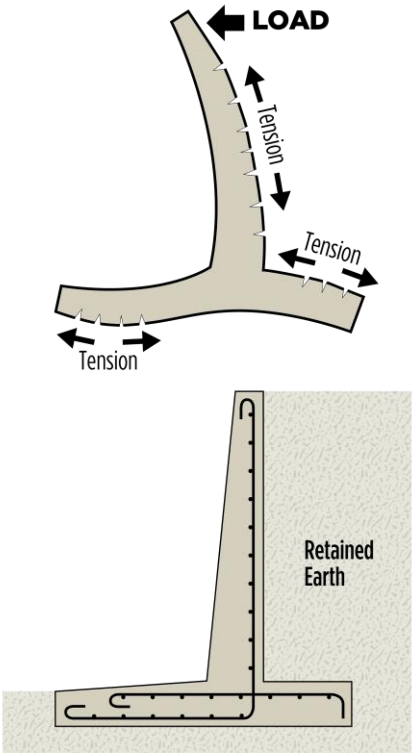


Figure I.16 – Retaining Walls

This is illustrated in **Figure I.17** which shows a column supporting a series of beams. As may be readily imagined, the loads on this column could change quite significantly as the loads on the beams change. Hence the column could tend to bend in any direction.

To resist the tensile stresses caused by bending in a column, vertical reinforcement is placed in the outer faces. This is illustrated in **Figure I.18**. In addition, stirrups or ties are used to:

- Help prevent lateral bursting of the column under axial loads;
- Restrain the longitudinal reinforcement from buckling; and
- Hold the main reinforcement firmly in place during concreting.

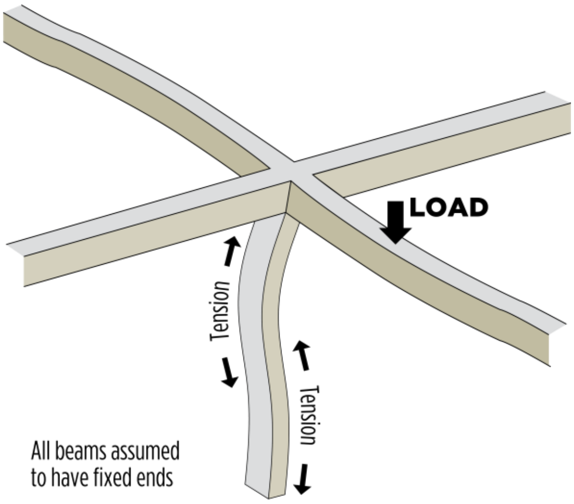


Figure I.17 – Stresses in Columns

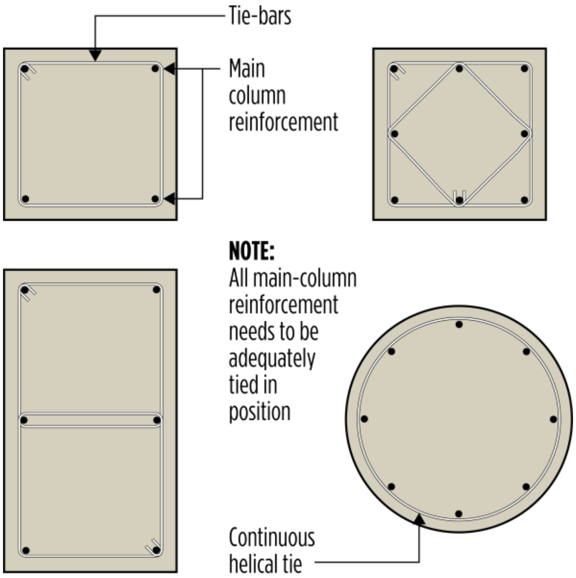


Figure I.18 – Typical Arrangement of Column Reinforcement

3.4 BOND AND ANCHORAGE

As has been noted already, steel and concrete act compositely when they are firmly bonded together. The strength of this bond is an important consideration in the design of reinforced concrete. It is dependent on the concrete being thoroughly compacted around the reinforcement and on the latter being clean and free of loose scale, rust or other material. Formwork oil, for example, will destroy the bond between steel and concrete. The bond may be increased by the use of higher strength concrete or by the use of deformed reinforcing bars. These ribs or deformations rolled onto the bar surface results in the bond with concrete being increased. AS 3600 requires that all reinforcement except that for fitments be deformed bars, see **Figure I.19**.

