CHAPTER 1

Engineering Application Module 1 – Civil Structures

Historical and Societal Influences

Explanatory Note: The term civil structures relates to all engineered structures in our world. Due to the limited scope of this book it is impossible to look at the development of all civil structures, so bridges are the only ones considered.

Historical Developments in Civil Structures

The bridge is an important engineered structure. Transport would not have developed as easily without the development of the bridge. In the following section, bridges are grouped according to their design, and their development traced. There is an immense variety of bridges around the world and there is limited scope in this book to cover them, therefore only an overview of bridge development has been given.

Beam Bridges

The word beam comes from the Old English word for wood. A beam is simply a member that is supported in such a way that the supports do not carry any longitudinal forces. Beams may be loosely grouped into two types; if the beam is supported at both ends then it is a *simply supported beam*, whereas if it is only supported at one end it is a *cantilevered beam*. A beam may be wood, metal or stone. A beam does not have to be solid; it may be a tube, and a truss is a type of beam. Thus a variety of truss bridges fall under the category of beam bridges.

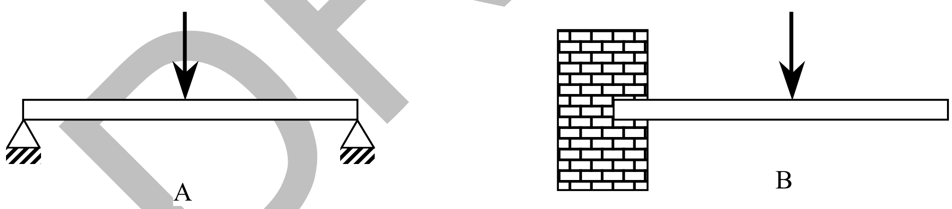


Fig. 1.1: *Two beams are shown above.* A *represents a simply supported beam with a single point load, while* B *represents a cantilever anchored to a wall with a single point load.*

The Greek historian Herodotus wrote of a multi-span beam bridge in Babylon (present day Iraq) in the 5th century BC. Each span was only 1.52 m long but a total length of 200 m was attained by having 100 stone piers, each linked by a separate beam.

Early beam bridges often used timber, but because timber rots and is attacked by borers and termites there are few left.

In 55 BC Julius Caesar built a 550 m long wooden beam bridge that incorporated 50 spans; construction took ten days.

By 1570, Italian architect, Andrea Palladio had developed a truss girder bridge. The idea had come from timber roof trusses used in Gothic churches. One of his timber trusses was used to span the River Cismone and it was approximately 30 m long.

Early in the 19th century, English engineer James Warren developed a truss girder bridge that would be extensively utilised by railway engineers. One example is the Crumlin Viaduct (1857) in South Wales. This carries the Taff Vale railway 67m above the River Ebbw over a span of 45.7 m.

It was in America, however, that the truss girder was developed to its modern day form. Engineer Ithiel Town developed a truss girder bridge with criss-cross diagonals in 1820. This was suitable for light road traffic but not sturdy enough for railways, which required the development of a truss, built up of triangles (the strongest geometric shape). Wooden trusses designed by William Howe (1840) and Caleb and Thomas Pratt (1844) fulfilled this requirement.

In 1847, Squire Whipple developed the iron truss, a design that carried on to the twentieth century. More importantly, he developed a way to determine the force in each member of the truss. Through mathematics, it was now possible to determine how to build safer and more cost effective bridges.

In 1849, the famous English engineer, Robert Stephenson, developed the Bowstring Girder. This consists of an arch (the bow) and a horizontal tie (the string) that constrains the bow from spreading. It is a beam and is used with a support at either end. This bridge, in Fig. 1.2, is like two Sydney Harbour Bridges, but unlike our famous landmark the bowstring girder, like all beams, does not place any lateral thrust on the supports. The Sydney Harbour Bridge, being an arch bridge, does. Stephenson designed the bowstring girder for his High-Level Bridge to cross the River Tyne at Newcastle. There are six spans, each 38 m long, with the roadway running under the railway.

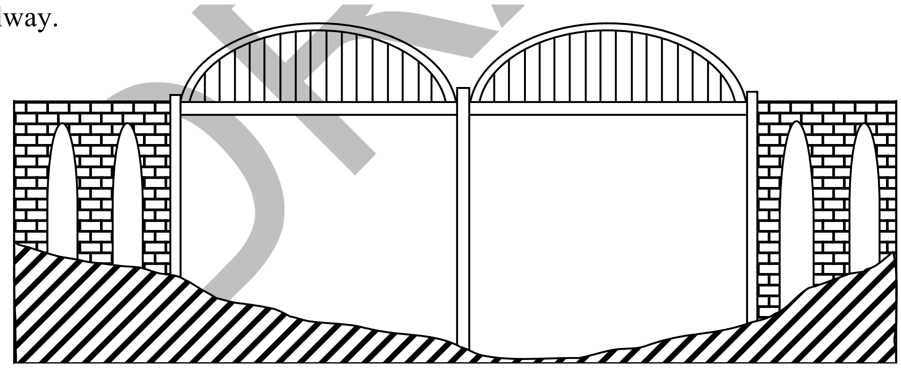


Fig. 1.2: *A bowstring girder (or tied arch). It may look like an arch bridge but the abutments carry no lateral thrust, only vertical forces.*

In 1850 Stephenson collaborated with others to complete another important type of beam bridge. The Admiralty had requested a high bridge that would not impede shipping. Suspension bridges had too much flex for railways, so Stephenson, Eaton Hodgkinson and Sir William Fairburn developed the Brittania Bridge. It carried the railway over the Menai Strait in North Wales, and consisted of rectangular wrought iron tubes, or tunnels, so that trains could run through them. The bridges consisted of two end spans each 70 m and two central spans each 140 m. The tubes were joined as they passed through the pylons, creating two tunnels, one for each track. One of the greatest problems with this structure was that the wrought iron plates that made up the tubes tended to buckle. Many models were made and tested until the cellular box beam was developed to alleviate this problem.

In 1867, Heinrich Gerber built the first balanced cantilever bridge over the River Main in Germany. The balanced cantilever consists of two side spans that extend past a central pylon to form cantilevers.

The first large-scale balanced cantilever bridge for rail was the Forth Bridge in Scotland. It has two main spans that are 521 m long (at the time the longest in the world) and overall the bridge is around 3.2 km long. It was completed in 1890 after a construction time of eight years. It consists of over 51,000 tonnes of steel. The main spans are constructed as a simply supported steel truss 106 m long, connecting the cantilevers.

In 1879 the Tay Bridge (on the same rail line as the Forth Bridge) was built. This consisted of 85 lattice girder spans creating a bridge over 3 km in length. The girders were supported by slender cast iron columns. The 13 central spans were termed ‘high girders’ because they were mounted above the railway line to provide clearance to shipping. In the last week of 1879 a train and the high girders were blown off into the river below. Investigations revealed that the designer, Sir Thomas Bouch, had not allowed enough tolerance for wind and that the columns and had been filled with substitutes, such as wax, to save on recasting. This incident is a good example of the responsibility that engineers have.

1948 saw the development of one of the most commonly used beam bridges today, the box girder bridge. This is a tube with a rectangular cross section stiffened by a series of internal walls, creating a box. Bridges may use a box girder on each edge of the roadway, or there may be a central girder with the roadway forming cantilevers on each side. Originally made of steel, box girders are now also made from reinforced or pre-stressed concrete.

Fig. 1.3: *Cars exiting the northern end of Tom Ugly’s Bridge over the Georges River (NSW). It utilises a truss style beam while the new bridge alongside uses box girder construction.*

After WWII most of the medium bridges (150-300 m span) in Germany and Austria had been destroyed. The steel box girder was the solution to this vast rebuilding project. Most road and freeway road bridges seen today utilise the box girder design.

Arch Bridges

The use of an arch for bridge construction dates back thousands of years. Nowadays the arch bridge may come in a variety of forms.

Masonry Arch Bridges

The Stone Arch bridge was extensively used by Roman engineers from 200 BC to 400 AD. The Romans built bridges that were to last for many years, and many still exist today.

The oldest Roman bridge is the Ponte Rotto in Rome. Built in 179 BC, it has since been rebuilt and altered. Another old Roman bridge is Ponte de Augusto at Rimini over the River Marecchia, built in 20 AD. The piers are squat. As the bridge was built, a pier would have an arch on one side only, so to stop the pier falling over it was enlarged in cross section. This problem was solved by building an arch on either side of the pier at the same time. In the building of aqueducts, the Romans learned to use lighter piers using this method

The biggest Roman bridge span was 42 m on a four span viaduct in Narni, on the Via Flaminia. They dammed the river to make construction easier.

After the fall of the Roman Empire in 400 AD, Europe entered the Dark Ages, a period of little learning. Much information on Roman technology and engineering was lost. Medieval bridges were not up to the standard of Roman bridges. London Bridge was typical of these. Built to replace a small timber bridge over the River Thames, it was completed in 1209 after 30 years of work. Its 276 m length consisted of 20 small spans of differing shapes and sizes ranging from 7.5 to 10.4 m in length. The bridge actually had houses built on it and it blocked three-quarters of the width of the River Thames. So great was the blockage that at half-tide there was a difference of 1.5 m in the water level on opposite sides of the bridge, causing a problem for navigation.

The Renaissance followed the Middle Ages. Learning and technological development began again. Bridge development started in earnest. Medieval bridges used pointed arches, which resulted in a lot of material between the arch and the roadway but Renaissance designers developed lower arches to alleviate this. A fine example of a low-rise Renaissance bridge is the Rialto Bridge in Venice, completed in 1591 after three years construction time.

Renaissance engineers further developed the low arch bridge to incorporate narrow piers and an arch with a small rise. Jean Perronet designed the Pont de la Concorde, completed in 1791 and still standing today. It consists of five, 31 m arches which only rise 4 m. Low arches place large loads on the piers but this is offset by the adjacent pier pushing in the opposite direction, but the load on the abutments is very high. This elegant bridge, however, with its narrow piers has a roadway level with the bank and only obscures 35% of the river.

If an arch bridge is to be built over a low bank river on flat ground, the challenge is to try to attain a very low rise. Jean Perronet achieved this, as did the English engineer Isambard Kingdom (I.K.) Brunel. He designed a brick arch bridge at Maidenhead to carry the Great Western Railway over the River Thames in 1837. Because of the low banks, the bridge was built with two 39 m spans with a rise of only 7.3 m. The public and pundits alike thought the bridge would collapse, and as a joke Brunel left the wooden supports in place to make people think the bridge needed them. After a year the supports were destroyed in a storm and, of course, the bridge remained in place.

Only then did Brunel explain that the supports had been clear of the bridge for most of the time. The bridge still stands today, carrying far heavier loads than Brunel ever envisaged.

Fig 1.4: *The Richmond Bridge in Tasmania is the oldest bridge in Australia; it is a sandstone arch bridge. (http://en.wikipedia.org/wiki/File:Richmond_Bridge_Panorama_Restitch.jpg)*

Cast Iron Arch Bridges

Although some societies had entered the Iron Age about 1500 BC, European civilisations could not yet melt iron and cast it. The Chinese could in 600 BC, but Europe didn't achieve this feat until the 14th century. Cast iron was not widely used until the Industrial Revolution, which commenced around 1750.

Cast iron has similar properties to stone. It is strong in compression and, although weak in tension, it can be cast as an open frame thus reducing weight over a similar size stone block. It is cheaper to cast iron than to carve stone.

The first cast iron bridge was the Coalbrookdale Bridge built over the River Severn at Shropshire in 1779. It consists of five cast iron ribs, forming a 30m semi-circular arch. Interestingly, it used joining methods now more often associated with woodworking. Joints were constructed using tenons and dovetails, as new technology for joining cast iron was not yet developed. Steel was not used, as it was not yet cheaply made.

Thomas Telford built a cast iron bridge over the same river at Buildwas in 1796. This bridge, which had a span of 40m, used a segmental arch and used half the iron of the Coalbrookdale Bridge.

Steel Arch Bridges

The first noteworthy steel arch bridge was the St Louis Bridge, which crosses the Mississippi River. Designed by James Eads, it was completed in 1874. Steel was now a viable bridge material thanks to Henry Bessemer's converter developed in 1856, which produced relatively cheap steel in large quantities. Ead's bridge consists of three arches, each with a span of 152m, with a railway running over the arches and a roadway running over the railway. Eads devised special caissons or devices used to sink piers to the river bed without damming the whole river, to reach the bedrock 40m below the river level.

The Hells Gate Bridge, completed in 1917, crosses East river at New York. It has a suspended roadway, which means that the roadway does not travel over the arch but is actually suspended under it. Suspended roadway arch bridges look similar to bowstring girder bridges but differ because an arch bridge pushes horizontally as well as vertically on the supports, whereas the bowstring girder supports only carry vertical loads.

The Hells Gate Bridge is a railway bridge carrying four railway lines over a span of 298m connecting the New York, New Haven, Harrford and Pennsylvania Railroads.

The most famous Australian bridge, the Sydney Harbour Bridge, was commenced in 1924 and completed in 1932. This bridge finally linked the North Shore with Sydney City. The span of the bridge is 503m, making it longer than Hells Gate Bridge. It is also wider, carrying 8 traffic lanes, two railway lines and 2 footpaths, with a total deck width of 49m. It was built from either side of the harbour while anchored to the shore, finally meeting in the middle at a pin joint. It is long enough to cross the Mississippi at St Louis in one single span, as opposed to three spans for the St Louis Bridge.

The Sydney Harbour Bridge is not the largest span steel arch bridge. That honour goes to the Bayonne Bridge in New York, deliberately built 600mm longer, to out do the Sydney bridge. It, however, only carries traffic lanes.

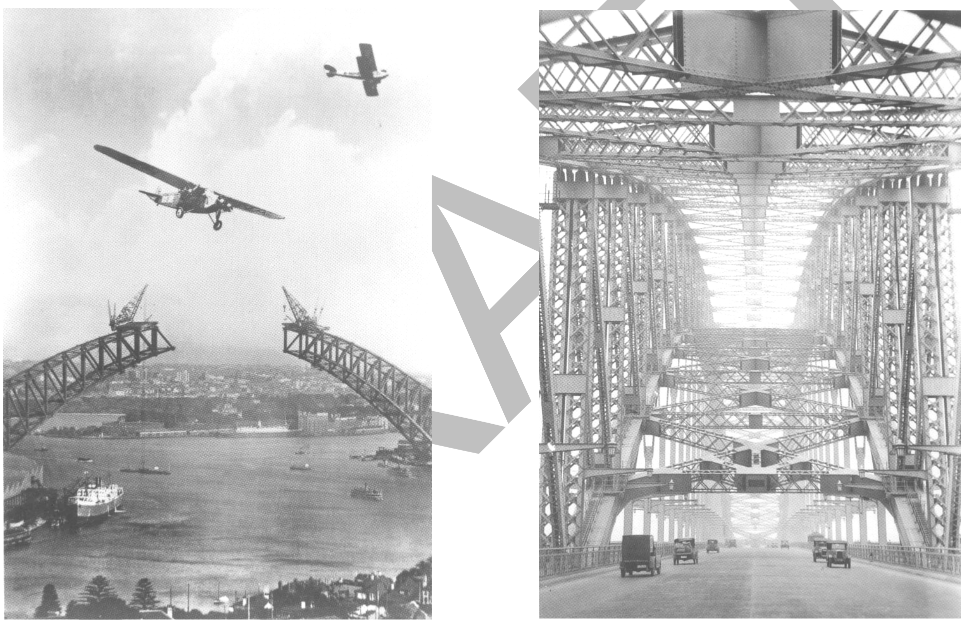


Fig 1.5: *The Sydney Harbour Bridge; left, during construction and right, the day after the 1932 opening. (Photographs reproduced with permission, State Library of NSW).*

Concrete Arch Bridges

Concrete is now the most commonly used material in bridge design. It is very strong in compression so it is ideal for an arch. With steel reinforcing, it is suitable for beam or cantilever use. Concrete, however, is subject to shrinkage. As a concrete bridge sets (this can take a whole year) the bridge shrinks and without some compensatory feature to deal with this it may crack and fail. The solution is a third hinge. Most steel arches are continuous throughout with a hinge at each end. Robert Maillart, a Swiss engineer, was the first to realise the possibility of the third hinge in the centre of the bridge to allow for shrinkage. In 1901 his first three-hinged, reinforced concrete bridge was built over the River Inn in Switzerland.

In 1904, Eugene Freyssinet came up with the idea of pre-stressed concrete but could not manufacture it until high tensile steel wire was developed after World War II. Then he designed five bridges over the River Marne in France at Esbly, Annet, Tribardos, Changis and Ussey. They are flat arches with a span of 74m.

To achieve the required strength, pre-stressed, concrete ducts were run through the lower arches. These had wires passed through them which were pulled tight after the arch was constructed. The compression greatly enhanced the strength of the bridge and reduced the probability of tensile failure.

The Gladesville Bridge, built in 1966 in Sydney, is a good example of a concrete arch bridge.

Suspension Bridges

Suspension bridges support the deck (roadway, railway) on steel cables strung between support towers. The cables are in tension. Since tension members do not buckle they can be thin and thus light, offering lightweight and longer spans than other types of bridges.

In the Stone Age, before 4000 BC, suspension bridges were simply built by having tension members, vines or creepers, slung across a river or ravine with wooden slats connecting the two to form a walkway. Many movies have featured adventures on these primitive suspension bridges over steep ravines.

The oldest suspension bridges are in China. One in the Yunnan Province, built in 1470, with a span of 69 metres, uses wrought iron chains. In Europe wrought iron was not available in commercial quantities until the 19th century, when the modern suspension bridge started to develop.

Early suspension bridge designs suffered from a lack of lateral stability. The remedy for this was to use a stiffened deck hanging from the suspension cables with wire ropes. To produce a horizontal deck the cables ran over two towers and were anchored at their ends. The Austrian Bishop, Fausto Veranzio proposed this design in 1595, but it was James Finlay, of Pennsylvania, who in 1801 built such a bridge. It was only 21.3 m long.

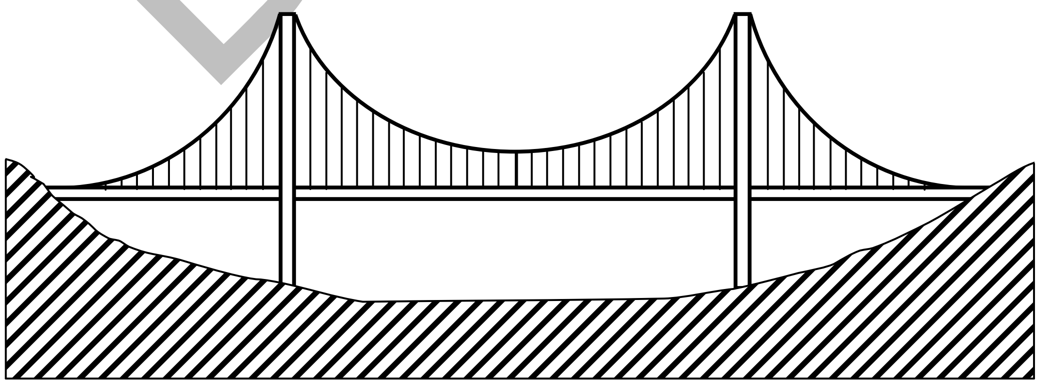


Fig 1.6: *The basic form of the suspension bridge devised by James Finlay.*

Thomas Telford produced the first successful large-scale suspension bridge; the Menai Strait Bridge, completed in 1826 in Wales. The towers were 47 m high, and the 16 chains that comprised the suspension members were made of wrought iron. These chains consisted of 3 m bars linked by 75mm diameter pins. The chains were dipped in linseed oil to preserve them. The 9 m roadway was timber, 176.5 m long and hung from the chains by iron rods 1.5 m apart. In 1896 the roadway was replaced by metal and wrought iron chains were replaced by steel in 1936.

In 1829 a committee called for submissions for a bridge across the Avon Gorge at Clifton. Brunel submitted four designs. His favoured design was a suspension bridge, using the cliffs as anchors. The judge, Thomas Telford, rejected all of the designs, so the committee asked Telford to submit a design. His submission was so poor that the committee rejected his design and called for a further round of submissions. Brunel's design for a 214m suspension bridge with Egyptian style piers and an abutment on one side was successful. The design set Brunel's career on a prosperous path, even though the bridge itself was not built until 1864, eight years after Brunel's death.

Fig. 1.7: *Brunel's Clifton suspension bridge; the "chains" are made with wrought iron plates.*

John Roebling was primarily responsible for the introduction of wire cables for suspension bridges instead of chains. He designed suspension bridges over the Niagara Gorge in 1855 and over the Ohio River at Cincinatti in 1867 but his true masterpiece was the Brooklyn Bridge. The Brooklyn Bridge has a span of 486 m and was the first to use steel wire cables. Work on the bridge began in 1869 and shortly afterwards Roebling died of tetanus when his foot was crushed by a ferry. His son, Washington Roebling took over. By 1876 the 82.5 m masonry towers were complete and they set about producing the four 400 mm diameter cables, which housed 1932 km of wire. With no rock to anchor the cables, large masonry gravity anchorages were built at each end of the bridge. These had a mass of 44,000 tonnes. The bridge was opened in 1883.

After the completion of the Brooklyn Bridge, American engineers built suspension bridges, each of which was longer and narrower than the last. In 1940 the Tacoma Narrows Bridge over Puget Sound in Washington State went just too far. At the time it was the third longest suspension bridge in the world, with a span of 853 m yet it was only 11.8 m wide and was stiffened by 2.4 m plates along each side. It was designed to withstand winds of up to 200 km/h. On November 7th, four months after it opened, a wind of 67 km/h occurred. The deck began to oscillate in vertical waves of 9 m height. After three hours, the waves stopped and the deck started to twist through 90 degrees until several suspension cables snapped and 300m of the centre span fell into the river. Following this the side spans started to "dance" until they too, fell into the river.

After this monumental failure, the American engineers returned to their previous practice of building heavier and more rigid suspension bridges. This rigidity was achieved by adding a thick layer of concrete to the deck and placing deep stiffening trusses on the sides. This seemed the best way to deal with side loads caused by wind.

Twenty six years later British engineers came up with a better solution. The Severn suspension bridge is an important milestone in bridge design. Originally designed as a heavy, stiff bridge with a span of 988 m, designer Gilbert Roberts experimented with a fin-shaped box-section deck in a wind tunnel. This shape proved less susceptible to side loadings from wind so the deck could be made lighter without the stiffness previously required. The new deck was only 3 m deep. A 30% saving was made in the amount of steel used. The only fault was a vibration at low wind speeds. This was alleviated by alternately inclining the suspension cables.

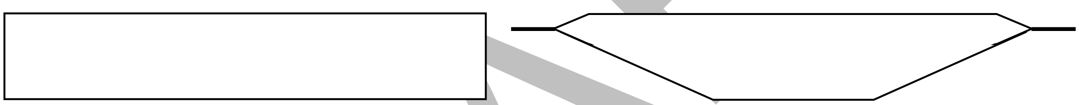


Fig 1.8: *The cross section of the Severn bridge deck on the right shows a more aerodynamic shape than the conventional rectangular box on the left.*

Another type of suspension style bridge is the *cable-stayed* bridge. This differs from true suspension bridges in that the roadway is supported by cables attached directly to the vertical columns. In Australia one of the most recognisable cable stayed bridges is the Anzac Bridge (originally called the Glebe Island Bridge). Made from reinforced concrete and steel cables, with the two tall concrete towers at each end, it dominates the Sydney skyline.

Opening Bridges

It is often inconvenient or excessively costly to build a bridge over a waterway high enough not to impede the flow of water traffic. In England during the 19th century, the Admiralty often set the height so that shipping would not be impeded. In Sydney there are three different types of opening bridges.

a) *The Pyrmont Bridge* at Darling Harbour used to be a roadway but now carries a footpath and monorail. It opens by rotating on a turntable to turn through 90 degrees and allow ships with high masts to pass through the opening. It is the world's last example of an early DC electric powered opening bridge.
b) *The Spit Bridge* in the northern suburbs of Sydney opens by raising a cantilevered opening section of the bridge through an angle of 90 degrees to allow watercraft through. Since it is on a busy arterial road route it is only allowed to open at certain times.

c) *Ryde Bridge,* in the mid western suburbs of Sydney, opens by the centre section being raised up by a gear system on a set of runners.

All of these bridges are variations on beam bridges. The Pyrmont Bridge is a type of balanced cantilever. Opening bridges tend to slow up road and waterway traffic and are only used where there is no other option.

Engineering Innovations in Civil Structures and Their Effect on People's Lives

Invention is the development of something entirely new. Innovation means making an alteration to something that has already been invented, and improving upon it.

Innovation is an important part of design and engineering, for through it engineers improve on an original concept. The suspension bridge was an invention, but the many variations that have improved it are innovations. Some innovative steps in bridge design along with their effects are listed below. It should be noted that prior to the Industrial Revolution water transport was the most important form of transport so keeping rivers open to water traffic was essential. Only with the advent of railways did this start to change

Summary.

- From 10,000 BC – primitive beam and suspension bridges – transport across rivers and ravines.
- Greeks perfect beam bridges – improve transport for human and animal drawn traffic.
- Roman engineers – arch bridges – revolutionary design – more stable and secure – improved transport – arch did not impede water traffic as much as early beams.
- The fall of the Roman Empire, 5th century – backward step – medieval arch bridges, not as efficient in design and impede water traffic, e.g. London Bridge.
- 16th century – the truss girder improves beam bridge design – longer spans – greater safety – less pylons.
- The Renaissance – improvement in arch bridge design – back to Roman standard – improved clearance for water traffic – lower arches
- James Finlay, early 19th century – modern suspension bridge – long spans – little impediment to water traffic.
- The bow-string girder, 19th century – embraced by railway engineers – cheap and simple
- 20th century – first box girder – useful design for freeway construction – freeways improve road transport especially for road freight – contributes to railway decline.
- First modern balanced cantilever bridges – limited impediment to water vehicles – effective use of materials.
- The Brooklyn Bridge – first suspension bridge to use steel cables – improved safety.
- Concrete used as a building material for arch bridges. After WWII – most used building material - alters bridge design significantly.
- The Sydney Harbour Bridge completed 1932 – cuts travel times from the north to the city – speeds development, northern Sydney

- Tacoma Narrows Bridge failure – shows danger of poor design – leads to safer suspension bridges
- Severn Suspension Bridge – streamlined cross section to deal with wind.
- Akashi Kaikyō suspension bridge, opened in 1998, becomes the longest span bridge in the world with a span of 1991 m.

Construction and Processing Materials Used In Civil Structures Over Time

Bridge development has been facilitated by the development of different materials that have proved suitable in bridge construction. The following is a list of materials used in bridges.

Timber was used in the earliest bridges, which may have been as simple as a log between two banks. Originally used in its natural state (a tree), it has been developed to having pieces of timber cut and fabricated into a truss to form a beam bridge. Timber was also used as the deck in early suspension bridges. Many old bridges in country NSW are timber. A good example is the Gundagai rail bridge. It is the longest timber truss bridge remaining in NSW. Timber offered ease of manufacture and was a readily available resource. Its main disadvantage is that it rots away.

Rope was used, by early cultures, on early suspension bridges. Just like timber, it rotted away and could only carry small loads.

Stone is a far more permanent building material than timber or rope. Many Roman arches were made from stone and still stand today. Stone is strong in compression yet weak in tension, so it is perfect for use in arch bridges. Not until cast iron and steel were developed was stone replaced for arch bridge construction. Now another ceramic, concrete, is used.

Bricks are sometimes used in bridge manufacture. Although they have similar properties to stone they are manufactured from clay and not chiselled to shape from natural stone. Brunel's low arch, Maidenhead Bridge is an example of a brick bridge. Often bricks were used in making viaducts that led to a bridge. See Fig. 1.2.

Cast iron became readily available during the Industrial revolution, and by the late 18^{th} century it was used in bridges. Like stone, it is weak in tension but strong in compression. Unlike stone it can be melted and cast, thus saving on time and also introducing the concept of pre-fabrication. Cast iron bridges could be made of frames which provided a strength equal to stone but with greatly reduced weight.

Wrought iron was used in early suspension bridges, by Thomas Telford and others, in the chains from which was suspended the deck. Wrought iron was an unreliable material due to the fibrous structure present in the ferrite, which tended to weaken it and make it difficult to tell if this affected the whole of the wrought iron. This lack of reliability in structure (compared to steel wire) was the reason that suspension bridges were limited in length. When wrought iron was replaced with steel, suspension bridges could be built much longer.

Steel was mass-produced in 1856 by Henry Bessemer and it changed bridge design. The steel arch became a viable option; the St Louis Bridge has a roadway over steel arches while the Sydney Harbour Bridge has a suspended roadway below the arch. Steel is equally strong in both tension and compression compared to stone and cast iron; so steel arches differ in construction from masonry arches. Steel cables proved valuable in suspension bridges as greater spans could be achieved, and at the turn of the century steel was used to create reinforced concrete. Eventually, with the development of high tensile steel, it was possible to produce pre-stressed and post-stressed concrete.

Concrete was not used in bridge construction until the shrinkage problem was addressed by the third hinge, and due to its weakness in tension it was only used when reinforced with steel. Reinforced concrete has been developed into pre-stressed concrete and post-stressed concrete to improve strength and performance. Concrete is the bridge construction material of the 20th century with most new bridges using concrete of some type.

Stainless Steel is now being used in certain bridges, often pedestrian bridges. The Marina Bay Bridge in Singapore uses 2205 duplex stainless steel for its tubular spiral stainless steel members. It is 280 metres long and 6 metres wide.

Environmental Implications of Materials used in Civil Structures

Since all building materials are derived, at some stage, from the earth, there will always be some impact when the raw material is gathered. The following information describes the environmental impact of the use of some bridge construction materials.

Timber's use as a source of heat for steam power, and as a building material, resulted in deforestation of the surrounding area. As that area ran out of trees they were sought elsewhere. Trees take centuries to grow and old growth forests have never recovered from the onslaught.

Stone does not magically appear in the shapes needed. Ancient and medieval cultures had to mine stone and they did this by digging large quarries. These scarred the landscape and had a severe impact on natural fauna and flora.

Bricks require vast amounts of clay and shale to manufacture, so large pits were dug to find these materials. Often the brick works were alongside the pit. The environmental impact of such pits was similar to that caused by stone quarries. When the pit was no longer used it was filled in and then reclaimed. Subsidence is often a problem on old brick pit sights.

Cast and wrought iron were true products of the Industrial Revolution. They were one of many products requiring the combustion of fossil fuels. Before the industrial revolution our impact on the environment was relatively small, so in the 300 years since, humans have had a greater impact than our predecessors had over 100,000 years. Cast and wrought iron required iron to be mined and smelted. This required, not just a mine, but also processing plants and transport facilities, which involved railways. All these associated industries had a huge impact on the landscape, and we are starting to feel the legacy of such impacts today.

Steel falls into a similar category to cast and wrought iron. However its impact is even greater due to its proliferation through more industries. Steel has allowed longer bridges to be built, using more steel and greater processing. Steel helped to open access to other areas and reduce transport times so it was possible to gain resources from places that previously would have been unviable. Steel is also required for locomotives and motor vehicles so the demands have increased exponentially over time.

That said, longer bridges with fewer piers have less impact on waterways, so by comparison with earlier bridges, are less likely to interrupt the delicate marine ecosystem that lives in the waterway.

Concrete, in its various forms, is a popular material in bridge building. Like other bridge construction materials, it requires vast amounts of minerals to manufacture it, and obtaining these has an adverse environmental impact. Also, some would argue that it is visually unappealing. Like steel, however, it has resulted in bridges, which have a reduced impact on waterways, compared with earlier bridges.

Engineering Mechanics

Truss Analysis

Since the development of the truss it has become one of the most important engineered structures. Trusses are based on the use of the strongest geometric shape, the triangle. Unlike polygons with more sides, a triangle cannot pivot at its joints to deform so it is a very rigid structure when made of timber, steel, etc. Trusses take advantage of this by taking any shape and triangulating it to maximise strength.

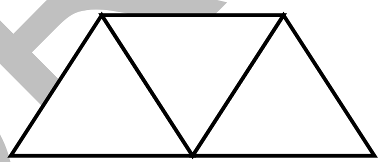


Fig 1.9: *A simple Warren truss is made up of equilateral triangles.*

A truss is essentially a form of simply supported beam and usually is supported at either end on supports which provide reactions to the applied loads acting on the truss. The types of supports are shown in Table 1.1.

Reactions at the Supports

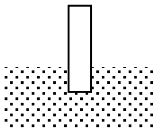
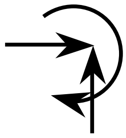
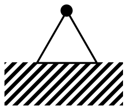
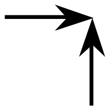
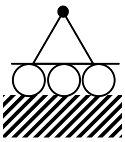
Solving any problem involving a truss usually involves finding the reactions at the supports of the truss. When doing this it is helpful to follow this sequence,

1. When the diagram given is overly complex, draw a free body diagram showing all loads and dimensions.
2. Determine the horizontal and vertical components of any angled forces.

3. Take moments about the non-roller support first (as you always know the direction of the roller supports reaction) to determine the reaction at the roller support.
4. Once this reaction is found then use ΣF_V and ΣF_H to find the vertical and horizontal reactions at the pin support.
5. Find the total reaction at the pin support.

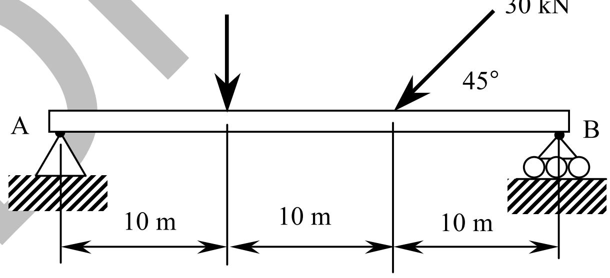
Note: If all loads are vertical or horizontal then the procedure is greatly simplified.

Table 1.1: *Types of supports for beams and trusses.*

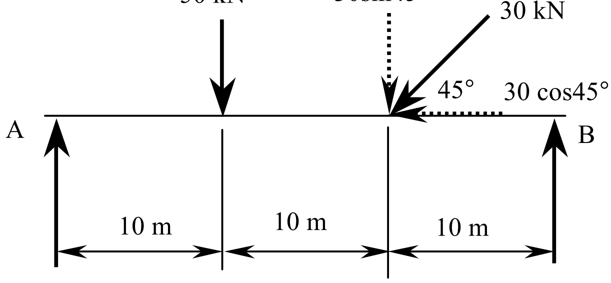
Support	**Image**	**Free Body Diagram**	**Attributes**	**Reason for Use**
Fixed			Can support vertical and horizontal loads and moments.	To firmly anchor a structure
Pin or hinge			Can support vertical and horizontal loads. Free to rotate	To provide a non-moving support for a bridge.
Roller			Can only provide reactions normal to the surface. Free to rotate	To allow side movement for expansion in a truss.

Example 1.1

Find the reactions at the supports for the beam shown below.



We will first take moments about point A as it is a fixed support and we must break up the inclined force into vertical and horizontal components.



$\circlearrowright^{+} \Sigma M_A = 0$

$$0 = 50 \times 10 + 30 \sin 45^\circ \times 20 - 30 R_B$$
$$30 R_B = 500 + 424.26$$
$$R_B = \frac{924.26}{30}$$
$$R_B = 30.8 \text{ kN} \uparrow$$

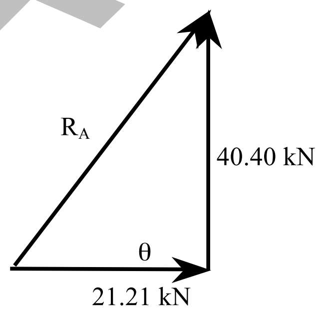
Now to find the reaction at A we must add the vertical and horizontal forces. This will find us the components of R_A that we must, in a vectorial manner, add together to find R_A.

$+\uparrow \Sigma F_V = 0$

$$0 = 30.81 - 50 - 30 \sin 45^\circ + R_{AV}$$
$$R_{AV} = 40.40 \text{ kN} \uparrow$$

$\xrightarrow{+} \Sigma F_H = 0$

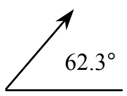
$$0 = -30 \cos 45^\circ + R_{AH}$$
$$R_{AH} = 21.21 \text{ kN} \longrightarrow$$



$$R_L = \sqrt{40.40^2 + 21.21^2}$$
$$R_L = 45.63 \text{ kN}$$

$$\tan\theta = \frac{40.40}{21.21}$$
$$\theta = 62.3^\circ$$

So we can now state that the reactions at the supports are:

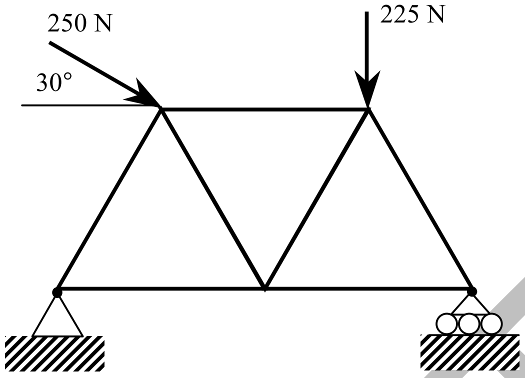
R_L =45.63 kN 

R_R = 30.8 kN ↑

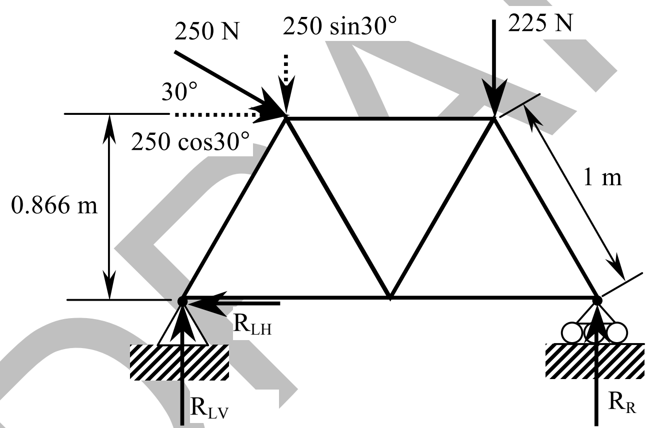
Note that the directions must be given, because forces are vector quantities.

Example 1.2

A Warren truss shown below is subjected to two loads. Find the reactions at the supports.



We must now break up the angled force into vertical and horizontal components, and also draw in our reaction forces. Since a Warren truss is made up of equilateral triangles, all sides are equal. As such we do not need actual dimensions and we can consider the sides to be 1 unit long. We can then find the height of the horizontal component of the truss.



$$\circlearrowleft + \; \Sigma M = 0$$

$$0 = 250\cos 30^\circ \times 0.866 + 250\sin 30^\circ \times 0.5 + 225 \times 1.5 - 2R_R$$

$$2R_R = 187.49 + 62.5 + 337.5$$

$$R_R = \frac{587.49}{2}$$

$$R_R = 293.75 \text{ N} \uparrow$$

Now that we have determined R_R we can find R_{LV} and R_{LH}.

$$+\uparrow \; \Sigma F_V = 0$$

$$0 = 293.75 - 250\sin 30^\circ - 225 + R_{LV}$$

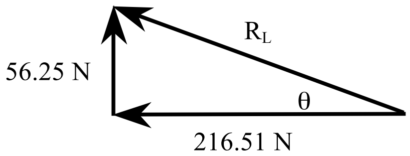
$$R_{LV} = 56.25 \text{ N} \uparrow$$

$$\xrightarrow{+} \; \Sigma F_H = 0$$

$$0 = 250\cos 30^\circ - R_{LV}$$

$$R_{LV} = 216.51 \text{ N} \longleftarrow$$

Now we can determine the total reaction R_L by vectorially adding the components:



$$R_L = \sqrt{56.25^2 + 216.51^2}$$
$$R_L = 223.70 \text{ N}$$
$$\tan\theta = \frac{56.25}{216.51}$$
$$\theta = 14.56^\circ$$

The reactions at the supports are:

$R_L = 223.7$ N $\;14.56^\circ$

$R_R = 293.75$ N $\uparrow$

Analysing the Truss Members

Although a truss is considered as a beam to determine the supports, the frame that is the truss also contains forces. The framework allows the truss to span greater distances than a simple beam, and it also has better capacity to support greater loads. There are two methods available for finding the reactions at the supports of a truss, the Method of Joints and the Method of Sections. In both methods we must state the direction of the force in the truss members, by classing it either as tension or compression. Tension forces will stretch the members, while compressive force will tend to shorten the members.

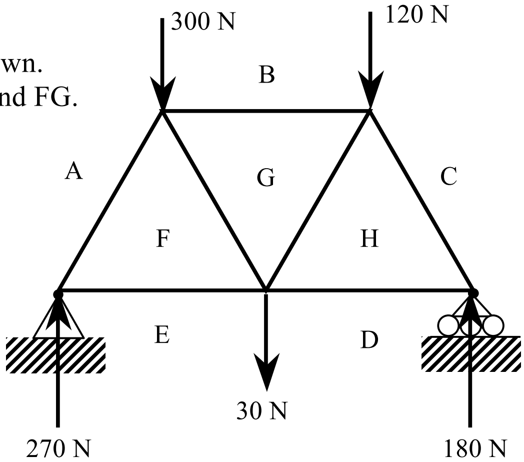
For the sake of simplicity, let us assume that each joint of the truss is pinned, and can rotate in relation to another. By doing this, we can ignore any moment at the joint. In actuality truss joints are usually welded, riveted or bolted in such a way that rotation is prevented, so the joints actually have resistance to rotation which complicates the truss analysis, which is why we simplify it for calculations.

The Method of Joints

The Method of Joints is a process used to find the forces in truss members by analysing each joint as a concurrent force system. One starts at one end and works through to the other. Example 1.6 outlines the process of Method of Joints.

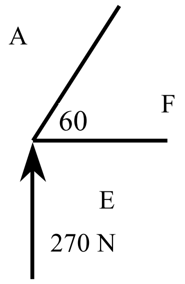
Example 1.3

A truss is loaded and produces reactions as shown. Determine the force in members AF, EF, BG and FG.



The truss has already been labelled using Bows notation, which involves labelling the spaces between forces and members and naming the force according the letter on either side. This is not always done; often the joints themselves are labelled.

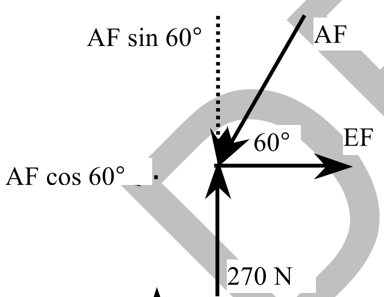
To find the force in members AF and EF, look at joint AEF.



It can be seen that we have a three-force system that must be in equilibrium or the system will fail. It follows that if a total mechanical system is in equilibrium, as our truss is, then all of its components are also in equilibrium. Procedure 1 is shown to the left, while Procedure 2 is shown on the right.

• Procedure 1

This method involves breaking the AF into horizontal components and then finding the sum of the vertical and horizontal forces, remembering ΣF_V and ΣF_H is equal to zero.



$$+\uparrow \ \Sigma F_V = 0$$

$$0 = 270 - AF\sin 60^\circ$$

$$AF = \frac{270}{\sin 60^\circ}$$

$$AF = 311.77\text{ N (compression)}$$

$$\longrightarrow +$$

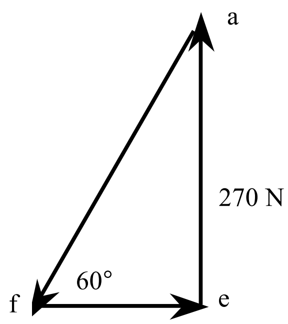
$$\Sigma F_H = 0$$

$$0 = EF - 311.77\cos 60^\circ$$

$$EF = 155.88\text{ N (tension)}$$

• Procedure 2

This method involves considering the three forces as they are and drawing up a force triangle to solve the values for AF and EF.



$$\tan 60^\circ = \frac{270}{EF}$$

$$EF = \frac{270}{\tan 60^\circ}$$

$$EF = 155.88\text{ N (tension)}$$

$$\sin 60^\circ = \frac{270}{AF}$$

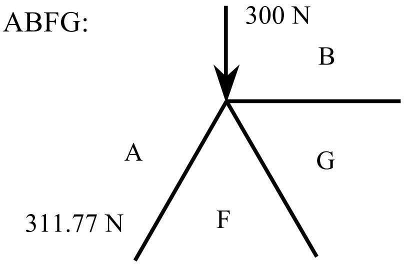
$$AF = \frac{270}{\sin 60^\circ}$$

$$AF = 311.77\text{ N (compression)}$$

The same answers are derived from both methods. The tension and compression are determined by looking at the force and the way it travels. In the case of EF the force is moving to the right and away from the joint, stretching the member tension.

Procedure 2 can be done graphically, and in fact on any joint with more than three members when Procedure 2 is used it must be solved graphically since the force polygon will have more than three sides and trigonometry cannot be used. However such a joint can be solved mathematically using Procedure 1. It should be noted however that for joints with more than three forces, the graphical method is significantly quicker than the analytical method in procedure 1

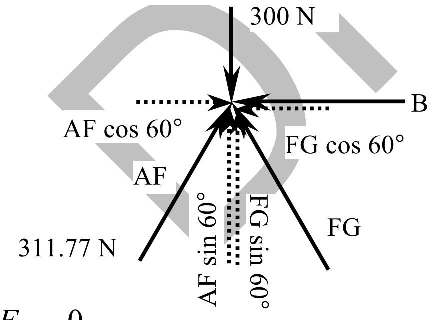
Consider joint ABFG:



Since we have found AF this joint can now be solved as we have two known members and two unknown members. It would not be possible to go directly to this joint at the start, as one would have three unknown members. Let us once again look at the two procedures.

• Procedure 1

As at the previous joint we shall break up all inclined members into horizontal and vertical components, the sum of the vertical and horizontal forces.



$$+\uparrow \Sigma F_V = 0$$

$$0 = 311.77\sin 60^\circ - 300 + FG\sin 60^\circ$$

$$FG = \frac{30}{\sin 60^\circ}$$

$$FG = 34.64 \text{ N (comp)}$$

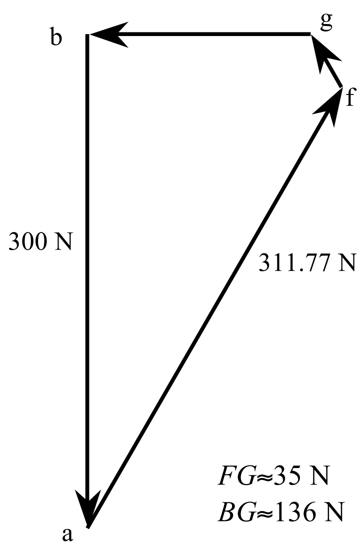
$$\xrightarrow{+} \Sigma F_H = 0$$

$$0 = 311.77\cos 60^\circ - 34.64\cos 60^\circ - BG$$

$$BG = 138.54 \text{ N (comp)}$$

• Procedure 2

Since there are four forces we cannot use sin, cos or tan for determining the values so we must do it graphically. To do this we must draw a scale diagram.



$FG \approx 35$ N
$BG \approx 136$ N

FG=34.64 N (comp)
BG=136 N (comp)

The accuracy of a graphical solution depends on the scale and precision to which it is drawn. Use as large a scale as possible to improve the accuracy of your answer.