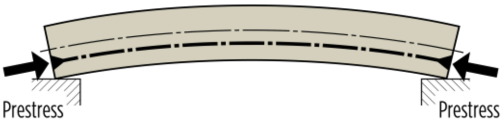
Figure I.19 – Typical 500-MPa Deformed Bar

To ensure that adequate anchorage is achieved in the reinforcement, it is normally extended beyond the region of tensile stress for a sufficient length so that the bond between the reinforcement and the concrete can develop the tensile stress required at that point in the bar. Where this is not possible for some reason, or as an additional safety factor, bends or hooks in reinforcement are often used to provide the anchorage required.

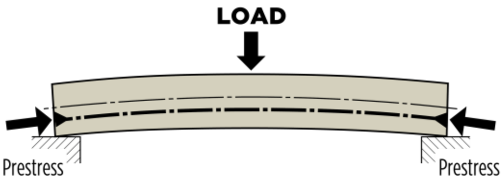
4. BASIC PRINCIPLES OF PRESTRESSED CONCRETE

4.1 GENERAL

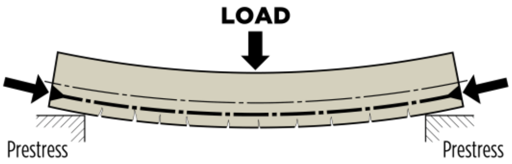
The action of a simply-supported reinforced concrete beam under load is described in sub-section 3.3 and shown in **Figure I.12**. In a simply-supported prestressed concrete beam, the application of the prestress normally results in a small upward camber or deflection of the beam as the concrete, on its underside, compresses under the action of the prestress (**Figure I.20(a)**). When an external load is then applied, the beam deflects or moves downwards, negating (or neutralising) the upward camber (**Figure I.20(b)**). If an overload is applied, the beam will deflect still further and commence to behave in the same way as a reinforced beam. Tensile stresses will occur in the concrete and cracking will result (**Figure I.20(c)**). Severe overloads will cause the beam to fail as the steel is stretched beyond its ultimate limit.



(A) Prestressed concrete beam not under external load



(B) Prestressed concrete beam under external load



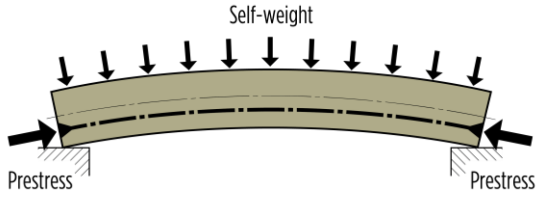
(C) Prestressed concrete beam under moderate overload

Figure I.20 – Simply Supported Prestressed Concrete Beam under Load

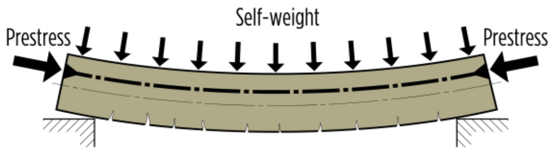
There are a number of special features about the behaviour of prestressed concrete beams (and columns) that should be noted:

- The positioning of the prestressing tendons within a member is very important. Because of the magnitude of the forces involved, minor changes in the location of tendons can have severe consequences. For example, in the beam shown in **Figures I.20(a)** and **I.20(b)**, location of the prestressing tendons closer to the bottom than was intended would cause an increased upward camber on the beam which may be unacceptable, and could even cause tension cracks to open in the top surface, which could be deleterious to the long-term durability of the beam;

- The magnitudes of the stresses in a prestressed member are such that when it is precast it must be handled with considerable care. For example, the self-weight of a correctly positioned prestressed beam will tend to counteract the camber or upwards deflection (**Figure I.21(a)**). Placing a beam in an upside-down position (not unknown) will accentuate the deflection or camber and may even cause the beam to fail (**Figure I.21(b)**). Attempting to lift a beam by other than its designated lifting points may have similar consequences.



(A) Precast prestressed beam correct way up



(B) Precast prestressed beam wrong way up

Figure I.21 – Position of a Precast Prestressed Concrete Beam

4.2 PRE-TENSIONING

In a pre-tensioned member, tendons are first carefully positioned within the formwork and the design load or tension is applied to them. Then, whilst tensioned, the concrete is cast around them and allowed to harden until it achieves sufficient strength (usually 32 MPa or higher) to resist the forces to be applied to it. The ends of steel tendons are then released from their restraints and the stress is transferred to the concrete by the bond between the two materials.

The tendons used in pre-tensioning are usually in the form of small-diameter wires or strands (a combination of smaller wires – **Figure I.22**). The diameters of these materials are kept small to increase the surface area available for bonding with the concrete. Indented wire is also commonly used to further increase bond.

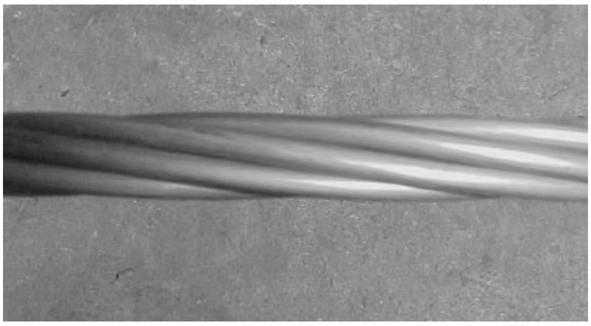


Figure I.22 – Prestressing Strand and Wire

4.3 POST-TENSIONING

When a member is to be post-tensioned, the concrete is first allowed to harden before the steel tendons are stretched or tensioned. They cannot therefore be allowed to bond with the concrete, at least not initially. Usually they are placed in ducts or holes which have been cast in the concrete, although sometimes they are greased and encased in a plastic tube to prevent bond. In other cases, the tendons are fixed to the outside faces of the member.

After the concrete has gained sufficient strength, the wires or cables are tensioned and then fixed or anchored in special fittings cast into the ends of the concrete member. A wide variety of patented fittings and systems are available for this purpose. Typical slab and beam anchorages are shown in **Figures I.23** and **I.24** respectively.

Figure I.23 – Typical Slab Anchorage

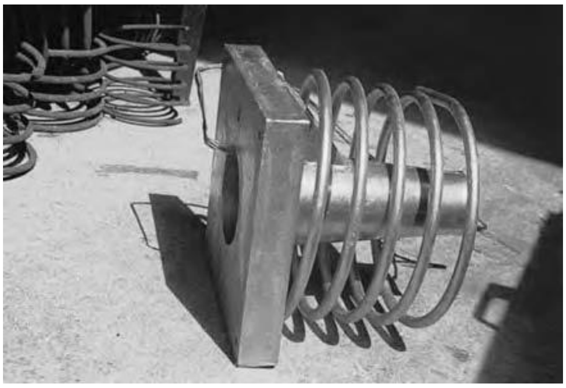


Figure I.24 – Typical Beam Anchorage

4.4 APPLICATIONS

Although both pre-tensioning and post-tensioning systems are designed to apply prestress to concrete members, there are some practical differences in their fields of application. Pre-tensioning is normally confined to the factory production of repetitive units where the cost of the relatively large abutments or restraints, against which the prestressing jacks operate, can be justified. Alternatively, very strong and robust formwork may be constructed and wires are anchored against its ends.

Post-tensioning is more flexible in its application and may be carried out on-site. It permits the use of curved tendon profiles and is also suited to a wide variety of construction techniques, such as 'segmental construction' and 'stage stressing'. Since stressing is not carried out until the concrete has hardened, the concrete member itself provides the restraint against which the stressing jacks operate (**Figure I.25**).

Figure I.25 – Post-Tensioning Jack Operating at an End of a Concrete Girder

5. BASIC PRINCIPLES OF FIBRE REINFORCED CONCRETE

5.1 TYPES OF FIBRES

Another form of reinforcement of concrete is available with the use of fibres. The more common forms of fibres currently available are discussed in this section but it must be noted that new forms of fibres, including variations in material used to manufacture the fibre, shape and size are being developed all the time.

The common broad material types used in fibres are summarised below:

- Steel;
- Synthetic/Polymer;
- Glass;
- Carbon;
- Natural.

Each of these materials will produce varying properties to the concrete. In addition, the characteristics of fibre reinforced concrete change with varying concretes, fibre materials, shape, size and dose rate.