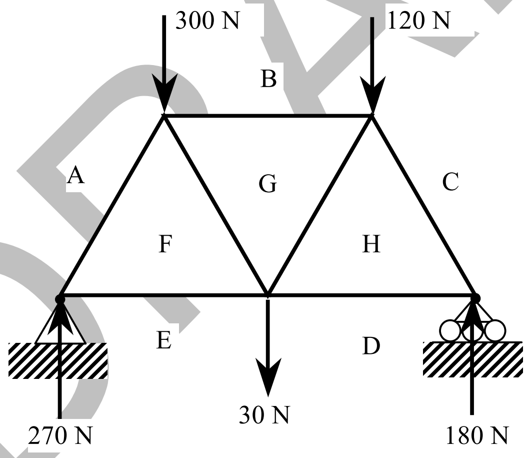
As with the previous joint we were able to determine the nature of the force due to the direction each travels. The Method of Joints solution will continue across the truss to find the force in all the members.

The Method of Sections

Often it will not be necessary to find the force in all members of a truss, perhaps only one or two. If these members are on the ends Method of Joints will be fine, but if they are in the middle of the truss, the Method of Joints is cumbersome and slow. The Method of Sections allows us to find the force in a member in the centre of a truss directly.

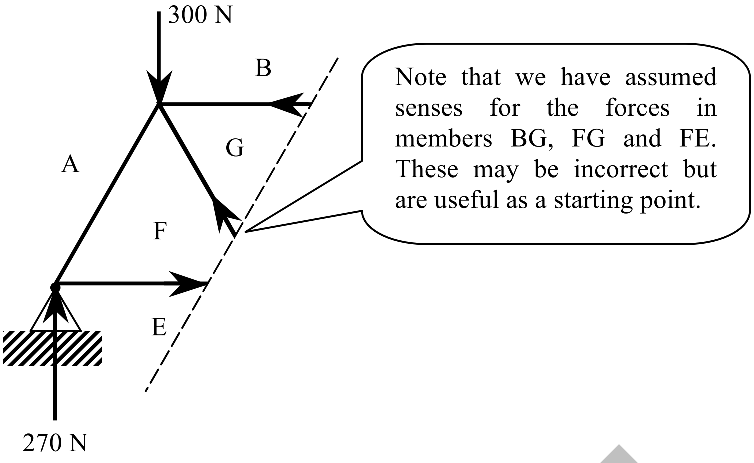
Example 1.4

A truss is loaded and produces reactions as shown. Determine the force in members BG, FG and FE. Assume each side of the truss is 1m long.



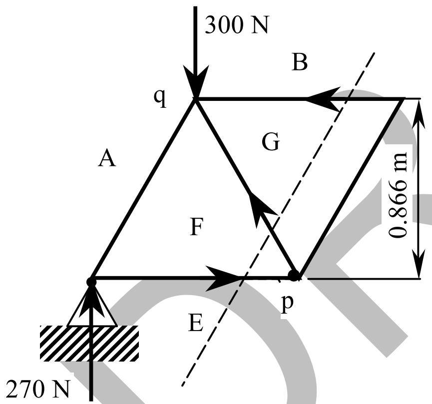
The principle of this method is based on the fact that if the whole truss is in equilibrium, then any part, or component will also be in equilibrium. If we 'cut' the truss through at least two members and 'remove' a portion, the system that remains must also be in equilibrium.

To solve this Method of Sections problem pass a section plane through the truss that cuts through the members we are trying to find. We then consider the cut members as external forces of one half of the truss.



We now consider the left hand side of the truss only. The forces FE, FG and BG are balancing the two external forces. We will use a combination of the three equations for equilibrium (i.e. $\Sigma F_H=0$, $\Sigma F_V=0$ and $\Sigma M=0$).

To find the force in BG we must take moments. There are five forces on the truss that create moments and three are unknowns, so we must take moments about a point that eliminates FG and FE, so we need to find a point that these two both pass through. Although that point is on the half of the truss we removed, we can still take moments about that point since we can take moments about any point in space. We know the position of this point and it is the point we need. We shall call it point p.



$$\circlearrowleft^{+} \quad \Sigma M_p = 0$$
$$0 = (270 \times 1) - (300 \times 0.5) - (BG \times 0.866)$$
$$0.866BG = 270 - 150$$
$$BG = \frac{120}{0.866}$$
$$BG = 138.56 \text{ N (compression)}$$

We can see our assumed sense for BG was correct and the member is in compression, as the force tends to squash it.

Now find the force in member FG. Since it is the only unknown with a vertical component it is possible to use $\Sigma F_V=0$ to solve this problem. Note that the vertical component of FG is FGsin60°.

$$+\uparrow \quad \Sigma F_V = 0$$
$$0 = 270 - 300 + FG \sin 60^\circ$$
$$0.866FG = 30$$
$$FG = \frac{30}{0.866}$$
$$FG = 34.64 \text{ N (compression)}$$

We can now find FE and since it is the last unknown we can either take moments about point ABFG (point q) or we can find the sum of the horizontal components of the forces. Both methods are shown below. Note that the horizontal component of FG is FGcos60°.

$$\circlearrowleft + \quad \Sigma M_q = 0$$
$$0 = (270 \times 0.5) - (FE \times 0.866)$$
$$0.866FE = 135$$
$$FE = \frac{135}{0.866}$$
$$FE = 155.88 \text{ N (tension)}$$

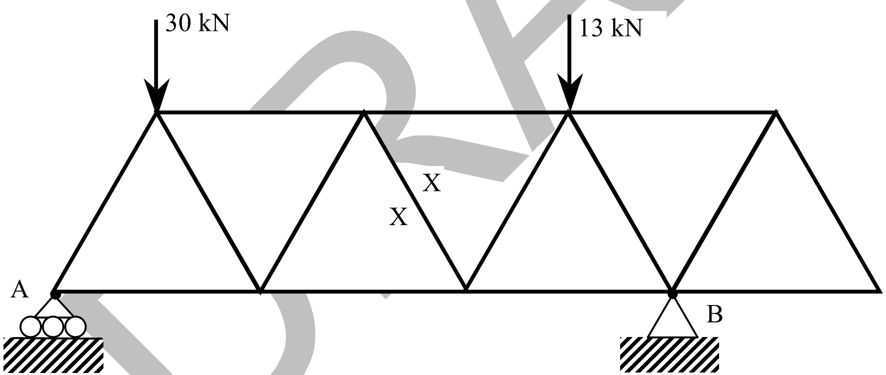
$$\longrightarrow +$$
$$\Sigma F_H = 0$$
$$0 = FE - 138.56 - 34.64\cos 60^\circ$$
$$FE = 138.56 + 17.32$$
$$FE = 155.88 \text{ N (tension)}$$

It is apparent that it is simpler to merely find the sum of the horizontal components however in some problems this may be difficult.

Although the Method of Sections may not seem any simpler, on a truss like the one in Example 1.8, it will be much simpler to find member XX using Method of Sections than it would be Method of Joints. Let us see the method.

Example 1.5

Find the force in member XX of the truss below.

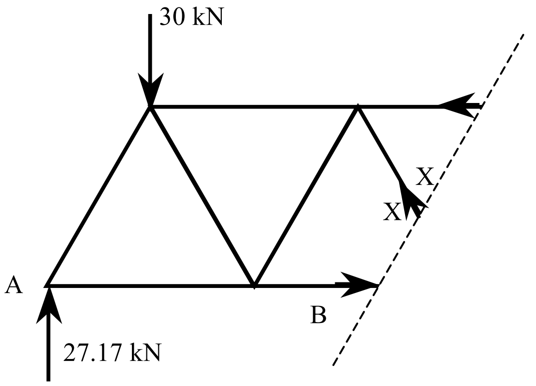


Since we have not been asked to find the reactions at the supports we will only find one, then consider that side of the truss to find XX.

Let us find the reaction at the left support (R_A) by taking moments about B. This will be a vertical force due to the roller support.

$$\circlearrowleft + \quad \Sigma M_B = 0$$
$$0 = -(13 \times 0.5) - (30 \times 2.5) + 3R_A$$
$$3R_A = 6.5 + 75$$
$$R_A = \frac{81.5}{3}$$
$$R_A = 27.17 \text{ kN}$$

We have found the reaction at support A, so we shall now cut the truss in half through member XX and consider the left side. Remember we guess the senses of the forces in the cut members.



To find the force in XX we shall find the sum of the vertical forces.

$$+\uparrow \Sigma F_V = 0$$
$$0 = 27.17 - 30 + XX \sin 60^\circ$$
$$XX = \frac{2.83}{0.866}$$
$$XX = 3.27 \text{ kN (comp)}$$

As you can see, this is quite a quick method of finding the force in a member located away from the ends of the truss.

Bending Stresses Induced by Point Loads

Whenever a non-axial (eccentric or transverse) force acts on a beam there will usually be some bending that takes place. This force tends to create a bending stress that is a measure of the beam's internal resistance to bending. In this section we discuss shear force and bending moment, how to graph these quantities, and then determine the bending stress (or internal resistance to bending) of the beam.

Concept of Shear Force and Bending Moment

In order for us to understand the behaviour of a loaded beam we must introduce the concept of shear force and bending moment. Shear force at any point on a beam may be defined as the algebraic sum of all external forces to one side of the beam. The shear force is actually the reaction, at a given point along a beam of the material to being sheared apart by the external forces.

Bending moment at a given point along a beam is equal to the total moment developed at that point by the external force system. If we sum moments at a given point along a beam that is in equilibrium, the value will be zero. Therefore to find bending stresses we have to only find the moment set up in one section of the beam.

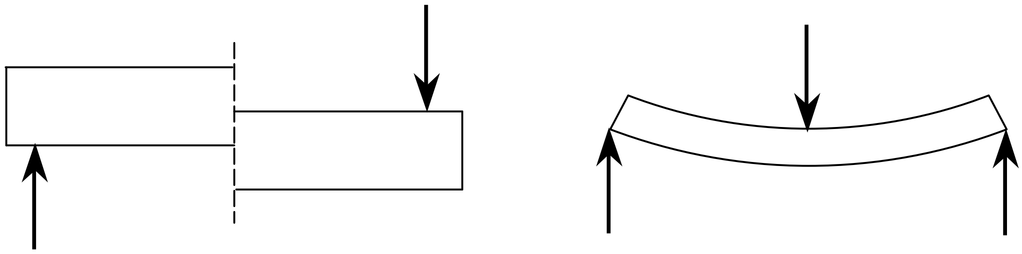


Fig. 1.10: *Diagrammatic representation of shear (left) and bending (right).*

Sign convention

Sign convention is always a hot topic for engineers in relation to shear force and bending moment, particularly for shear forces. In this book, the following sign convention is used for positive shear forces and bending moments.

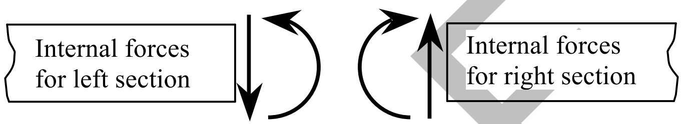


Fig 1.11: *The positive senses for the internal reactions for shear force and bending moments.*

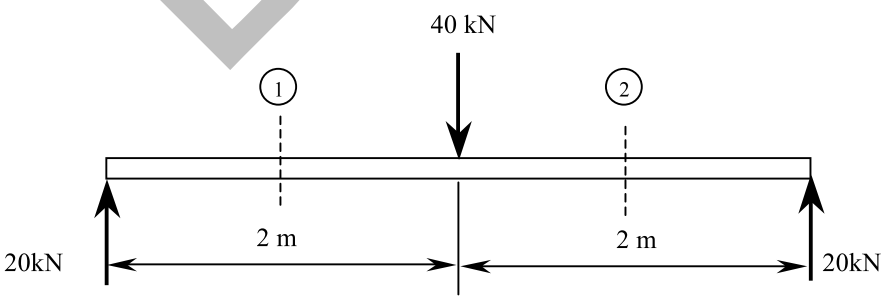
Some publications use a different convention for shear force but this type is considered simplest, particularly when drawing shear force diagrams.

Calculating Shear Forces

This involves progressively working your way along a beam summing the external forces to determine the shear force.

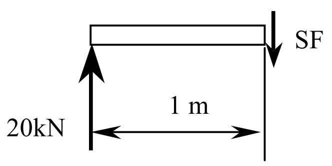
Example 1.6

Find the shear forces and bending moments at the labelled cross sections of the beam below.



First find the sum of the vertical forces that exist to the left of the section. Remember that since the shear force is equal to the sum of all external forces we shall make it the subject of the equation. Although the downward shear force is positive we shall consider downwards-external forces to be negative.

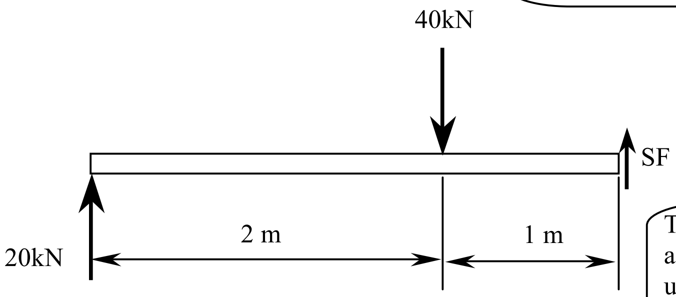
Shear Force At Point 1



$$+\uparrow \Sigma F_V = 0 = 20 - SF$$
$$SF = 20 \text{ kN (positive SF)}$$

The positive SF value means our assumption that the SF is acting downward was correct.

Shear Force At Point 2

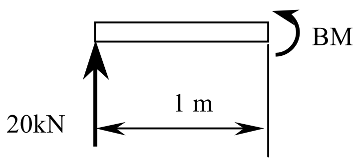


$$+\uparrow \Sigma F_V = 0 = 20 - 40 + SF$$
$$SF = 20 \text{ kN (negative SF)}$$

The positive SF value means our assumption that the SF is acting upward is correct. Therefore, by our sign convention it is a negative SF.

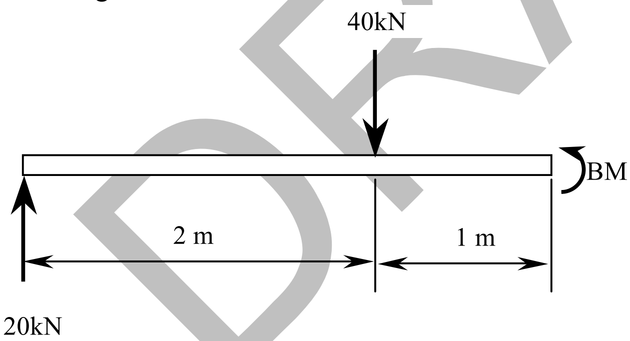
Now find the bending moment at the points shown on the diagram.

Bending Moment At Point 1



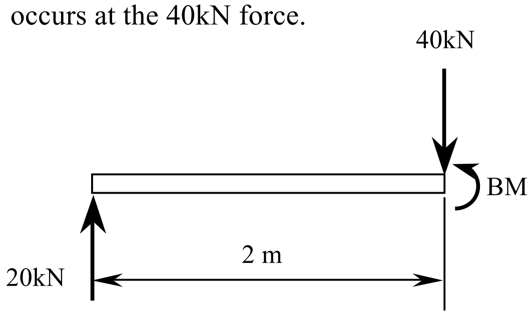
$$\circlearrowright + \quad \Sigma M_1 = 0 = 20 \times 1 - BM$$
$$BM = 20 \text{ kNm}$$

Bending Moment At Point 2



$$\circlearrowright + \quad \Sigma M_2 = 0 = 20 \times 3 - 40 \times 1 - BM$$
$$BM = 20 \text{ kNm}$$

Now we have determined the bending moments at the same points as we did for the shear force. However these are not necessarily the maximum values. Engineers are concerned to find the maximum shear force and bending moment, because that is where the stresses will be the greatest. In this beam the maximum bending moment occurs at the 40kN force.



$$\circlearrowright + \quad \Sigma M_{centre} = 0 = 20 \times 2 - 40 \times 0 - BM$$
$$BM = 40\text{kNm}$$

So the bending moment rises from zero at one end of the beam up to 40kNm at the centre then back to zero at the other end, while the SF is 20kN between the left end and the centre and –20kN from the centre to the right end.

It is better to make bending moment calculations at points where there are applied forces, particularly when there is more than one.

Shear Force and Bending Moment Diagrams

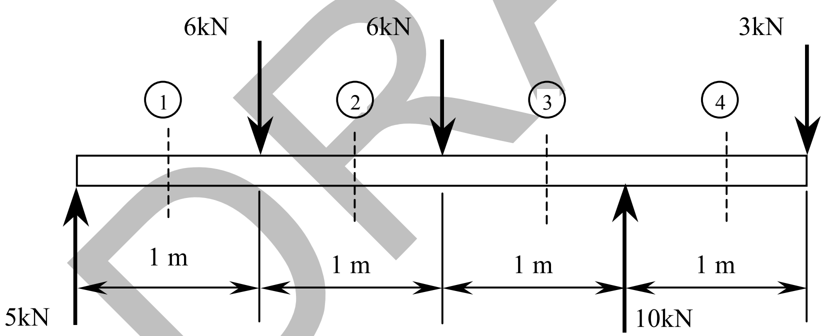
It is often useful to place the shear force and bending moment values onto a graph to show the nature of these values across the length of the beam. It is here that sign convention plays an important part.

Shear Force Diagrams

This is a graphical representation of the distribution of shear forces across a beam. There are two ways of determining the shear force diagram, the long way and the short way. The long way never fails, while the short way works best with point loads, which is what we are considering at the moment. Example 1.10 outlines both methods.

Example 1.7

Determine the shear force diagram for the beam shown below.



a) Method 1: Start at the left and add the forces at the numbered points and at the point loads. (Note upward forces are assumed positive)

SF at left reaction (5 kN): $\Sigma F_V = 0 = 5 - SF$

$$SF = 5 \text{ kN (positive SF)}$$

SF at point 1: $\Sigma F_V = 0 = 5 - SF$

$$SF = 5 \text{ kN (positive SF)}$$

SF at 6kN force: $\Sigma F_V = 0 = 5 - 6 + SF$

$$SF = -1 \text{ kN} = 1 \text{ kN (negative SF)}$$

SF at point 2: $\Sigma F_V = 0 = 5 - 6 + SF$

$SF = -1\,\text{kN} = 1\,\text{kN}$ (negative SF)

SF at 2nd 6kN force: $\Sigma F_V = 0 = 5 - 6 - 6 + SF$

$SF = -7\,\text{kN} = 7\,\text{kN}$ (negative SF)

SF at point 3: $\Sigma F_V = 0 = 5 - 6 - 6 + SF$

$SF = -7\,\text{kN} = 7\,\text{kN}$ (negative SF)

SF at right reaction (10kN): $\Sigma F_V = 0 = 5 - 6 - 6 + 10 - SF$

$SF = 3$ kN (positive SF)

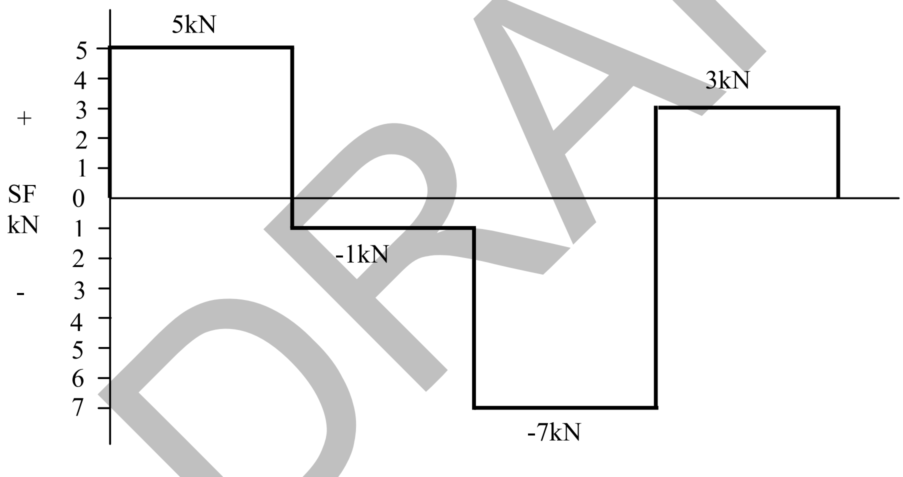
SF at point 4: $\Sigma F_V = 0 = 5 - 6 - 6 + 10 - SF$

$SF = 3$ kN (positive SF)

SF at right end: $\Sigma F_V = 0 = 5 - 6 - 6 + 10 - 3 + SF$

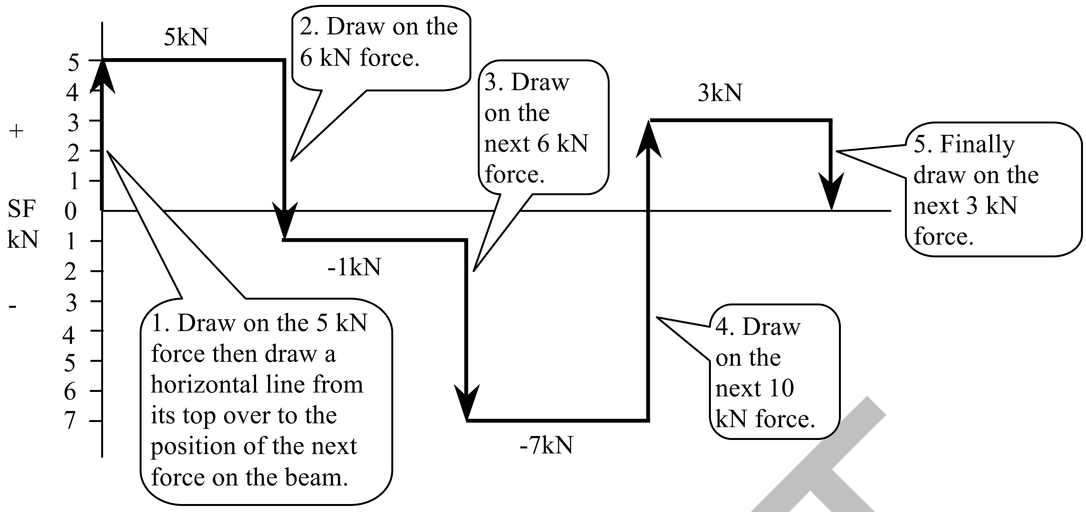
$SF = 0\,\text{kN}$

Now that we have the figures we can draw up a diagram and plot the values.



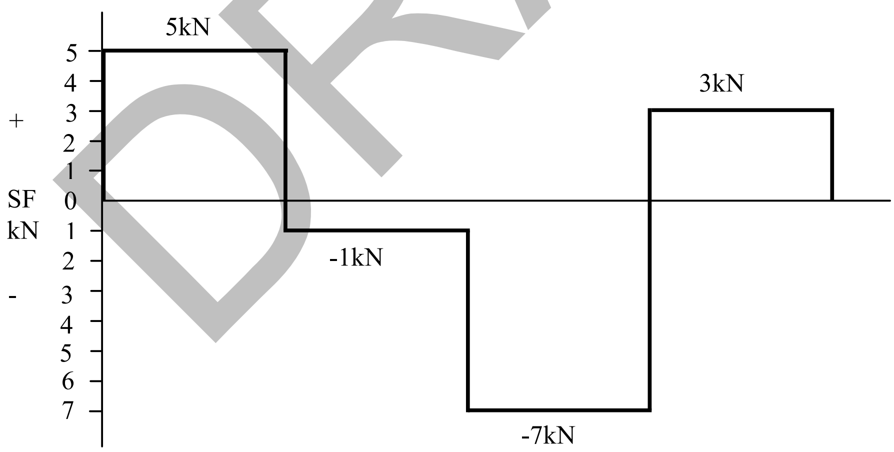
b) Method 2: Solve the problem using the "Follow the Force Rule"

This simple method involves drawing on all the external forces and linking them with horizontal lines. The result is a SF diagram that is very easy to determine.



Note that the next force will be drawn from the level that the previous force has reached and that the forces are merely drawn in the position in which they exist on the beam. When you draw a force, remember to draw the horizontal line over to the position of the next force. Finally, there is no need to put arrowheads on the SF diagram; they are only there so you can see the connection to the external forces. The final SF diagram on the next page is exactly the same as the one you would get in summing up forces.

The "Follow the Force" method is the reason we use the sign convention listed, otherwise this method must be used backwards, which is likely to cause errors. In most cases this is the simplest and quickest method to use.

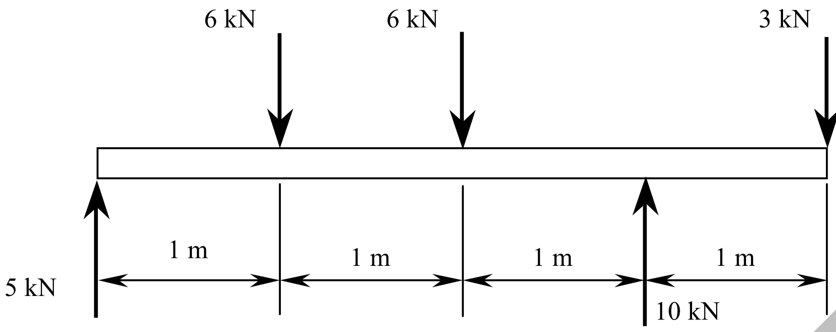


Bending Moment Diagrams

Like shear force diagrams there are two ways to determine the bending moment diagram for a beam. One method is simpler than the other, but does require the SF diagram to be drawn already.

Example 1.8

Determine the BM diagram for the beam used in Example 1.10.



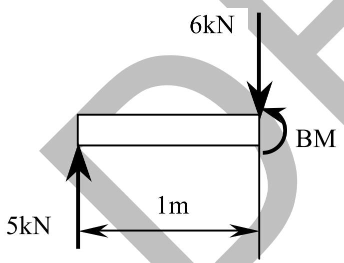
When calculating bending moments we take moments about the applied forces and reactions, as this is where there is a change in value. In between the forces, the bending moment will be a straight line (when dealing with point loads).

a) Method 1: summing up moments about active and reactive forces.

At 5kN force:

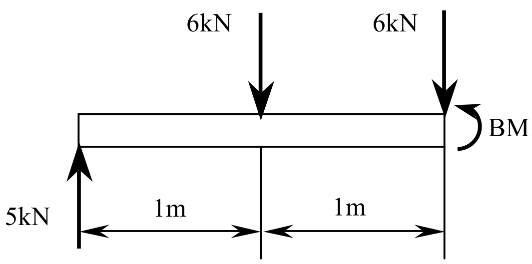
$$\circlearrowright + \quad \Sigma M_{5kN} = 0 = 5 \times 0 - BM$$
$$BM = 0\text{kNm}$$

At 6 kN force:



$$\circlearrowright + \quad \Sigma M = 0 = 5 \times 1 - 6 \times 0 - BM$$
$$BM = 5\text{kNm}$$

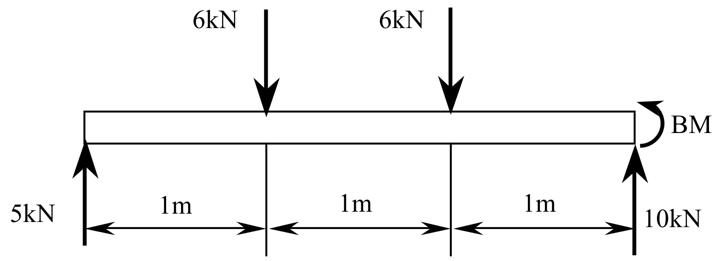
At next 6kN force:



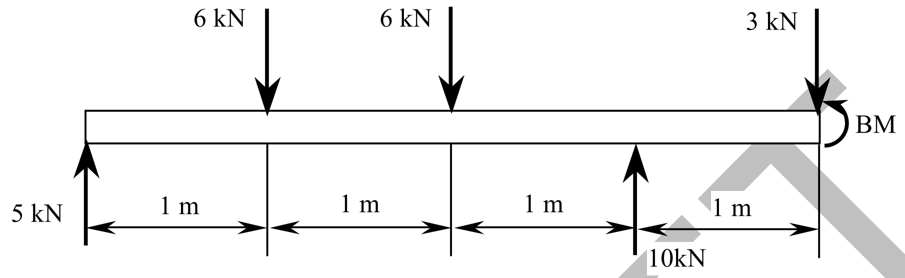
$$\circlearrowright + \quad \Sigma M = 0 = 5 \times 2 - 6 \times 1 - 6 \times 0 - BM$$
$$BM = 4\text{kNm}$$

At 10kN force:

$$\circlearrowright + \quad \Sigma M = 0 = 5 \times 3 - 6 \times 2 - 6 \times 1 + 10 \times 0 - BM$$
$$BM = -3\text{kNm}$$
$$BM = 3\text{kNm (negative BM)}$$

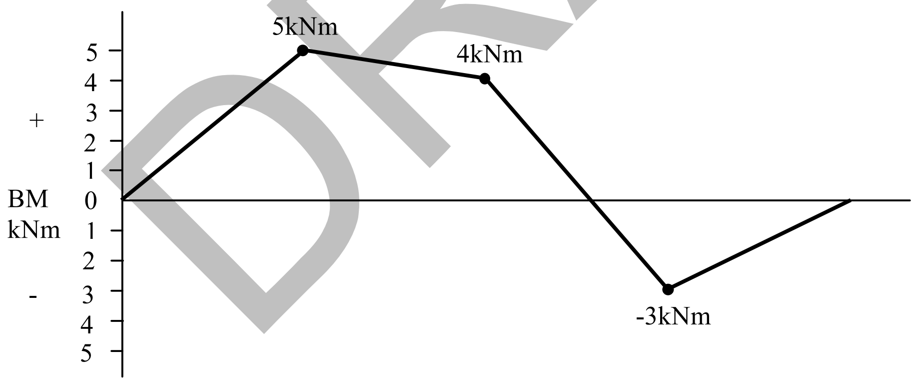


At 3kN force:



$$\circlearrowleft^{+} \ \Sigma M = 0 = 5\times4 - 6\times3 - 6\times2 + 10\times1 - BM$$
$$BM = 0\text{kNm}$$

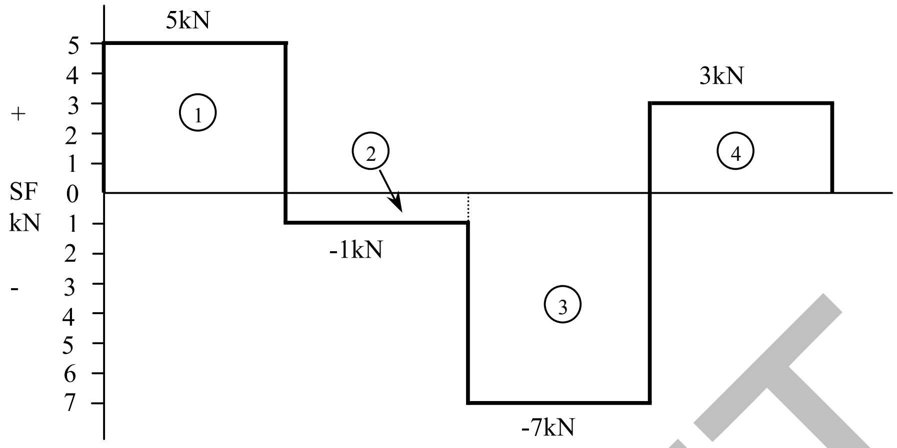
Now that we have all the relevant values, we can draw the bending moment diagram on the axes below.



From this diagram it is possible to tell that the beam predominately tends to "sag", that is, flex in a way that the ends flex upwards, while a part tends to "hog", that is flex so the middle will flex upwards.

b) Method 2: area under the SF diagram

To determine the BM diagram in this way we must work out the area under the curve from left to right of the SF diagram. Negative areas are subtracted from positive areas to give a cumulative total. The SF diagram has the areas labelled 1 to 4. The area is found by multiplying the value of the SF (height) by the length that the beam would be, in this case all rectangles have a length of 1m.



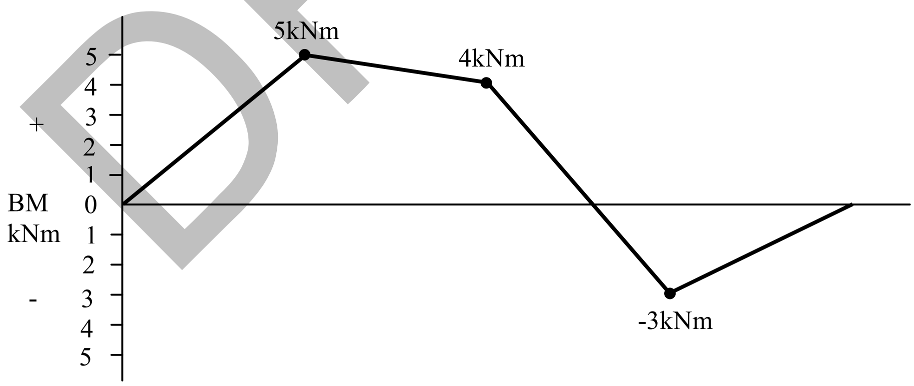
BM at 6 kN force = Area 1 = 5×1 = 5kNm

BM at next 6 kN force = Area 1+Area 2 = 5+(-1×1) = 4kNm

BM at 10 kN force = Area 1 +Area 2 + Area 3 = 5+(-1)+(-7×1) = -3kNm

BM at end = Area 1 +Area 2 + Area 3 + Area 4 = 5+(-1)+(-7)+(3×1) = 0kNm

The same values have been attained as for the previous method, but more quickly. We can now plot these values to form the same BM diagram as the one above.



Method 2 is the better and quicker option if a SF diagram has already been drawn.

Hints for Drawing Shear Force and Bending Moment Diagrams

1. If possible, draw both SF and BM diagrams below one another and either follow the scale given, or use a suitable one for magnitudes on the diagrams.
2. Draw a FBD (Free Body Diagram) of the beam showing all known loads (watch for the weight of the beam). Calculate the reactions and show them on the FBD.

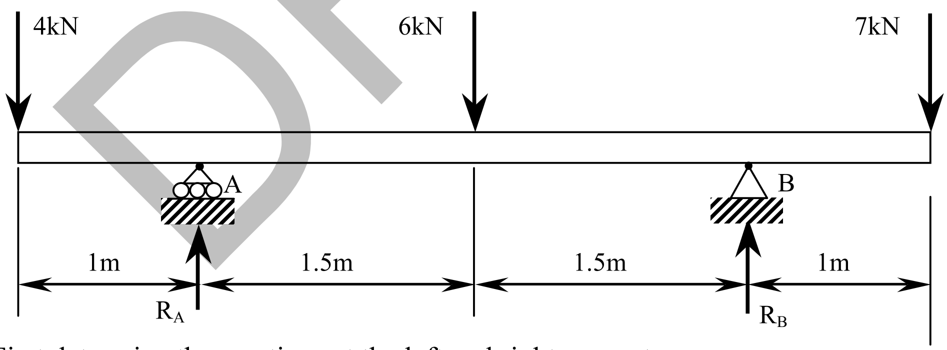
3. Draw the S.F. diagram, with reference to the FBD, by starting at the left hand end, plot upwards for upward forces and downwards for downward forces. This is called the *Follow the Force* rule.
4. Find the positions of zero S.F., for these will be the positions where the BM is a maximum i.e. SF = 0, BM = maximum).
5. Forces going down produce positive bending moments (sag); forces going up produce negative bending moments (hog).
6. Bending moments are always zero at the ends of a beam (unless a couple acts at the end e.g. a cantilever beam).
7. Calculate the B.M. either by adding moments or adding areas at the following significant positions:
   - at the supports;
   - at each point load;
   - at points where the SF is zero (this point is where the maximum BM should be).
8. Between the significant positions listed in 7, draw suitable lines according to the following: if the beam is unloaded the B.M. varies linearly (i.e. it forms straight lines)
9. Point loads produce sharp changes in the S.F. diagram, but merely slope changes in the B.M. diagram.

Point 4 is a useful check. If you refer to our example you will note that at the maximum BM the SF diagram travels across the zero axis; this is a useful thing to remember as a check when drawing BM diagrams.

We will do one more example to reinforce our knowledge.

Example 1.9

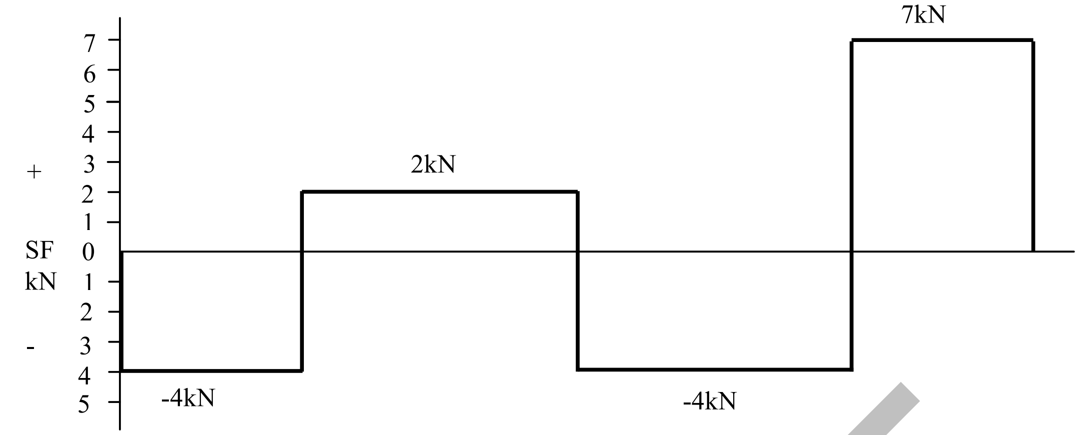
Draw the shear force and bending moment diagram for the beam when it is loaded as shown below.



First determine the reactions at the left and right support.

$$\circlearrowright + \quad \Sigma M_A = 0 = -(4\times1) + (6\times1.5) + (7\times4) - 3R_B$$
$$R_B = 11\text{kN}$$
$$\Sigma F_V = 0 = -4 - 6 - 7 + 11 + R_A$$
$$R_A = 6\text{kN}$$

Draw the SF diagram using the Follow the Force method



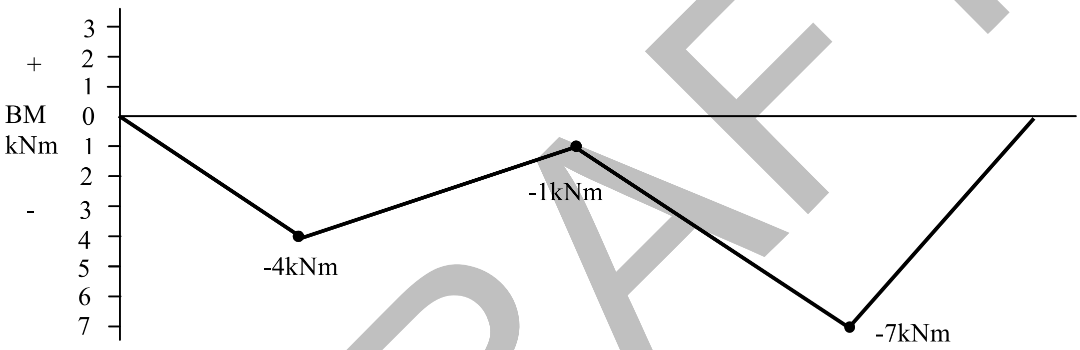
To draw the BM diagram we must find the cumulative area from left to right.

At both ends BM = zero

At R_A BM = -4×1 = -4kNm

At 6kN force BM = -4+(2×1.5) = -1kNm

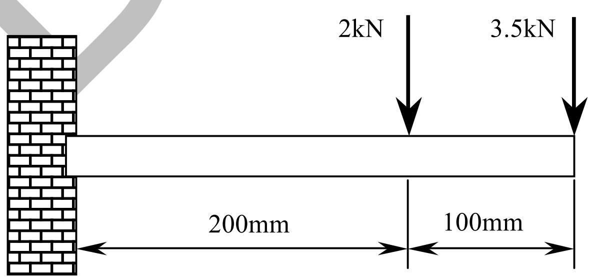
At R_B BM = -1+(-4×1.5) = -7kNm



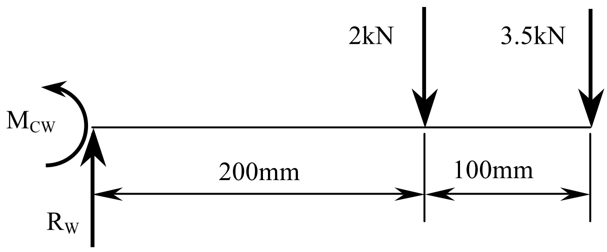
This example is a good illustration of how easy these problems can become when we use the methods above. Now consider an example with a loaded cantilever beam.

Example 1.10

The cantilever shelf in a shop is loaded as shown. Determine the shear force and bending moment diagrams.



With a cantilever there is only one fixed end, so that end must provide a force couple to stop the beam falling or rotating. The force will be equal in magnitude but opposite in direction to the sum of the vertical forces, while the reactive couple will equal the sum of all couples but have the opposite direction. Let us now draw a free-body diagram (FBD) and determine the reactions.



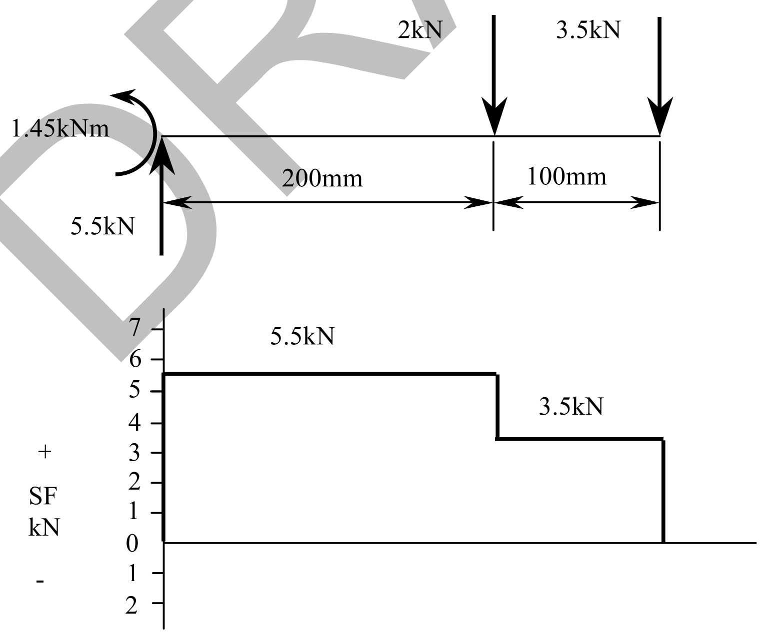
Now for the couple. It would be simple to just take moments about this point and have the couple reacting in the opposite direction. Although this works out, it is conceptually incorrect (as outlined in Volume 1 p. 62: a couple can only be balanced by another couple). Since the vertical reaction is in essence two vertical forces together (2 kN and a 3.5 kN), we must add two couples together; one couple is 2 kN times 0.2m the other is 3.5 kN times 0.3m.

Therefore: $\Sigma M_W = 0 = 2 \times 0.2 + 3.5 \times 0.3 - M_{CW}$

$$M_{CW} = 1.45\text{kNm}$$

Now that we have the reactions we can produce the SF and BM diagrams. The FBD has been reproduced above the SF and BM to clarify the method.

Cantilever beams do not lend themselves as well as simply supported beams to the quicker methods for solution. With this cantilever we are dealing with the right section where the SF is positive if going up (see p. 28).

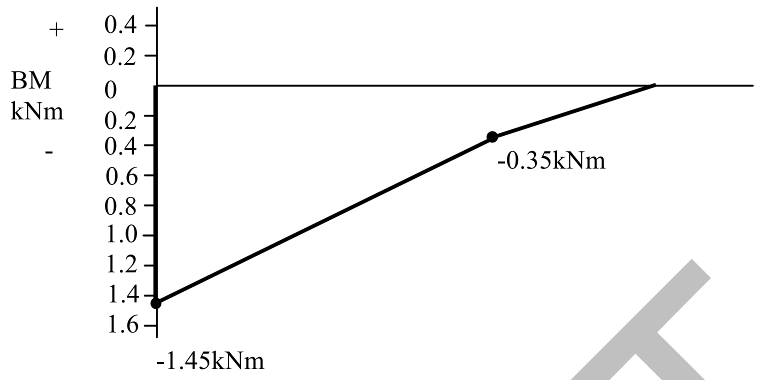


The BM diagram is still created using the area under the SF diagram. However the BM diagram will be negative since cantilevers always have a negative BM diagram. The calculations are shown below.

At 350 N force, BM = 0

At 280 N force, BM=3.5×0.1 = 0.35kNm

At end, BM = 0.35+5.5×0.2 = 1.45kNm



Note that the SF diagram for cantilevers can be either positive or negative, but the BM diagram will *always* be negative. This is useful when calculating the area under the SF diagram.

The Neutral Axis and Outer Fibre Stress

When a beam is subjected to bending, not all of the beam undergoes the same types of stress. Let us consider a beam (Fig. 1.14) bent so that the ends are up and the centre down (positive bending), the upper surfaces will be in compression and the lower surfaces will be in tension. A good test of this is to wrap a tissue over a rule and bend it. The tissue on the upper surface will wrinkle while the tissue on the lower surface will tear.

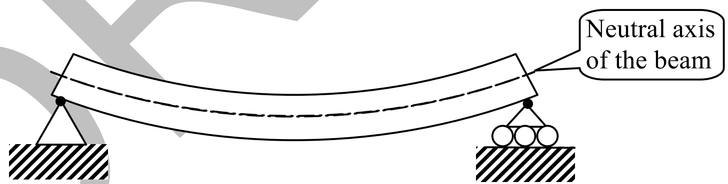


Fig 1.12: *A beam undergoing positive bending. The upper surfaces undergo tension, the lower compression and somewhere in the centre will be the neutral axis with no stress.*

Since the stresses in the beam basically reverse from top to bottom there must be a portion of the beam undergoing zero stress. This is called the neutral axis.

It follows that the greater the distance from the neutral axis the greater the stress present. In the case of a concrete beam, failure occurs on the lower surface as the tensile stress is greatest here and concrete is typically weak in tension. This is circumvented by placing steel rods in the concrete to reinforce it and take the tensile load.

It follows that there must be some relationship between stress due to bending, the bending moment present, and the distance of the section under consideration from the neutral axis.

Bending Stress Calculation

The relationship of bending stress (σ_b) to certain characteristics of the beam my be expressed mathematically as follows:

$$\frac{M}{I} = \frac{E}{r} = \frac{\sigma_b}{y}$$

M = bending moment at section (Nm)
I = second moment of area (m^4)
E = Young's Modulus for the material (Pa)
R = radius of curvature (m)
σ_b = bending stress at section (Pa)
y = section's distance from neutral axis (m)

The most used form of this relationship is the formula below,

$$\sigma_b = \frac{My}{I}$$

Radius of Curvature and Second Moment of Area – Or What are r and I?

The radius of curvature (r) is a measure of the curve the beam takes on when loaded. The smaller the value, the more bowed the beam is. It is not constant along the beam and is affected by the bending moment at that point of the beam.

The second moment of area (I) is a measure of the resistance the beam's cross-section offers to bending. The formula for the second moment of area for most cross-sectional shapes is very complex. To simplify discussion in this book, the second moment of area will be given. To help you understand what effect the second moment of area has on the body's resistance to bending, do the investigation below.

Investigation: Get two pieces of timber with the same cross-sectional dimensions and place one flat and one on its edge. Place weight on both. Which has the greatest resistance to bending?

I-beams are used extensively in civil structures. An I-beam has a cross section with greater depth than breadth, and it also places a majority of the material at the outer fibres where bending stress will be the greatest. This efficient shape uses the web to control shear stresses, the flanges to control bending stresses and also will be lighter than a solid beam with the same cross sectional dimensions.

Bending Stress and How to Calculate it.

Now that we know what "I" represents we can start to determine the bending stress in beams.