Steel fibres are the most commonly used fibres for increasing the strength of concrete elements and therefore are described by shape, aspect ratio, length and tensile strength. Some typical shapes for steel fibres are shown in **Figure I.26**.

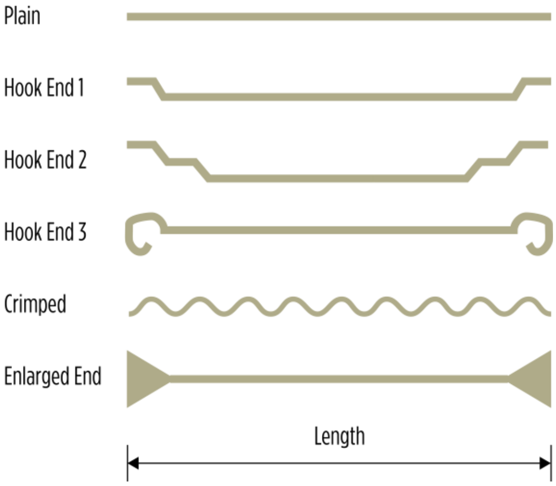


Figure I.26 – Some Common Steel Fibre Shapes

The aspect ratio of a fibre is defined as the length of the fibre divided by the average cross section diameter of the fibre. Steel fibre tensile strength typically ranges between 800 MPa and 2000 MPa. Each fibre type and source have a typical design tensile strength measured in accordance with Eurocode or ASTM standards (e.g. ASTM A820 or EN 14889-1). The steel fibre tensile strength, aspect ratio, length and shape all impact on the final concrete hardened properties containing these fibres.

Synthetic fibres have been largely composed of polypropylene or nylon but newer fibres are being developed from other materials such as recycled waste. Fibres may contain polyolefin varieties such as polypropylene or polyethylene terephthalate and other suitable plastics. Synthetic fibres are commonly used to resist spalling of concrete during a fire.

Synthetic fibres come in two main groups:

- Macro Synthetic (also known as Structural Synthetic);
- Micro Synthetic.

Macro synthetic fibres are made from a number of polymers and were originally developed to provide an alternative to steel fibres in some applications. They generally have a high tensile strength and a moderate modulus of elasticity. Unlike polypropylene micro synthetic fibres, they can significantly increase the post-cracking capacity of concrete. The properties of Macro and Micro Synthetic fibres are provided by EN 148892. Macro synthetic fibres come in varying lengths, aspect ratios and degree of surface texture to aid shear connection to the concrete.

Micro synthetic fibres are commonly produced from polypropylene. There are two forms of these fibres:

- Monofilament;
- Fibrillated.

Monofilament fibres are defined by length (typically 20 mm to 60 mm) and generally have diameters of 0.05 mm to 0.3 mm. These fibres are not considered replacement of steel fibres or macro synthetic fibres but have beneficial properties when correctly used in concrete. Some of these properties include reduction of plastic cracking in concrete, some reduction of spalling of concrete subjected to fire and improved impact resistance of concrete.

Fibrillated fibres are defined by length (typically 6 mm to 15 mm) and generally have diameters of 0.030 mm to 0.040 mm. These are beneficial to concrete when correctly used. Some of these properties include reduction of plastic cracking in concrete and significant reduction of spalling of concrete subjected to fire when used at the correct dose rate.

Glass fibres for concrete are generally composed of alkali resistant glass. Glass fibres have been more commonly used in the production of thin lightweight precast panels. In this application higher additions of glass fibre improve the tensile strength and toughness of the panels.

Natural fibres and carbon fibres are less commonly used. Natural fibres may include basalt fibres and various types of plant sourced fibres. Asbestos fibres are also a natural fibre but are no longer used due to safety concerns.

Other types of fibres noted have their own specific properties and impacts on concrete. In all cases the supplier’s information on their correct use must be considered before they are specified.

5.2 ACTION OF FIBRES IN CONCRETE

All fibre types can be used in conjunction with standard steel reinforcement to improve the structural and durability performance of a concrete member. It is possible that some varieties of fibre when used in the correct applications can be the only reinforcement in concrete.

Plain concrete generally shows brittle behaviour leading to failure after the first tensile stress crack is formed under load. This property of plain concrete can be enhanced in some applications by using suitable fibres to provide a more ductile behaviour under load.