Example 1.11

Find the bending stress in the lower surface of a beam that has a depth of 300mm, a BM of 25kNm applied and the second moment of area is 3.4×10^{-4} m^4. Consider the neutral axis to be at the midpoint of the cross-section.

$$\sigma_b = \frac{My}{I}$$

$$\sigma_b = \frac{25000 \times 0.15}{3.4 \times 10^{-4}}$$

$$\sigma_b = 11024911.76 \text{ Pa}$$

$$\sigma_b \approx 11 \text{ MPa}$$

So the stress present in the lower surface of the beam is approximately 11MPa.

Example 1.16

A steel I beam has a second moment of area of 1.67×10^{-4} m^4, and a Young's Modulus of 206GPa. If the applied moment is 12kNm, then what will be:
a) The stress in the surfaces of the beam if y = 140mm, and
b) The radius of curvature of the beam?

We shall solve a) first:

$$\sigma_b = \frac{My}{I}$$

$$\sigma_b = \frac{12000 \times 0.14}{1.67 \times 10^{-4}}$$

$$\sigma_b = 10059880.24 \text{ Pa}$$

$$\sigma_b \approx 10.06 \text{ MPa}$$

Now solve b):

$$\frac{E}{r} = \frac{M}{I}$$

$$r = \frac{EI}{M}$$

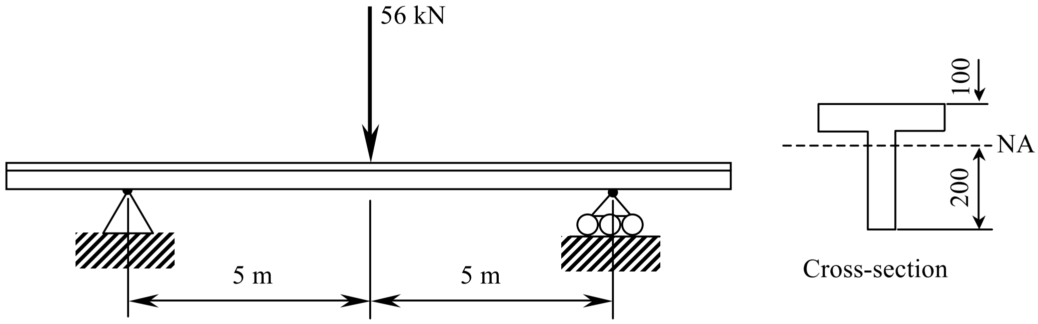
$$r = \frac{(206 \times 10^9) \times (1.67 \times 10^{-4})}{12000}$$

$$r = 2866.83 \text{ m}$$

Example 1.12

A beam is loaded as shown below. Find:

a) The bending stress at the applied force in the upper and lower surfaces of the beam shown ($I = 4.6 \times 10^{-4}$ m^4);
b) The Value for Young's Modulus if the beam has a radius of curvature of 230 m.

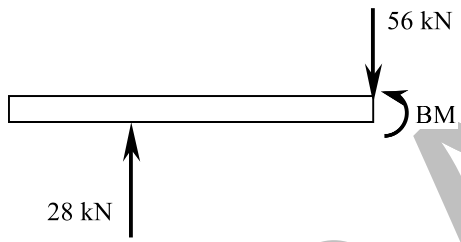


This cross section differs from the previous I beam as it is not symmetrical about two axes. As a result the neutral axis (NA) is not halfway between top and bottom.

Let us solve part a):

First we must find the bending moment that exists at the load. Since the load is midway between the reactions then each reaction must be half of the load. Therefore both reactions are 28 kN vertically up.

So the BM is:



$$\circlearrowleft + \quad \Sigma M = 0 = 28 \times 5 - 56 \times 0 - BM$$
$$BM = 140 \text{ kNm}$$

For the upper surface

$$\sigma_b = \frac{My}{I}$$
$$\sigma_b = \frac{140000 \times 0.1}{4.6 \times 10^{-4}}$$
$$\sigma_b = 30434782.61 \text{ Pa}$$
$$\sigma_b \approx 30.43 \text{ MPa}$$

For the lower surface

$$\sigma_b = \frac{My}{I}$$
$$\sigma_b = \frac{140000 \times 0.2}{4.6 \times 10^{-4}}$$
$$\sigma_b = 60869565.22 \text{ Pa}$$
$$\sigma_b \approx 60.87 \text{ MPa}$$

The stress in the lower surface will be twice the amount of the stress in the upper surface, as the lower surface is double the distance away from the neutral axis. If this was a material weak in tension, such as concrete, there would need to be reinforcing done on the lower surface, or the section of the beam would be changed.

Now we shall solve part b).

$$\frac{E}{r} = \frac{M}{I}$$
$$E = \frac{Mr}{I}$$
$$E = \frac{140000 \times 230}{4.6 \times 10^{-4}}$$
$$E = 7 \times 10^{10} \text{ Pa}$$
$$E = 70 \text{ GPa}$$

With such a figure for E, it is likely that that beam is made of an aluminium alloy. If the alloy was steel with a higher value for E, then the radius of curvature would be *larger*, since the beam would not bend as much. The smaller the radius of curvature, the more a beam has bent.

Uniformly Distributed Loads

Unlike a point load, a uniformly distributed load (UDL) is a load that is uniformly spread across a beam. If you are to stand on a beam on one foot and allow all your weight to be supported by that one foot, then your weight is concentrated as a point load. However if you lie face down on the beam your weight will be uniformly spread across most of your length, hence your weight will be spread out.

Good examples of uniformly distributed loads are wind blowing against a building, a fish tank on a shelf, and perhaps best of all, the weight of a beam itself. When a beam is placed on supports the beam itself has mass that acts on the supports. We usually neglect this since it simplifies the problem and the engineer has already designed the supports to take this load in addition to any further external loads.

If a beam is uniform it means that its mass is evenly distributed across its length. Fig. 1.15 (a) shows a beam resting on supports. If it has a mass of 1000 kg and is 10 m long then it is considered to have a mass of 100 kg per metre (kg/m). Now the UDL of this beam will be the weight, so if the total mass was 1,000 kg then the weight is 10,000N or 100 kN, so the UDL will be 10 kN/m. Fig 1.15 (b) shows how we represent the UDL of the beam.

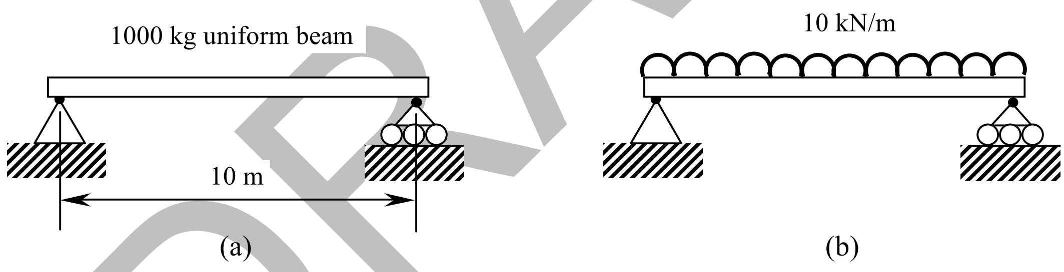


Fig 1.13: *The same beam: (a) shows it simply with its mass listed, (b) shows it with its weight as a UDL.*

A UDL will tend to produce a different shape in shear force and bending moment diagrams, while you are not expected to be able to draw them for the course you must be able to recognise them. In a shear force diagram the angled lines replace the horizontal lines of a point load SF diagram. In the shear force diagram the UDL is represented by the slope of the lines, if the UDL is large the SF diagram will have a large gradient.

Whereas in a BM diagram point loads create angled lines, with a UDL the lines will be curves. This curve will at times be parabolic in nature and a simple UDL with no point loads will bring about pure parabolic curve for the bending moment diagram.

In most UDL situations there will be a mix of point loads and UDLs, which means the key features to check for in the UDL regions are angled lines in the SF diagram and curves in the BM diagram.

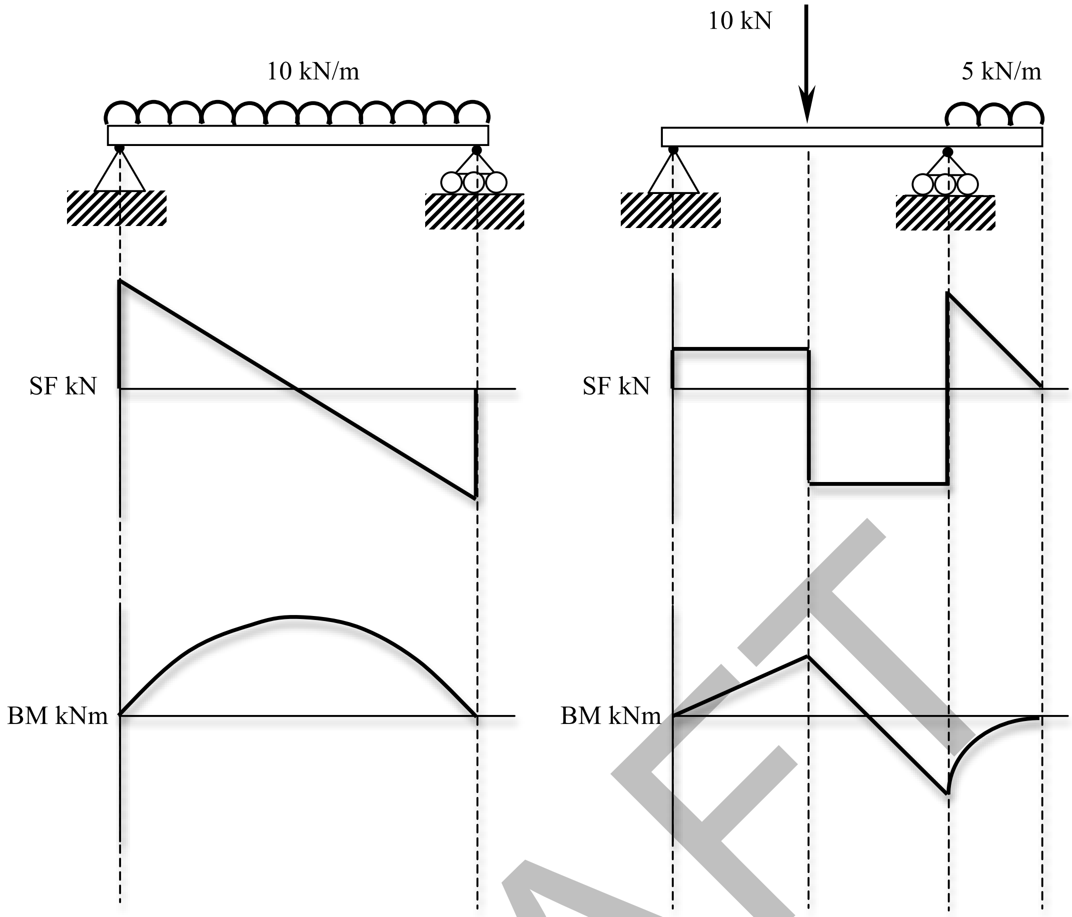


Fig 1.14: *Two beams with UDLs with the resulting Shear Force and Bending Moment Diagrams.*

Stress and Strain

Stress and strain were concepts first covered in Volume 1. To recap what they are: Stress may be defined as a measure of the internal reaction that occurs in response to an externally applied load. This internal reaction is related to the original cross sectional area to quantify the nature of the reaction. The unit for stress is the Pascal (Pa) and one Pascal is 1 N/m^2. The formula for stress is as follows:

$$\sigma = \frac{P}{A}$$

σ = stress (Pa)
P = load (N)
A = cross sectional area (m^2)

Strain is defined as the proportional change in length caused when a specimen is under an axial load. Strain may be found using the following formula:

$$\varepsilon = \frac{e}{L}$$

ε = strain
e = extension (m)
L = original length (m)

Both of these concepts are important in the design of civil structures, as stress and strain are primary factors in material choice and design style.

In mechanically elastic structures such as bridges and buildings, stress is directly proportional to strain.

Shear Stress

Shear stress differs slightly from tensile and compressive stress. It is essentially the same concept but it is a measure of the internal reaction to a shearing force. Although the formula is of the same form it is the value for area that differs. In compressive and tensile stress the area used for computation is the cross-sectional area, whereas with shear stress, the area represents the shear area, which is decided by the type of shearing performed. So the formula becomes:

$$\sigma_s = \frac{P}{A}$$

σ_s = shear stress (Pa)
P = load (N)
A = shear area (m^2)

If the shear plane runs perpendicularly across the object, the shear area will be the cross-sectional area. If, however, the shearing operation punches a hole then the shear area will be the circumference of the hole multiplied by the thickness of the material.

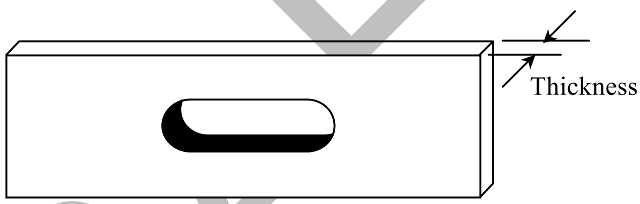


Fig. 1.15: *The shaded portion of the opening shows part of the shear area. This total shear area is calculated by multiplying the perimeter of the shape by the thickness.*

Example 1.13

Find the shear stress present when a circular hole of diameter 30 mm is punched in a plate for use on a bridge, when the plate is 20 mm thick and the punching force is 60 kN.

The shear area is found by finding the circumference of the circle and multiplying that figure by the thickness of the plate.

$$C = \pi D$$
$$C = 3.14 \times 0.03$$
$$C = 0.0942 \text{ m}$$

$$A = C \times d$$
$$A = 0.0942 \times 0.02$$
$$A = 1.88 \times 10^{-3} \text{ m}^2$$

Once the area is found it is possible to find the shear stress.

$$\sigma_s = \frac{P}{A}$$

$$\sigma_s = \frac{60000}{1.88 \times 10^{-3}}$$

$$\sigma_s = 31914893.62 \text{ Pa}$$

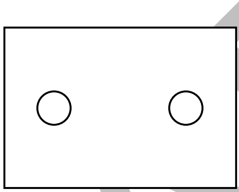
$$\sigma_s = 31.9 \text{ MPa}$$

So the shear stress set up by punching this hole into the plate is 31.9MPa.

Sometimes a punching operation will punch out the exterior shape and holes at the same time. This is outlined in Example 1.2.

Example 1.14

A rectangular plate for a truss bridge is to be punched from 10mm sheet steel with a force of 60kN. During the punching operation two 25mm diameter holes are also punched. Find the shear stress if the plate has dimensions 150mm by 120mm.



A diagram of the plate is shown above (note the diagram is not to scale). We must find the total perimeter by taking the perimeter of the rectangle and adding it to the circumferences of both circles, then multiplying that total perimeter by the thickness to find the shear area.

$$\text{Total Perimeter} = 2b \times 2h + 2\pi D$$

$$\text{Total Perimeter} = 0.3 + 0.24 + 2(3.14 \times 0.025)$$

$$\text{Total Perimeter} = 0.54 + 0.157$$

$$\text{Total Perimeter} = 0.697 \text{ m}$$

The shear area is now found by multiplying the total perimeter with the thickness of the plate. Hence,

$$\text{Shear Area} = \text{Total Perimeter} \times \text{Thickness}$$

$$\text{Shear Area} = 0.697 \times 0.01$$

$$\text{Shear Area} = 6.97 \times 10^{-3} \text{ m}^2$$

Now we can find the shear stress using the load given and the shear area we just determined.

$$\sigma_s = \frac{P}{A}$$

$$\sigma_s = \frac{60000}{6.97 \times 10^{-3}}$$

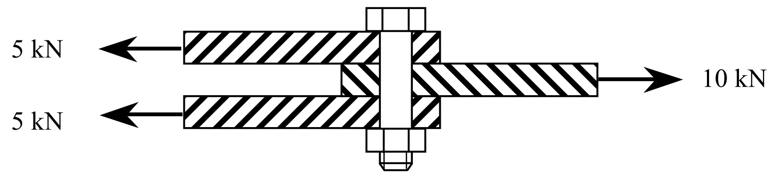
$$\sigma_s = 8608321.38 \text{ Pa}$$

$$\sigma_s = 8.61 \text{ MPa}$$

The shear stress in the material is 8.61MPa.

Example 1.15

A bolt is used to hold a coupling together. If the coupling takes a load of 10 kN and the maximum allowable shear stress of the bolt is 30 MPa, determine the minimum diameter of the bolt.



This situation is a classic shear stress problem, for it illustrates the concept of double shear. The arrangement of the coupling means the bolt will try to shear in two places. This means that the area is doubled in the calculations.

$$\sigma_s = \frac{P}{A}$$

$$\sigma_s = \frac{P}{2A}$$

$$\frac{\pi d^2}{2} = \frac{P}{\sigma_s}$$

$$\pi d^2 = \frac{2P}{\sigma_s}$$

$$d = \sqrt{\frac{2P}{\pi \sigma_s}}$$

$$d = \sqrt{\frac{2 \times 10,000}{\pi \times 30 \times 10^6}}$$

$$d = 0.014567 \text{ m}$$

$$d = 14.57 \text{ mm}$$

This means that the minimum size for the bolt must be 14.57 mm. As no such bolt is readily available the engineer will choose a commercially available size larger than this, such as 16 mm.

Engineering and Working Stress

In Module 3 in Year 11 we discussed stress/strain diagrams. Examples are shown in Fig. 1.16 (stress/strain diagrams are covered in greater detail in this chapter on page 46).

One thing that puzzles most students is why the stress falls away at the end of the diagram for ductile materials. This is because engineers tend to cheat a little with these diagrams; they show *engineering stress*. Engineering stress is calculated with the load always divided by the original cross sectional area, even though the cross section actually reduces just before failure. So this type of engineering does not take into account the falling cross sectional area. This is done for ease of calculation otherwise the cross sectional area would need to be determined continually, making tensile testing a laborious process. The term used to describe the "real" stress is *true stress*.

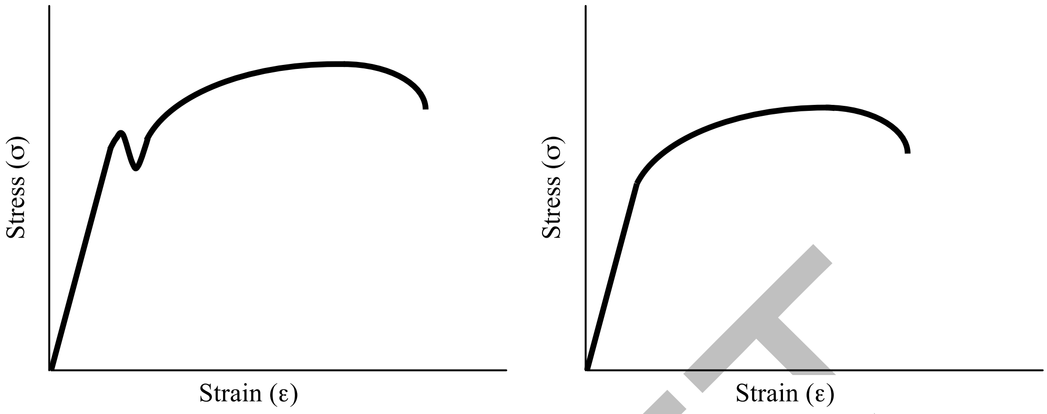


Fig 1.16: *Two stress/strain diagrams. The one on the left shows definite yield points and the other shows progressive yield.*

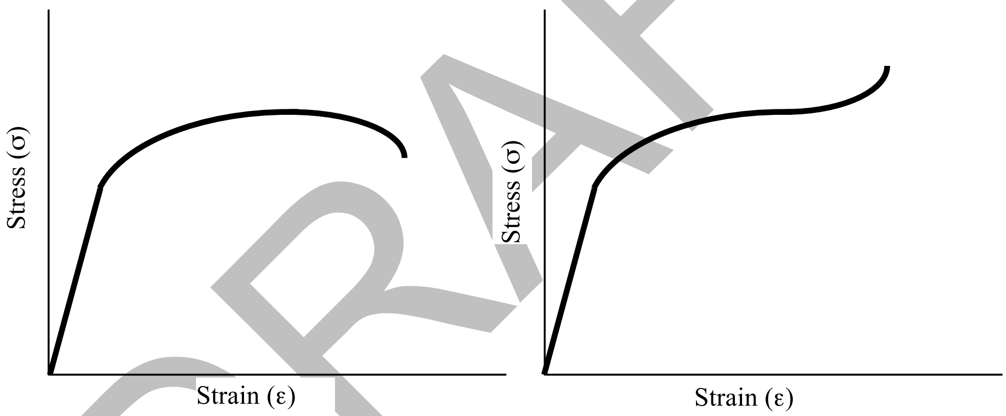


Fig 1.17: *Two stress/strain diagrams, the one on the left shows engineering stress and the other shows true stress.*

Maximum allowable stress, or safe working stress, may be defined as the maximum permissible stress that a material or object will be subjected to when in service. Working stress is usually less than the yield stress and the UTS. The ratio of working stress to one of the other two values is called the Factor of Safety (outlined below) and it is an important consideration in designing equipment. Safe working stress is always less then the elastic limit for a given material.

Related Terms and Definitions

Elastic limit is the stress up to which the strain is elastic. This means that if the load is removed, the object will return to its original shape and size. Beyond this point, permanent deformation occurs.

Yield stress is the stress where there is a marked increase in strain without a corresponding increase in stress. In mild steel, there are definite yield points but most materials show progressive yield. The yield stress is always greater (though often only by a small amount) than the elastic limit, but less than the UTS.

Proof stress is the amount of stress necessary to bring about a certain amount of permanent strain in a material. Proof stress is used as a measure of yield on materials that do not show a marked yield point (i.e. progressive yield). Usually a set amount of strain is given, for example 0.2%, and the amount of stress necessary to record this level of strain is calculated.

Resilience is the ability of a material to absorb energy, but only up to the elastic limit. The area under the curve in the elastic deformation region represents the resilience of a material. The resilience represents the amount of strain energy that is stored in the deformed object.

Toughness is a measure of the ability of a material to absorb energy. Tough materials are those capable of absorbing strain energy or the energy of an impact, and are the opposite of brittle materials. The toughness found by the area under the stress/strain curve is a different value of toughness to that found in impact testing.

Hooke's Law may be stated as follows: "*Stress is proportional to strain up to the elastic limit*". This means that any increase in stress will bring about a proportional increase in strain up to a given point. English physicist Robert Hooke (1635-1703) studied elastic materials to establish this law. Written mathematically Hooke's Law is:

$$E = \frac{\sigma}{\varepsilon}$$

E = constant
σ = stress (Pa)
ε = strain

This constant is a measure of the materials resistance to stretching up to the elastic limit and is sometimes called the *modulus of stiffness* or *Young's Modulus*.

Young's modulus is actually the more common name for modulus of stiffness, represented by the constant in Hooke's Law. English scientist Thomas Young (1773-1829) determined this modulus and it was named *Young's modulus of elasticity* in his honour. Mathematically it can be written as follows,

$$E = \frac{\sigma}{\varepsilon} = \frac{P/A}{e/L} = \frac{PL}{eA}$$

E = Young's Modulus of Elasticity (Pa)
P = axial force (N)
A = cross-sectional area (m^2)
e = deformation (elongation, compression, etc.) (m)
L = original gauge length (m)
σ = stress (Pa)
ε = strain

Factor of Safety (FofS)

Factor of Safety is the ratio of Safe Working Stress to either the yield stress or ultimate tensile stress depending on the type of material. It is an important consideration in designing equipment.

For ductile materials

$$\text{FofS} = \frac{\text{Yield Stress}}{\text{Maximum Allowable Stress}}$$

For brittle materials

$$\text{FofS} = \frac{\text{UTS}}{\text{Maximum Allowable Stress}}$$

The FofS has a large impact on the design of an object. In buildings and bridges the FofS is usually large to ensure that there is no chance of failure. In aircraft design the FofS is as low as possible due to the problems related to the extra weight of a design. FofS is decided by both the application and the material.

Example 1.16

A bridge is designed to have a factor of safety of 8. If a member is made of steel and the yield stress is 250 MPa, what will be the maximum allowable stress?

$$\text{FofS} = \frac{\text{Yield Stress}}{\text{Maximum Allowable Stress}}$$

$$\text{Maximum Allowable Stress} = \frac{\text{Yield Stress}}{\text{FS}}$$

$$\text{Maximum Allowable Stress} = \frac{250}{8}$$

$$\text{Maximum Allowable Stress} = 31.25\ \text{MPa}$$

To achieve a low maximum available stress the member must be made larger than it would be for a lower FS.

Stress/Strain Diagrams

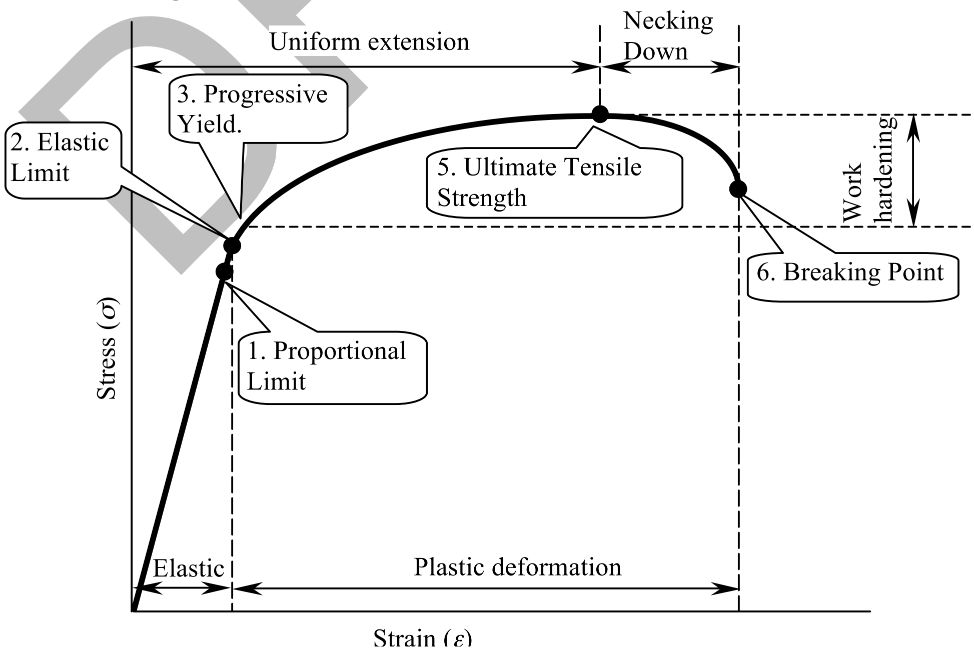


Fig 1.18: *A stress/strain curve for a material showing progressive yield.*

Stress/strain curves are graphs used to compare the stress and strain of a material loaded in a test. Originally a load/extension (or deformation) curve will be produced, but these values are converted to stress and strain respectively. The stress/strain curve will show features such as elastic limit, type of yield (progressive or definite), UTS and breaking point.

Stress/strain curves are very useful for determining the performance of different types of materials and different sized test pieces. A stress/strain curve (typical of 70/30 annealed brass) similar to one from Volume 1 is shown in Fig 1.10.

Engineering Materials

Testing of Materials

We learn a lot about how materials deform and crack by carrying out specially devised tests. Some testing for cracks and cracking can be carried out in situ using X-rays and ultrasound e.g. for cracks/inclusions in welded high pressure gas pipes and aircraft engine components. However, other destructive tests allow us to watch and analyse material behaviour under load.

Specialised Testing of Engineering Materials and/or Systems

Table 1.2: *Non-destructive and destructive tests used for civil structures*

Test	**Type**	**Use**
X-ray	Non-destructive	To determine if cavities are present.
Dye penetrant	Non-destructive	To find small cracks in the surface by placing a dye on the surface and examining the surface, after cleaning, under UV light.
Ultrasonic	Non-destructive	Ultrasonic pulses are used to determine if cavities are present.
Tensile	Destructive	Used to determine the tensile strength of materials used. Test piece is stretched and load and extension are recorded.
Compressive	Destructive	Used to determine the compressive strength of materials used. Test piece is compressed and load and deformation are recorded.
Transverse	Destructive	This test is used to determine a materials performance when undergoing bending and shear. Outlined in more detail below.
Torsion	Destructive	Torsion tests are done on material to see how they will cope with twisting forces (couples).

Often, when examining the materials suitable for use in civil structures, engineers will need to perform various tests, some non-destructive, others destructive. Table 1.2 lists some tests used in civil structures.

Non-destructive testing

There are a variety of non-destructive tests that can be used. For civil structures, X-ray testing, dye penetrant methods and ultrasonic testing are of primary importance.

X-ray testing

X-ray testing for engineering operates on the same principles as medical x-rays. X-rays are passed through an object and expose a photographic film on the opposite side. If there is a cavity in the material the x-rays will pass through that area more easily and thus more x-rays will reach the film. At that point the film will show a darker patch and reveal a possible cavity in the material. Nowadays x-ray testing is often linked to computerised systems that allow 3D imaging of fractures and imperfections in the component.

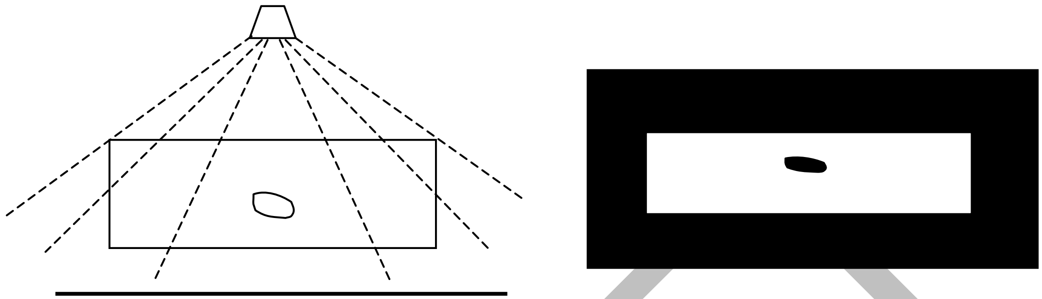


Fig. 1.19: *X-ray testing, the figure on the left shows the x-rays passing through an item to the photographic film, while the figure on the right shows the resulting exposed film with the cavity darker.*

Dye penetrant testing

This testing procedure is used to determine if cracks are present in metallic items. The surface is prepared by removing any oil or surface contaminants in the suspect area. The suspect area is heated and a dye is then placed over the surface and excess is wiped off. A developer (usually a white powder) is sprinkled over the area and then the object is cooled. If a crack is present the dye will be squeezed out of the crack by the contraction of the cooling item and reveal the presence of a crack.

Ultrasonic testing

This system works similarly to x-ray testing, but high frequency radio waves are used instead. A transmitter sends ultrasonic waves through a component and normally these pass through to the other side of the component and are reflected back to the sender. The reflected signals are recorded by a display. The height on the display is proportional to the thickness. If a cavity is encountered the sound wave will be reflected early and the display will show a lower reading.

Transverse test

The transverse test is useful for determining how a material will perform when bent. It is particularly useful for materials which are difficult to tensile test. The material is supported at either end and a load is applied on the opposite side in the centre of the two supports, or at positions a third and two-thirds between the supports. In both cases a measure is taken of the bending load and of the total deflection at rupture. The data is converted into stress and strain for analysis.

Testing of Concrete

Slump Test

The slump test is used to check that the concrete is of appropriate fluidity for casting. The concrete is cast into a conical mould, open at the top and the bottom. The mould is placed on a board then the concrete is poured in. Upon removal of the mould the conical wet concrete that is left behind, should slump slightly according to set specifications. If it simply collapses it is to wet, if it breaks in half and crumbles then it is too dry. If the concrete does not have the right consistency there may be difficulties with its casting.

Compressive Test

Concrete is strong in compression and after casting various specimens will be taken and subjected to compression tests after specified time intervals, e.g. 30 days. If the concrete fails any of the tests, then the material was a faulty mix and may need to be removed and re-cast, a very expensive and time consuming option.

Crack Theory

Stress concentration can have a large impact on the behaviour of a material or object in service. At the turn of the century much effort was put into trying to explain why some ships broke in half in heavy seas, when theoretically they were capable of the loading. Professor Inglis, in 1913 showed that the reason for this was that certain parts of the ship's structure e.g. doors and sharp corners tended to concentrate stress at a much higher level than if the irregularity had not been there.

In 1920, a gentleman by the name of A. A. Griffith published a paper that explained that the reason that the practical, mechanical strength of a material is lower than its theoretical mechanical strength is due to irregularities in the surface that cause stress concentrations and then cracks. Essentially it is the same concept that Inglis proposed, but on a much wider scale, because it was not just confined to ships.

The way cracks form and grow is closely linked to the applied stress, the Young's Modulus of the material and the strain energy present.

Strain Energy

Work and energy are important concepts. We first looked at these in Volume 1 (pp. 101-104). Work occurs when a force causes motion and work is closely linked to energy. Let us imagine you lift a 10 kg mass up 1 m, the work done is 100 J and the mass now has potential energy of 100 J; your work has become potential energy. Now let us suppose you compress some metal in a vice. You have done work but where has it gone? The metal doesn't have potential energy, as it is still at the same height as before and no kinetic energy as it isn't moving; instead it has gained *strain energy*.

Strain energy is a close relative of potential energy and is a measure of the amount of energy stored in a material that has undergone some strain, whether it be compressive, tensile, shear, bending or torsion. The strain energy per unit volume of a material is determined using the formula below.

$$SE = \tfrac{1}{2}\sigma\varepsilon$$

SE = strain energy/unit volume (J/m^3)
σ = stress (Pa)
ε = strain

If we can write strain in terms of stress and Young's modulus then the formula becomes:

$$SE = \tfrac{1}{2}\sigma\varepsilon$$

$$SE = \tfrac{1}{2}\sigma\left(\frac{\sigma}{E}\right) \qquad \left(\because \varepsilon = \frac{\sigma}{E}\right)$$

$$SE = \frac{\sigma^2}{2E}$$

We can say that strain energy is proportional to the square of stress and inversely proportional to Young's Modulus. That means if stress is increased then strain energy increases, and if Young's modulus for a material is high, strain energy will be less than for a material under equal stress with a lower Young's Modulus.

So why is strain energy important? When a crack begins to grow, the material is releasing its strain energy, and thus the strain energy present in a material will have a large impact on the formation and propagation of cracks in the material. Larger strain energy means more energy to release and greater chance of crack propagation.

Crack Formation and Growth

How do cracks form and grow? The answer is neither brief nor simple. A material has two methods of failure, brittle or ductile failure, and the structure of the material determines how it will fail. Metal alloys such as mild steel undergo ductile failure up to a point, so they extend in length until brittle failure takes over. Brittle materials like concrete and glass do not undergo ductile failure; they undergo immediate brittle failure. Crack formation and growth is a method of brittle failure.

Theoretically glass and other ceramics should be very strong in tension. Unfortunately they never achieve this good tensile performance because there are tiny micro cracks, micro gas bubbles and minute crystallites on the surface that concentrate stress at one point and from this grows a crack. Since these are brittle materials it is a healthy breeding ground for the crack to grow i.e. propagate through the material. So, how does a crack grow and why doesn't it stop?

Fig 1.20 (a) shows a set of atoms in a material with a perfect linking of the atomic planes, however (b) shows that an imperfection is present in the top layer. This will tend to concentrate twice the stress at the next bond, as it must do the work of two bonds. By (c) the crack is travelling through the bonds as they break and the remaining bonds become more and more highly stressed (d). As this continues the likelihood of the crack growing increases and eventually the crack will travel right through the material.

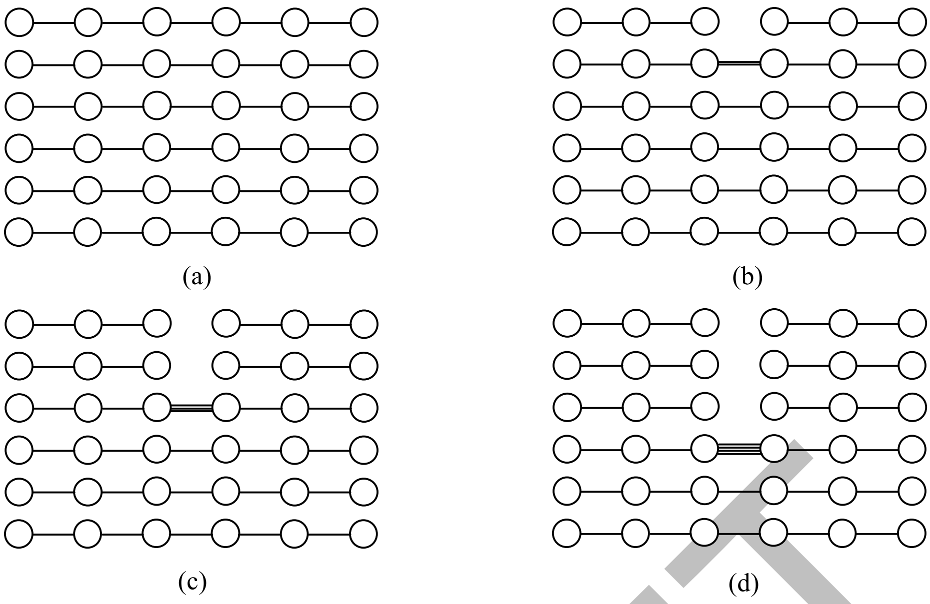


Fig 1.20: *The growth of a crack at the atomic level*

Strain energy is closely linked to the growth of cracks. When a crack forms, the strain energy held in the entire object is retained but it is released from the area adjacent to the crack. This released strain energy is now concentrated at the bottom of the crack, thus increasing the strain energy at the tip, so when cracks get larger they grow faster and faster.

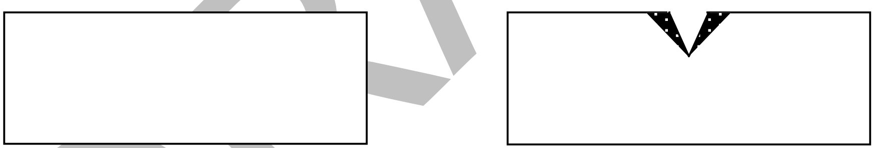


Fig. 1.21: *The left figure is one strained but without a crack, the right figure shows the growth of a crack and the release of strain energy around the crack.*

Critical Crack Length

There is a critical length that a crack must get to before it proceeds through a material. This is a particularly important factor in design of components in civil structures that use brittle materials e.g. concrete. Once this crack length is exceeded under the load that has created it, a crack will travel through a material until failure occurs.

While determining critical crack length is beyond the scope of this course it is crucial in the design of many objects, for a material will fail once this length is exceeded, even if the stress applied is lower than that which the material can theoretically allow. While students will not be expected to manipulate the critical crack length formula we can say that critical crack length is directly proportional to Young's Modulus, and inversely proportional to the applied stress. This means for a given stress a material with a higher Young's Modulus should have a longer critical crack length.

The longer the critical crack length is the less likely it is that a material will fail. As stress increases the critical crack length will decrease, so to compensate we want a material that has a high stiffness (Young's Modulus). One such material is mild steel; along with the fact that it is cheap and relatively easily shaped and fabricated this is part of the reason for its wide use.

Failure Due to Cracking

Failure due to cracking as outlined above is a brittle fracture mechanism. As a consequence some materials are more likely to crack than others. In accordance with a material's propensity to crack is its critical crack length; the more brittle a material, the shorter its critical crack length will be. Once the critical crack length is exceeded then failure is inevitable if stress levels are maintained.

One material that is greatly affected by cracking in bridges is concrete. Being a brittle material it has a far shorter critical crack length than steel, so engineers must take account of this in relation to stress levels that are placed on the material. Reinforced concrete has been developed in an attempt to overcome the fact that when a concrete beam bends, its lower surface is placed in tension and thus risks cracking. By placing steel rods in the concrete, in this area, the danger of a crack forming and growing is greatly reduced.

Repair and/or Elimination of Failure Due to Cracking

The next step is how to prevent cracking, and if it does occur, to repair it and stop it from occurring again.

In the event of crack formation we are aware that stress concentration plays a large role. Once a crack grows, the stress concentration increases, so if a crack forms, what can be done?

If the material in question is metallic then one option to repair a crack is through welding. This solution has problems, however, because although it will repair the crack, microstructural changes will appear around the weld that may further weaken the material, and the weld may be a point of stress concentration. After welding, it may be necessary to heat treat the area to avoid microstructural problems.

In polymeric materials it may be possible to use adhesive technology to repair cracking. If the failure is in a thermoset and adhesives are not available, replacement is the answer. However, for thermoplastic polymers, adhesives are not the only solution. Another option is polymer welding, which offers strengths close to the parent material.

Ceramic materials such as stone and concrete are more difficult to repair and often need to be replaced in the event of crack formation

But how do we eliminate cracks from forming? One method is to design the item without sharp corners, which tend to concentrate stress at a point. Another solution is to place interfaces within a material. An interface is an area within a material, weaker than the surrounding area that runs perpendicularly to the expected growth of the crack. When a crack travels through the material it reaches the interface but is blocked from passing it. By placing the interface at the correct position it is possible to avoid a crack getting to the critical length for the material.

Ceramics

Structure and Property Relationships/Applications

Ceramics are a diverse field of materials that are used extensively in civil structures. The structure that the ceramic takes tends to have a considerable effect on its appearance and behaviour. Below is a list of ceramics used in civil engineering, their structures, properties and their uses.

Stone

Stone may come in various forms. In Sydney many civil structures used sandstone in the early days of European settlement because of its availability. Sandstone is a sedimentary rock that forms by the build up of layers of sediment over millions of years. The pylons at either end of the Sydney Harbour Bridge are not sandstone but granodiorite. Granodiorite is a rock with a structure between that of granite and diorite. These three are examples of igneous rocks, which form by the cooling of lava from volcanic activity. Slate was used on many early buildings for roof tiles. It is a metamorphic rock, which is either an igneous or sedimentary rock that has metamorphosed into another form because of heat and pressure.

Sedimentary rocks, such as sandstone, characteristically tend to have a "grainy" appearance, while igneous rocks tend to have greater cohesion. Igneous and metamorphic rocks are dense because of their formation from the liquid state or compaction under pressure.

All stone exhibits similar mechanical properties; it is weak in tension, strong in compression and low in toughness, i.e. brittle. This brittleness made it easy to chisel but meant that the stone structure had to be made so it was loaded in compression. Sedimentary rocks such as sandstone characteristically tend to have a "grainy" appearance, while igneous rocks tend to have greater cohesion. Igneous and metamorphic rocks tend to be very dense due to the formation from the liquid state or compaction under pressure.

Glass and Cement

The structure/property relationships of these two materials are outlined in the next two sections.

Glass

Glass has found immense use in many civil structures. Originally used sparingly in openings on stone buildings, glass now dominates the architecture of many modern buildings. Glass is an amorphous solid. That is, it does not have a regular crystalline pattern like metals. In essence it is a very viscous liquid. This structural feature makes glass transparent, which provides it with its primary function. This feature, however, comes at a cost because the amorphous structure makes glass unfavourable to shaping by force as slip of the atoms cannot occur. Therefore, shaping must be done at elevated temperatures where the viscosity of the glass is reduced. Glass has low toughness, so it is brittle, and is weak in tension, which is why windows often break on impact. Glass shows almost perfect brittle fracture under tensile testing.

Common window glass is a mixture of silica (SiO_2) soda (Na_2O) and lime (CaO). The soda overcomes devitrification (where the glass crystallises) and the lime makes the glass non-water soluble. These glasses soften at temperatures above 850°C and are relatively cheap to make. As mentioned earlier, these glasses exhibit weakness in tension and are also brittle. This can be a problem in some civil structures where a window may be subjected to shock impact loads. To overcome this inherent weakness in tension *toughened glass* was developed.

Toughened glass is a heat treated glass that increases the toughness of a glass pane. The glass pane is heated then the outer surfaces are cooled quickly by blasts of cold air. This leaves the surface cold but the interior hot. As the interior cools it contracts and places the outer surface into compression, so to cause a tension failure in one of the surfaces the compressive force must be overcome first.

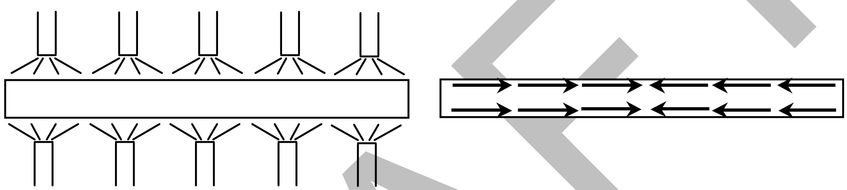


Fig. 1.22: *Toughened glass being produced with blasts of cold air at the surface. The outer layers are then placed in compression, which strengthens the glass.*

Cement

Cement is a ceramic material formed by complex reactions when alumina, soda and lime are reacted at high temperatures. Cement can come in two forms hydraulic cement, that which will harden underwater and non-hydraulic that which will not harden underwater. Portland cement, which is an hydraulic cement, is commonly used in civil structures. Like many other ceramics it is strong in compression but weak in tension, while also exhibiting low toughness. It has very similar properties to many types of stone but has the advantage of being able to be cast to almost any shape.

Cement and concrete are different although lay people use the two terms interchangeably. Cement is a ceramic material while concrete is a composite that in part consists of cement.

Cement powder is a mix of various materials. The steps for producing cement powder are listed below.

1. Limestone and shale are both crushed then mixed together, then pass through grinding mills into a kiln.
2. In the kiln, at an approximate temperature of 1480°C, the mix fuses and forms *clinker*. The clinker is now ground and stored ready for the next step.
3. The clinker is then mixed with gypsum (up to 5%) which slows down the setting time once water is added.
4. The clinker/gypsum mix is then reground and mixed to the very fine cement powder and stored in a moisture-free environment, ready for use.

Setting of Cement

When Portland cement is mixed with water a complex set of chemical reactions occur that tend to form a silicate gel. Essentially the setting involves both the evaporation of water and the formation of these silicates. This silicate gel accounts for about half the mass of the set cement and binds the other constituents together. The gel provides the strength of the set cement. These chemical reactions are exothermic which means they give off heat. This is the reason why setting cement is often hosed down during curing.

It should be noted that although cement (and concrete) dry hard with a day or two, they do not reach full bond strength for many years.

Bricks

Bricks are generally rectangular building blocks that are traditionally made of clay, but nowadays may be made form concrete. Very early construction in Sydney used sandstone blocks cut from quarries, but it is significantly more cost effective to manufacture bricks from clay. The clay is formed into the brick shape and then fired to set the clay to that permanent shape. Bricks may be pressed, recognised by being solid, or extruded where upon they will have a number of holes through them. Bricks are still used extensively in housing construction either as brick veneer or as double brick construction. Many large brick wall sections now user "besser" blocks, which are large concrete blocks, with two hollow channels in them.

Fig. 1.23: *Three bricks; left is a clay pressed brick, centre is a clay extruded brick and on the right is a concrete "besser" style brick.*

Composites

As we learnt in Volume 1, composite materials are where two or more materials are mixed or used together to take advantage of the best properties of each. There are however natural composites as well, such as timber.

Timber

Timber is a composite in that the cellulose fibres or *tracheids*, are held together by the *lignin*, a natural resin. The timber composite is tracheids in a lignin matrix. It was not until the 1940s that humans mirrored this type of structure to achieve lightweight composites such as fibreglass and carbon fibre.

Timber can come in two forms: softwood and hardwood. These are rather misleading terms though. For example balsa wood is quite soft yet it is a hardwood. A more correct terminology is to call them pored (hardwood) and non-pored (softwood) timbers. Structurally they differ in that the pored timbers have pores or vessels running through the structure between the tracheids to carry nutrients, while non-pored timbers have a neater, more uniform structure without pores, just the tracheids. Pored timbers come from flowering plants (angiosperms) while non-pored timbers come from the pines and conifers (gymnosperms).