Steel fibres and some structural synthetic fibres can provide useful tensile restraint and aid more ductile behaviour of loaded structures post cracking. This behaviour is discussed in AS 3600 and reference is made to the residual flexural tensile strength test per Euro standard EN 14651. **Figure I.27** is used in

AS 3600 and EN 14651 to demonstrate the relationship between the load supported by the test beam at various crack opening values (crack mouth opening displacement or ‘CMOD’).

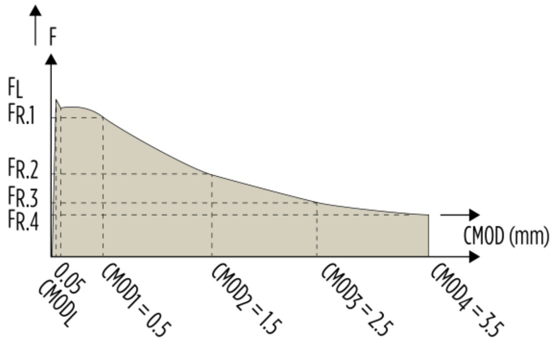


Figure I.27 – Load Versus CMOD for Residual Flexural Tension

Most types of fibres will reduce the likelihood of plastic cracking in concrete. Their performance at doing this is dependent on the individual product dose rate used. The dose rate for a specific fibre must be discussed with the fibre supplier.

The drying shrinkage of concrete can be reduced through use of steel fibres. In this case optimising the combination of steel fibre dose rate in concrete requires coordination with the concrete mix to achieve suitable workability with this dose rate of fibre.

Steel fibres, macro synthetic fibres and some specific micro synthetic fibres have proven to be useful for improving the impact resistance and abrasion resistance of concrete.

Specific types of micro synthetic fibres have proven very useful in reducing or eliminating spalling of concrete under aggressive fire testing. The concrete mixture should be assessed for performance in a fire to ensure that the correct dose of fibres is used where spalling mitigation is required. Fire testing is carried out in accordance with AS 1530.4.

Significant local and international research into the performance of steel fibres in providing enhancement to the shear resistance of concrete is being carried out. The result of some of this research is reflected in AS 3600. In AS 3600 a design value of the steel fibre impact on shear resistance of a reinforced concrete member is estimated based on the steel fibre component of the concrete.

In all cases the degree of benefit provided by an individual fibre needs to be assessed and will depend on using an adequate dose of fibres to achieve the targeted enhancement.

5.3 APPLICATIONS FOR FIBRES IN CONCRETE

Fibre reinforced concrete is used in structures with or without the addition of conventional forms of post-tensioning, bar reinforcement or reinforcing mesh. The type of fibres used will depend on the benefit being sought and the economics of the solution.

Common structures that use fibres as part of the concrete reinforcement system in Australia include:

- Industrial pavements;
- Concrete road pavements and roundabouts;
- Precast concrete elements used in tunnel lining;
- Underground shotcrete in tunnel and underground mining applications;
- Sprayed concrete swimming pools in stable foundations;
- Sprayed embankment stabilisation;
- Footpaths and driveways;
- Concrete road barriers;
- Concrete elements where resistance to spalling in a fire is critical.

6. REFERENCES

1) AS 3600 – *Concrete structures*
2) AS 5100.5 – *Bridge design – Concrete*
3) AS 1379 – *Specification and Supply of Concrete*
4) AS 1530.4 – *Methods for fire tests on building materials, components and structures. Fire-resistance tests for elements of construction*
5) EN 14651:2005+A1:2007 – *Test method for metallic fibre concrete. Measuring the flexural tensile strength (limit of proportionality (LOP), residual*
6) EN 14889-1 – *Fibres for concrete, Part 1: Steel fibres definitions, specifications and conformity*
7) EN 14889-2 – *Fibres for concrete, Part 2: Polymer fibres – Definitions, specifications and conformity*
8) ASTM A820 – *Standard Specification for Steel Fibers for Fiber-Reinforced Concrete*
9) ASTM C1116 – *Standard Specification for Fiber-Reinforced Concrete*
10) ASTM D7508 – *Standard Specification for Polyolefin Chopped Strands for Use in Concrete*
11) Putri EE, Kameswara Rao NSV & Mannan MA, *'Evaluation of modulus of elasticity and modulus of subgrade reaction of soils using CBR test'*, Journal of Civil Engineering Research (2012)

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