Although there are materials that now favourably compete with timber for use in civil structures, it still offers some desirable properties. It has an excellent specific strength (strength/weight ratio), and reasonable performance in bending. It also has a relatively high Young's modulus. It is, however, adversely affected by weather and also susceptible to attack from pests, such as termites. Most ancient timber structures do not exist today because of this.

Mortar

Mortar is the material used between bricks in building. Prior to the development of Portland cement, mortar consisted of slaked lime ($Ca(OH)_2$), sand and water. This creates a slow hardening paste that hardens, with the lime reacting with carbon dioxide to produce calcium carbonate ($CaCO_3$), which replaces the sand/slaked lime paste with a hard solid. Nowadays mortar contains Portland cement, sand and lime in the ratio of 3:2:1.

Concrete

Concrete and steel are two of the most important engineering materials used today. Concrete is a composite material that consists of cement, sand and aggregate (which is commonly basalt but some blast furnace slag may also be used). The sand fills the gaps between the aggregate while the cement acts as the binder or matrix that holds the sand and aggregate together. The sand and aggregate tend to bulk out the concrete and reduce the cost because of less cement being required. It so happens that they also contribute to the final strength. Concrete offers far greater strength than cement and is cheaper, so it is used extensively. There are some newer concretes that add glass fibre to the mix, to further improve the strength of the finished item.

When concrete is mixed, the ratio is usually 4 parts aggregate, 2 parts sand and 1 part cement.

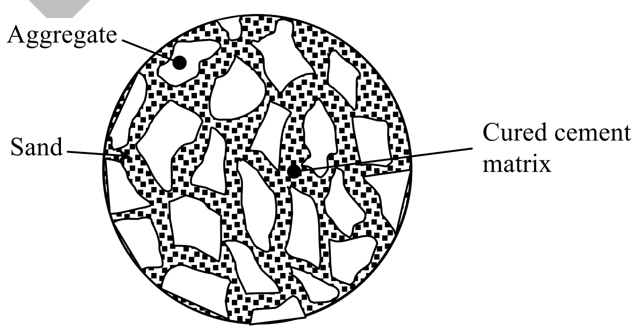


Fig. 1.24: *The microstructure of concrete. The sand fills the void between the aggregate and the cement binds the sand and aggregate together.*

Concrete behaves in a very similar way to stone, as it is strong in compression, weak in tension and has low toughness. Concrete is also fireproof and does not corrode.

The ratio of water to cement in a concrete is decided by two factors, the workability and the final strength. If there is too little water then the concrete will not be fluid enough and will not flow into the mould, while if there is too much, it will flow very well but the final strength will be low and shrinkage may become a problem. The ratio of water to cement is usually 0.45 to 0.55.

Reinforced Concrete

Because of concrete's inherent weakness in tension there may be problems when a concrete beam sags as the lower surfaces, when placed in tension, cause cracks to form. To overcome this, concrete may be reinforced with rods or steel mesh that takes the tensile load and makes the concrete more resistant to failure.

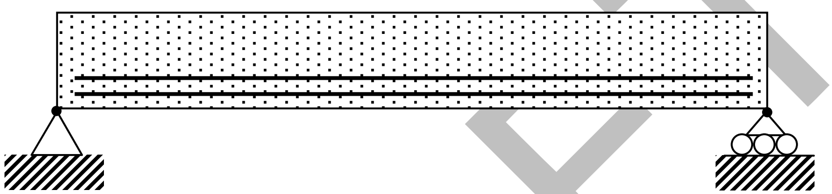


Fig. 1.25: *A reinforced concrete beam, the rods are placed on the tension side of the beam.*

Pre-stressed Reinforced Concrete

To improve the performance of reinforced concrete, two methods have been developed that place the concrete member into compression prior to loading, so for tensile failure to occur the compressive stress must first be overcome.

Pre-tensioned (pre-stressed) concrete is created when the concrete is cast over a series of steel rods or cables that have been tensioned prior to pouring. Once the concrete sets and cures the cables are released,. As they try to return to their unstrained state, they set up compressive stress in the concrete beam.

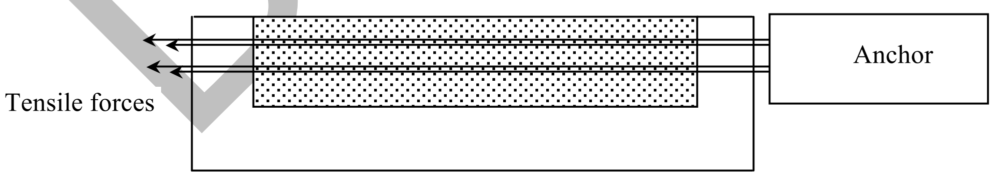


Fig. 1.26: *A pre-tensioned pre-stressed concrete set up. The concrete is cast over the tensioned rods. Release of these will place the concrete in compression.*

Post-tensioned (post-stressed) concrete is formed when concrete is cast with tubes running through the slab. After setting and curing, wires are pulled through the slab and anchored to plates at one end and tensioned at the other. This tensioning tends to compress the slab and place it into a state of compressive stress. Once the required tension is gained, the wires are anchored to the slab at the tensioning end. The process is completed when the cables are left in this state and cement slurry is injected into the tubes to stop corrosion of the steel.

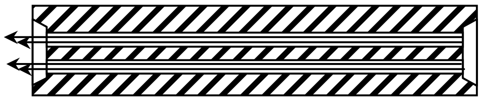


Fig. 1.27: *A post-tensioned pre-stressed concrete slab. Tension wires are passed through the tubes and are locked into place at the free end and the slab is placed in compression.*

Spalling (Concrete “Cancer”)

Reinforced concrete is not without its faults, one of which is spalling, also called concrete cancer. This happens when the reinforcing steel corrodes. When steel corrodes it expands which causes the concrete to crack, hence making the structure unstable and dangerous. Careful design and not placing reinforcing too close to the surface can reduce spalling.

The steel can corrode due to the presence of salt, air and water. This is why it is essential to ensure a correct water ratio, and to vibrate the concrete into position to reduce porosity.

Asphalt

Also called tarmacadam (or tarmac), this is the most widely used surfacing for roads in Australia. Asphalt is a composite with hard aggregate (often crushed blast furnace slag or basalt) and bitumen as the matrix. It is advantageous for roads as it is tough and crack resistant due to the bitumen, yet hard wearing due to the exposed aggregate. It is also impervious to contamination by oil. Asphalt is laid hot and when it cools the bitumen solidifies. It can deal with slight movements in the road base better than concrete can, because of its toughness.

Laminates

Laminates are materials that consist of varying materials sandwiched together. Examples of laminates are listed below.

Plywood is a laminate that is useful where the grain structure of timber causes weakness. It consists of layers of timber with the grain arranged at 90° to each successive layer.

Laminated glass is used when a shatter-resistant glass is needed. Two layers of glass are passed through rollers that compress a polymer sheet (usually polyvinyl butyral) lying between them. This creates a glass that will not shatter, making it more resistant to breaking into shards after impact.

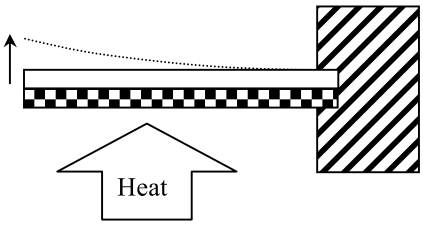


Fig. 1.28: *When heat is applied to a bimetallic strip one side will expand more than the other and deflect from centre.*

Bimetallic strips use two metals back to back. One metal will have a different thermal expansion rate to another so as it heats up it will deflect from its neutral position. This makes it highly useful for thermostats and protection circuits in gas systems.

Geotextiles

Geotextiles are woven polymers (usually polypropylene or polyester) or ceramic fibres that are used for a variety of purposes in civil construction. One application for geotextiles is for stabilising road base. When a road is constructed the asphalt is laid over a fine crushed material called road base. Over time the road base will often become contaminated by the clay, rock or soil it is resting on. To prevent this, geotextile sheet is placed between the subsoil and the road base, thus stabilising the road surface and making it less likely to form potholes.

Geotextiles are also used as filters for drainage systems. The NSW railways use geotextiles in drainages systems so the drains under the tracks do not fill up with silt and then clog. Geotextiles are also used to stop the road base around the drainage pipes from contaminating the ballast upon which the tracks rest. Geotextiles are also used on construction sites to stop dirt in water runoff from getting into storm water drains.

Corrosion

Corrosion may be defined as the chemical deterioration of a material. Although we often think of corrosion as only occurring in metals, ceramics and polymers also deteriorate or degrade, usually involving the breaking down of the material by chemical means such as the ultraviolet deterioration of a polymer.
Metallic corrosion involves the deterioration of metals or metal alloys, and is basically the reverse of the refining process. In nature, most metals exist as chemical compounds. Refining them produces the pure metal, while corrosion progressively returns them to the combined state.

Corrosion involves complex chemistry. The following section is an overview. More information may be found in references at the end of this chapter.

Oxidation and Reduction

Oxidation occurs when the metal loses electrons, and it occurs at the anode. Oxidation = loss.

Reduction is the consumption of electrons and occurs at the cathode. It is the opposite to oxidation thus reduction = gain.

An acronym to remember this is OILRIG (Oxidation Is Loss, Reduction Is Gain)

Some metals are more likely to be anodic while others are more likely to be cathodic. Cathodic metals tend to be more stable and less affected by corrosion. Table 1.3 lists metals and their reaction when immersed in seawater.

Dry Corrosion

Dry corrosion occurs through chemical reactions of metals or alloys with gases, in furnaces at high temperatures. Examples include fire tubes in steam locomotive boilers, water tubes in power station boilers and metal components in heat treatment furnaces. A principal cause is a reaction of the metal with oxygen and other molecules in flue gases.

Wet Corrosion

Wet corrosion occurs when a metal is placed into a fluid, usually an electrolyte. An electrolyte is a solution containing ions which carry electric charges.

Uniform attack

If a metal is placed in an electrolyte, some parts will become anodic while others will become cathodic. The locations of the cathode and anode will continually change, resulting in uniform corrosion. Steel, under certain circumstances, will form a uniform layer of rust as it corrodes.

Galvanic Attack

This type of corrosion comes in three forms,

Galvanic corrosion occurs when dissimilar metals are placed together in the presence of a corrosive environment. Different metals have a greater affinity to corrode than others; so one metal will become cathodic, while the other becomes anodic. Table 1.3 is useful for determining which metal will become the anode or cathode.

Table 1.3: *The Galvanic series in Seawater*

Anodic	Magnesium
	Zinc
	Galvanised Steel
	Aluminium Alloys
	Mild Steel, Cast iron
	Stainless Steel (active)
	Tin
	Aluminium Bronze
	Copper
	Nickel base alloys (passive)
	Stainless Steels (passive)
	Silver
	Titanium
	Graphite
	Gold
Cathodic	Platinum

Consider a steel pipe with a copper sleeve over it. The steel pipe under the sleeve will corrode as copper is more cathodic than steel. Composition cells also occur microstructurally, for example ferrite in steel will become the anode, while cementite will become the cathode.

Concentration cells occur when there is a difference in concentration of the electrolyte. A good example is the car door shown in Fig 1.25.

In the car door, the trapped water will become stagnant and the bottom of the pool will become low in oxygen (O_2), while the surface will have higher levels of oxygen. This differential in oxygen levels sets up a concentration cell and corrosion will occur. High O_2 will create a cathode while the area of low O_2 will become the anode. So the lower part of the door will lose electrons and deteriorate, while the cathode gains electrons and rust layers will build up. The result will be the eventual destruction of the door from the inside out. This is why a plastic coating on the outside does not stop the rust problem.

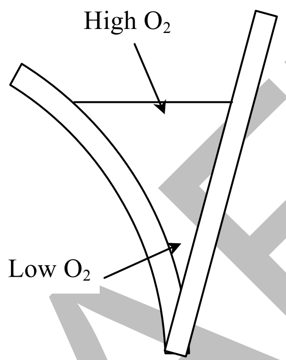


Fig. 1.29: *The bottom of a car door can hold water in dust and dirt. When this occurs a concentration cell develops and corrosion begins at the water surface.*

Concentration cells take a particularly damaging form as *crevice corrosion* in structures. Like the car door example above, crevice corrosion is where an electrolyte fills a crevice and we get different oxygen levels between the top and bottom of the crevice. Crevice corrosion can be problematic on any metal structure where joints may crate crevices.

Stress cells are the result of high residual stress in parts of a metal object. These areas of high stress tend to become anodic while the lower stress areas become cathodic. Often a stressed metal will corrode when an unstressed piece in similar conditions will not corrode as quickly.

Grain boundaries in metals tend to be a location of high stress and thus a metal with a fine grain is more liable to corrode internally than a coarse grained metal. This situation differs from a composition cell in the microstructure of steel, as stress corrosion at grain boundaries can occur in a pure metal where all grains have the same composition.

Corrosion – is it all bad?

Corrosion is always going to occur in metals. The effect corrosion has can be horrendous and so a lot of time and money is spent combating it. "Corrosion" is most often associated with steel and rust, and it is a problem that engineers have not yet overcome.

Some metals like steel will form a porous layer (rust) that allows corrosion to continue. Others, like aluminium, form a protective film that makes the metal passive and inert. Metals in this situation display a condition called *passivity*. Passivity is a condition where a metal that should be quite reactive appears inert. Metals exhibiting passivity have a corrosion product that is a non-porous tenacious film that protects the underlying metal from further corrosion. The film is self-healing, so when scratched it immediately reforms. Examples of passive metals are aluminium, titanium and chromium, while a passive alloy is stainless steel.

Rust is simply the name given to the corrosion product of steel. It is the antithesis of the corrosion products on passive metals. It is porous and flaky and as it grows and flakes it continually exposes fresh corrodible metal beneath. This is why most steel structures must be protected from the atmosphere or corrosive environments to ensure longevity.

Protecting Civil Structures

Most steel civil structures such as bridges use one of two protective mechanisms to stop corrosion. One is paint on the surface, e.g. The Sydney Harbour Bridge. Another method is to galvanise the steel pieces. Galvanising involves dipping the steel part into molten zinc, which then covers the steel and protects it from corrosion. To be technically correct the zinc coating is not passive, but very slowly corrodes away. Once it has corroded away after many years, the steel will then rust, but until that time it is readily protected.

To enhance the corrosion resistance of galvanised steel, other products like Zincalume® have been developed. Zincalume® coats the steel in a zinc/aluminium alloy which offers improved protection. Colorbond® steel uses a Zincalume® base and adds a polyester coating and then baked on colour top coat, to produce a decorative and durable steel sheeting product.

Some sheet aluminium alloy applications use Alclad™, which is duralumin (aluminium/copper alloy) coated with pure aluminium. The passive aluminium protects the more corrosive-susceptible alloy. Aluminium alloy window frames are normally anodised which involves creating a thick oxide layer to further enhance the oxide aluminium naturally forms.

Communication

Orthogonal drawing

There is a plethora of drawing texts available that should serve all needs. Please refer to the *Additional References* section to find some suitable drawing references. To augment your personal research, it is strongly suggested that you attain copies of previous Engineering Science orthogonal drawing questions and solutions.

In nearly every HSC students will be asked to complete some form of assembly orthogonal drawing. Students must consult previous HSC exam questions on this to get a feel for doing assembly drawings of various difficulty levels.

Threads in Orthogonal Drawing

Threaded features such as bolts and nuts are drawn using specific AS1100 standards. Below is a brief guide to drawing bolts and nuts, further consultation should be made to the AS1100 handbook.

When dealing with threads the size details of the thread are normally given as follows:

M10×1

- M represents metric, so we know it is a metric thread,
- 10 in this case is the diameter of the thread; and,
- 1 is the pitch of the thread.

So a thread described as M12×1.5 is a metric thread of diameter 12 mm and a pitch of 1.5 mm. The numbers are important when we are drawing threads to AS1100 standards because the size of the bolt head and nut is decided by the thread's diameter and the pitch decides the thread depth.

The AS1100 standard dimensions for hexagonal head bolts, hexagonal nuts and flat washers are outlines in Fig. 1.30.

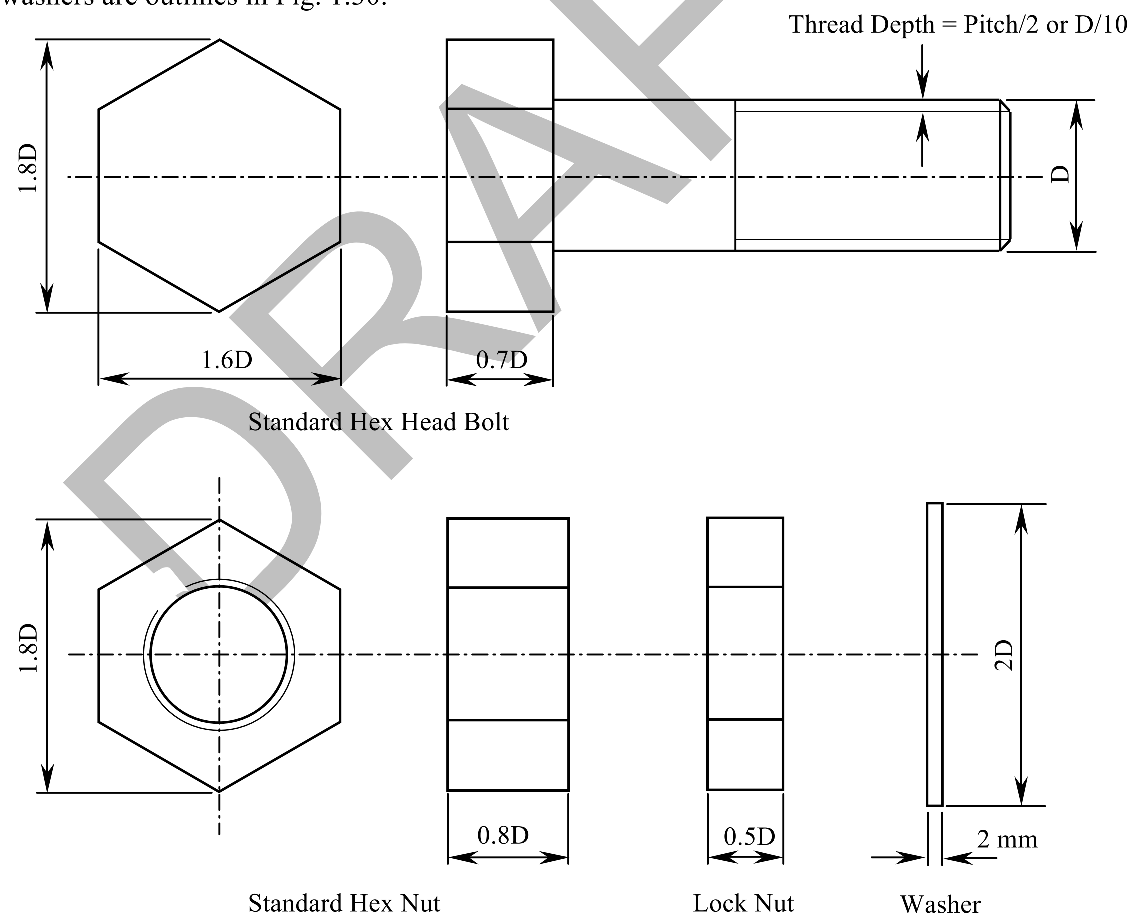


Fig 1.30: *AS1100 standard dimensions for screw thread representations. Note that the washer's thickness drops to 1 mm for thread diameters below 8 mm. Pitch/2 is the preferred way to calculate the thread depth.*

Orthogonal Drawing Features

Counter bores are used in engineering to allow a bolt head to be recessed below the face of an object. This is done by creating a lager diameter hole at the top of an existing hole through an object. Countersinking also allows a recessed head. Both of these features and their standard dimensioning methods are shown in Fig. 1.31.

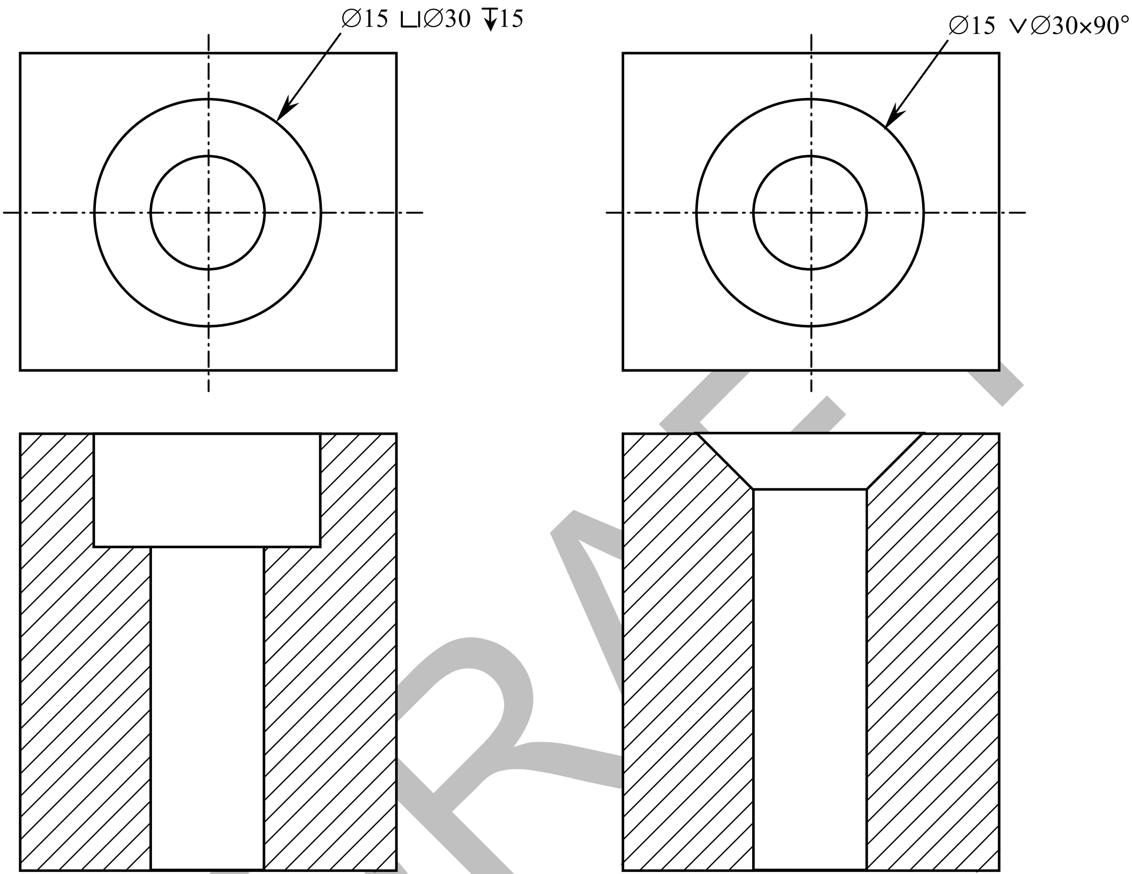


Fig. 1.31: *Sectioned views of a counter bore hole and countersunk hole. Dimensioning standards for them are shown.*

Computer Graphics

Computer Aided Drawing

CAD software has created massive advances in engineering communication. A software package such as PTC Creo, which is used by quite a number of high schools, is also used by large engineering companies like Toyota, Nokia and Raytheon. The software is not just a drawing program, it also allows features to be tested, allows engineers to roll back to previous designs, allows worldwide collaboration and also allows engineering material and mechanical analysis. All of this makes CAD an indispensible feature in Engineering.

Other CAD packages include but are not limited to, SolidEdge, AutoCAD, TurboCAD and Vectorworks. All of these along with Creo have their own way of approaching engineering communication but their common goal is to facilitate effective communication of engineering ideas, in a way that is time consuming and difficult to replicate with manual drawing techniques.

Problem solving Applications

There is now a range of applications about that allow the analysis of force systems. Some of these, such as Autodesk ForceEffect, are marketed for tablets so they are available for the engineer on the move. Others offer different analysis methods. But all offer something that twenty years ago were the preserve of high level computing. Now a smartphone can allow truss analysis.

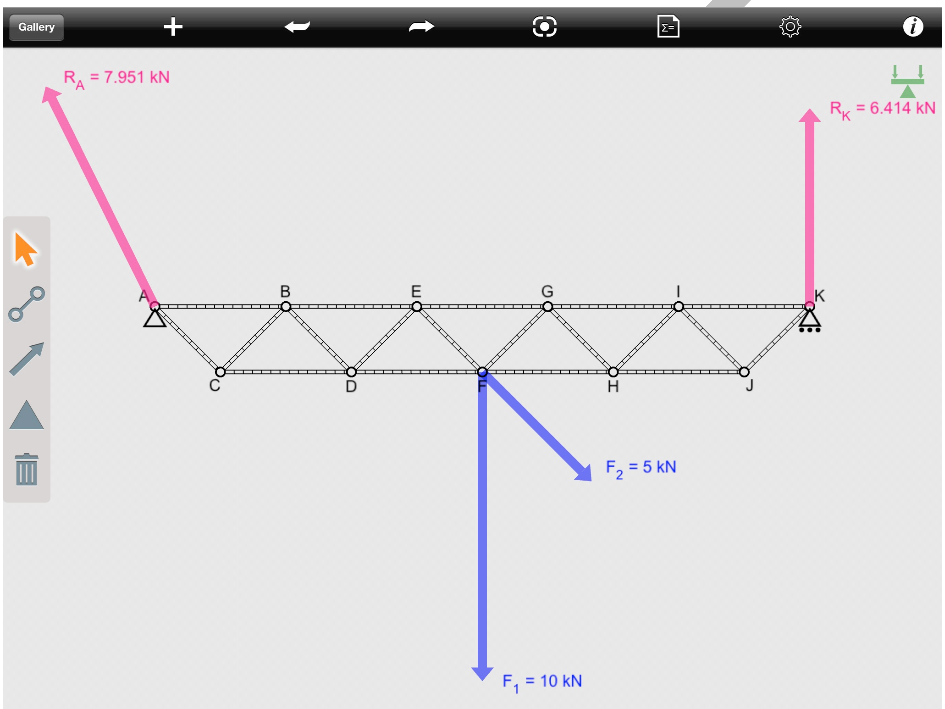


Fig 1.32: *A truss analysed using Autodesk ForceEffect.*

Engineering Report

In Volume 1 of this book the Engineering Reports were limited to a fairly simple approach using a comparison of engineered items. For the HSC course, however, we need to lift the reports to a higher level, using a more formal structure.

HSC Online provides an excellent range of guides for engineering report writing here: http://hsc.csu.edu.au/engineering_studies/reports/

Below is a list of headings that your engineering report could be based on.

Title page: This should list the title of the report and your or your group's name. A title page should be visually appealing. Make sure it presents your work well without overdoing it.

Synopsis: This is a summary of the content and aim of the report. The synopsis should provide enough information to give an overview, or outline, of the primary points of the report.

Introduction: The introduction sets the scene for the report by giving the subject, purpose and parameters of the report. You may also include a background for the report such as some history of the topic.

Methodology: This is the description of the method or process used to carry out the work required for the report. If you have had to conduct experiments then this section is where you outline the equipment and procedure used.

Results: It is here that the outcome of the investigation or experiment is recorded. It should include figures, graphs and perhaps tables that have allowed you to gain the results. Do not load up the results sections with a lot of calculations, pictures or drawings. It is better to place these in an appendix at the end and then refer to the appendix.

Conclusion: This is the resolution of the report, the judgement made from the evidence in the results section. It may be the choice of which alloy steel is best for reinforcing concrete, or which metal tube is best for bicycle manufacture.

Recommendation: After the report is concluded a recommendation may be made as to the final choice, such as, "The most appropriate tubing for the bicycle is an air hardening steel, such as Reynolds 853."

Acknowledgements: If somebody has helped you in any way in the preparation of your report, their names should be included here. This section is a good place to add names of people who have helped you obtain information from companies you contacted. Give these people the credit they deserve. It is unethical to use other people's work without due acknowledgement.

References: If you gain any information from books or journals then they should be included here. At university this will become an exceedingly important task, as to claim work that is not yours, is academic misconduct and may result in expulsion. Use a similar style for referencing to the method below, which is used by many tertiary institutions,

> Author Name/s. (Year), *Title of Book*, Location, Publisher. For example,
>
> Copeland, Paul L. (2011) *Engineering Studies – The Definitive Guide*. Sydney, Anno Domini 2000

Academic fraud or plagiarism is when you claim as yours work that is actually somebody else's. If you use somebody's work exactly as written you must quote him or her, while if you use his or her work as a reference then you must list it as a reference. With free online resources like Wikipedia it is often appealing to just cut and paste work into your document. This is fraudulent and should not be done. Make sure the report is your own work.

Moreover as digital citizens you must learn to be discerning consumers of the information you read. SAs outlines in Volume 1 you must use Wikipedia and similar resources sensibly, any online information that is not validly referenced must be treated with suspicion.

Appendix: Finally, at the very end, include any appendices, with calculations, drawings etc. This means that the readers do not have to read this information but it is there if required.

Presentation – Or… "Does this look OK?"

Many people will give very different views on how to present your report. These are some tips that could be useful.

- When you write headings do not use all capitals. They are hard to read. For example, try to read "LAUGH" from a distance, then try to read "laugh" with the font enlarged to a similar size.
- Underlining is out of date. Underlining affects the readability of words as it cuts through descenders (the bottom of letters that run under the line) and it tends to run all letters in the word together. A better option is to use *italics* or **bold** letters. Moreover nowadays underlining indicates a hyperlink.
- Fancy fonts or typefaces may look good on a party invitation but they are often harder to read. They also tend to make your report look too informal.
- Don't write the main body of your report in a font any larger than 12 point. Larger fonts look as if you are trying to pad out work that is insufficient.
- When choosing a font for the body of the report choose a serif font. A serif font is one with little tails on the end of the letters like the Times New Roman font used in this book. Sans serif fonts like Arial are not as easy to read in large blocks of writing. They are, however, good for headings and now find extensive use in websites where serif fonts look "fussy", particularly on modern LCD screens.
- When you write make sure you use a formal writing style. That means not using colloquialisms and limiting your use of contractions ('do not' instead of 'don't'). Do not write in the first person, i.e. do not write "I have conducted an experiment…"; rather say "An experiment was conducted...". Ensure that all sentences are in the same tense.
- In most word processors, many words that are spelt correctly will be listed as incorrect by the spell checker because spell checkers are automatically set to American spelling. Try to set the computer to British spelling (not Australian as the Australian spell checker is often, incorrectly, the same as American), and watch for words like 'aluminum' and 'airplane' in American texts. In Australia we say 'aluminium' and 'aeroplane'.
- Make sure you use the correct punctuation for the sentence; for example, a semi colon (;) is used when a sentence changes subject, not at the end of a sentence prior to a list.

Additional References

This list of useful references allows students to carry out further investigation. Any highly recommended book or website has two stars next to it.

Engineering Mechanics and Hydraulics

**Gordon, J. E., (1978), *Structures – or Why things don't fall down*, Da Capo Press, New York.
Ivanoff, V., (1996), *Engineering Mechanics*, McGraw Hill, Sydney.
**Schlenker, B. and McKern, D., (1976), *Introduction to Engineering Mechanics*, Jacaranda Wiley, Milton.

Engineering Materials

Askeland, D., (1989), *The Science and Engineering of Materials*, Chapman and Hall, London.
DeGarmo, E. P., Black, J. T. and Kohser, R. A., (1988), *Materials and Processes in Manufacturing 7th Edition*, Macmillan Publishing Company, New York.
**Gordon, J. E., (1974), *The New Science of Strong Materials – or Why you don't fall through the floor*, Penguin, Middlesex.
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Smith, W., (1990), *Principles of Materials Science and Engineering*, McGraw Hill, New York.

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**Boundy, A., (1991), *Engineering Drawing*, McGraw Hill, Sydney.
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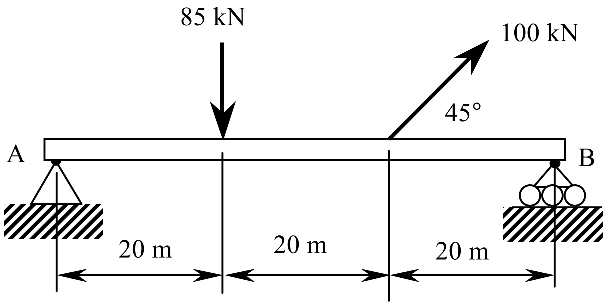
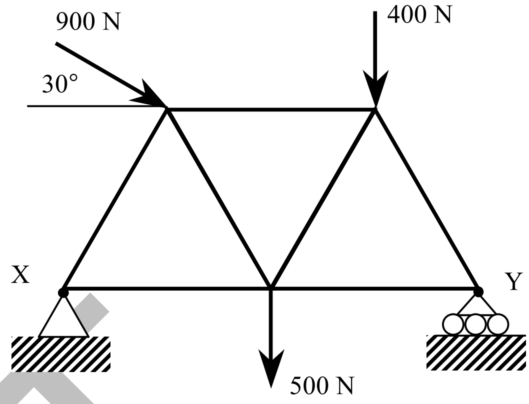
Park, A, Dodds, K and Bland, S., (1989), *Technology Drawing*, Longman Cheshire, Melbourne.

Review Questions

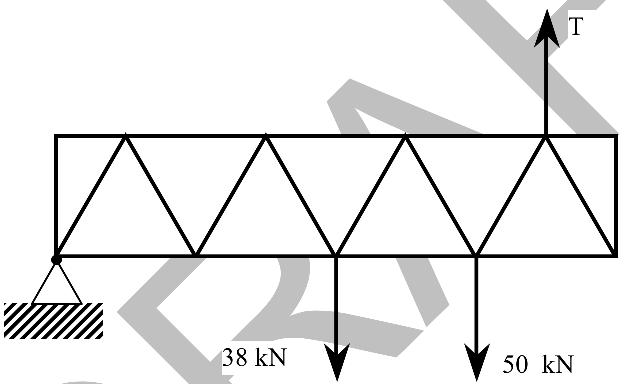
1. Explain what a beam is.
2. Explain the difference between a tied arch and an arch.
3. Why are suspension bridges usually lighter than equivalent span arch bridges?
4. What made cast iron appealing as a bridge building material?
5. What is significant about the Brooklyn (USA) Bridge in terms of suspension bridge design?
6. Why was the mass production of steel an important development in bridge design?
7. Why is concrete so popular in bridge construction?
8. Why do bridges not use roller supports at both ends?

9. Find the reactions for the following beam and truss?

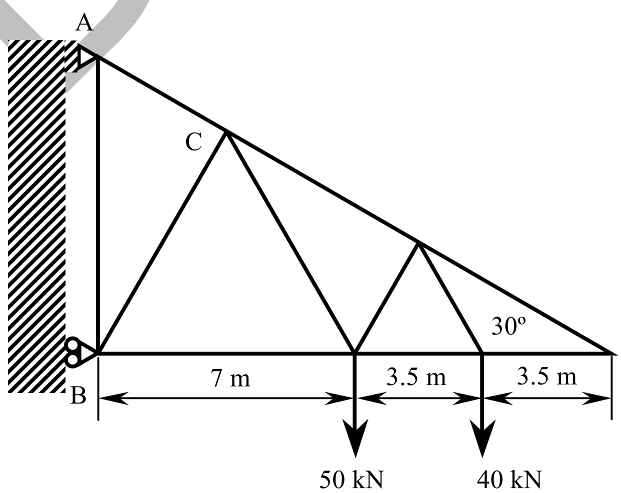




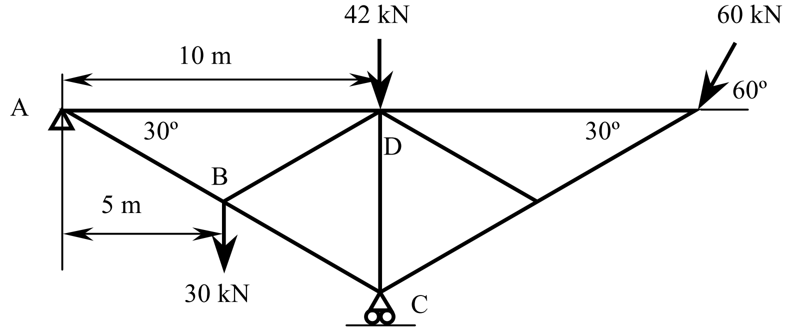
10. A truss for a gantry is anchored at one end and supported by a cable on the right hand end. Find the tension in the cable and the reaction at the support.



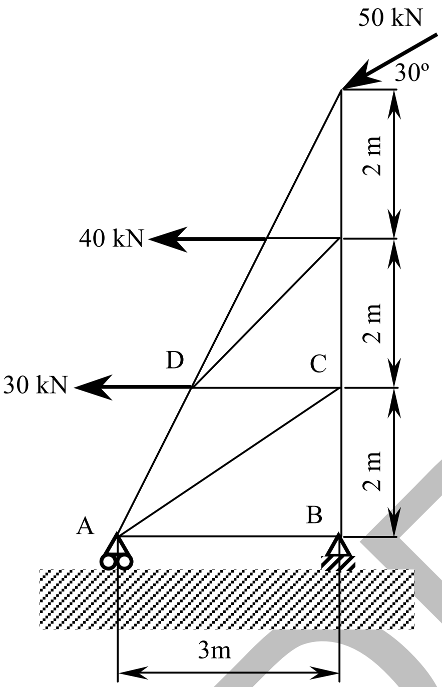
11. A triangular frame, shown below, is loaded as shown. Find the reactions at the supports and the force in member AB.



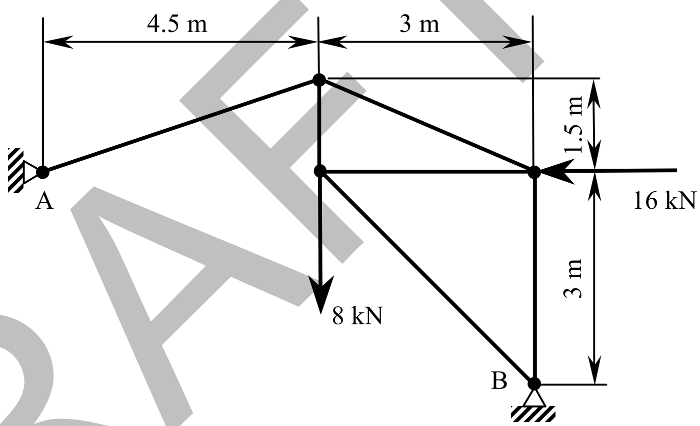
12. Find the reactions at the supports for the truss shown, and the force in members BC and BD.



Question 12

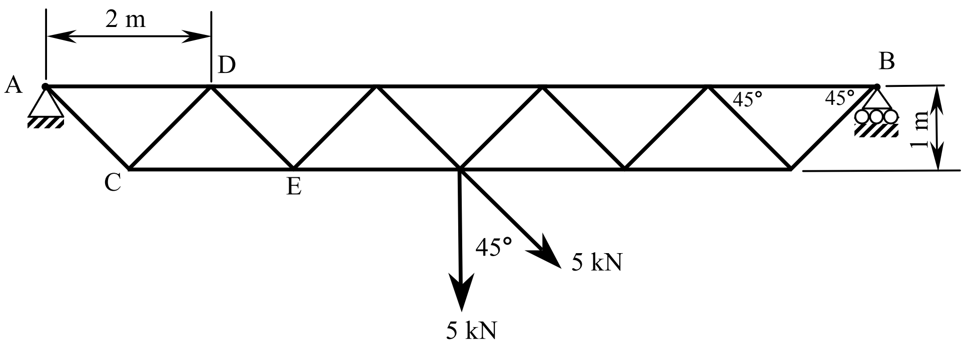


Question 13

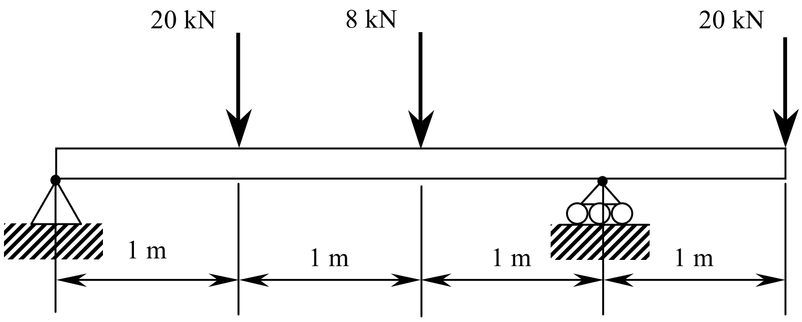


Question 14

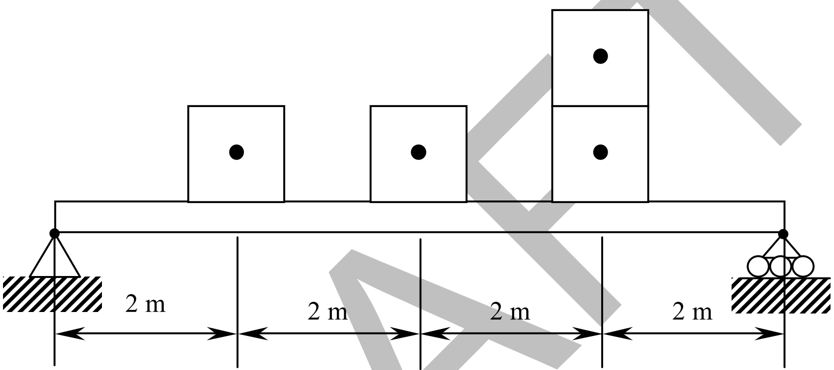
13. Find the reactions at the supports and the force in member DC.
14. Determine the reactions at A and B for the frame shown.
15. Shown below is a 10 m truss for a roof gantry. Determine the reactions at A and B and then determine the magnitude and nature of the forces in DE and CE.



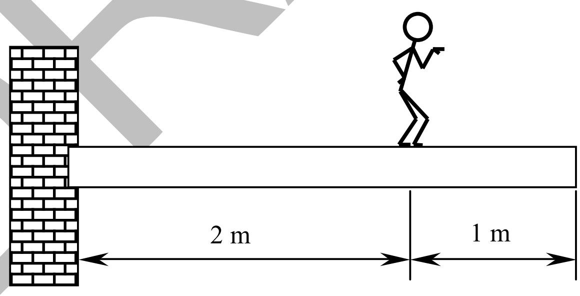
16. Produce the shear force and bending moment diagrams for the beam below.



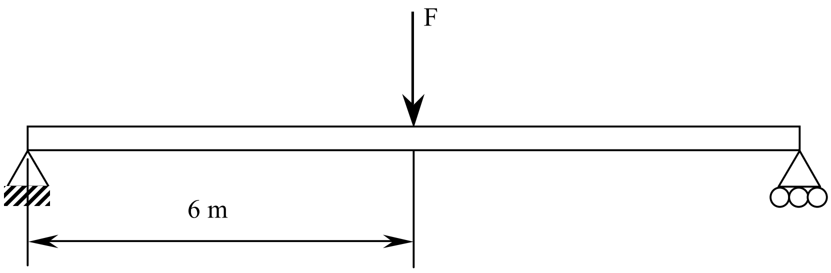
17. Draw the shear force and bending moment diagram for the beam below if each box has a mass of 25 kg (Ignore the weight of the beam).



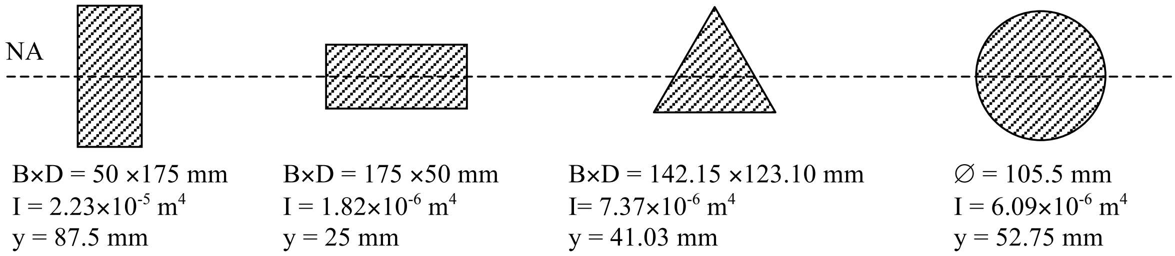
18. Draw the shear force and bending moment diagrams for the cantilever if an 80 kg person is standing 1m from the free end.



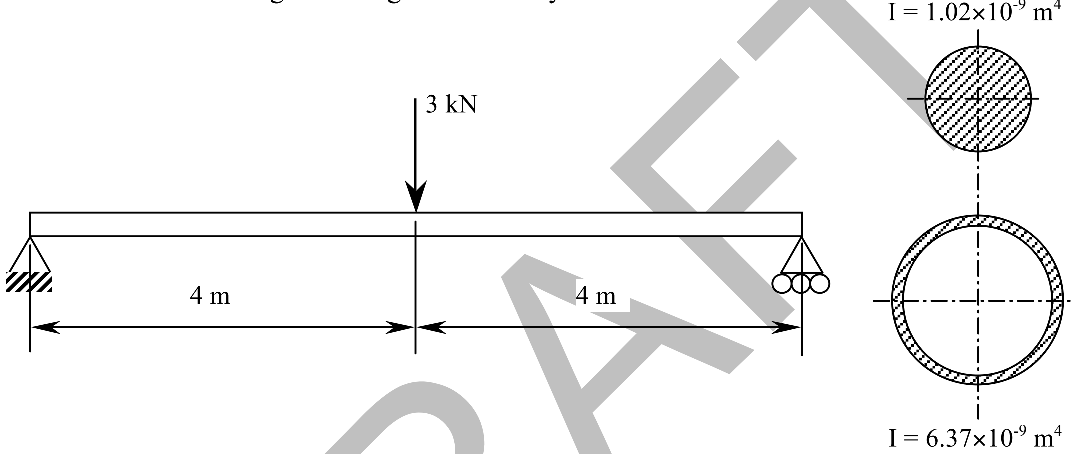
19. An engineer is planning a 12 metre beam that will be arranged as shown and is yet to decide the cross sectional shape (all cross sections have the same area). If the maximum permissible bending stress in the beam is 25 MPa, find the maximum load that the different cross sections will allow.



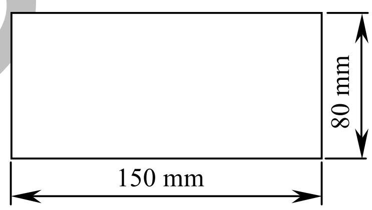
Cross sections



20. An engineer has the choice of either ∅12 mm solid bar or ∅25 mm tube (1.2 mm wall thickness). Find the maximum bending stress in the beam for each cross section when the beam is loaded as shown. Which material will have a better strength to weight ratio? Why?

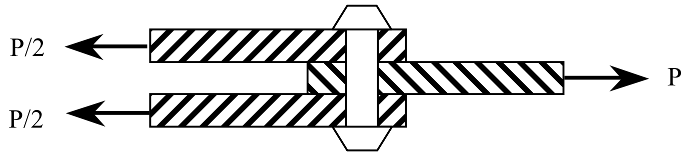


21. A steel bridge cable carries a load of 200 kN. What will be the tensile stress if the cable has a diameter of 20 mm?
22. A shape, as shown below, is punched from a 5 mm thick steel plate by a 20 kN force. What will be the maximum shear stress induced in the plate?

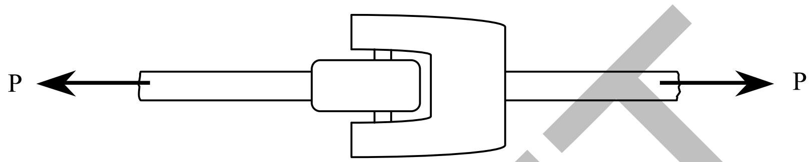


23. A punching machine can produce a shear force of 5kN. If a plate with holes in it is to be punched in one operation, and the plate is 100mm by 70mm, with two 15mm diameter holes in it, what will be the maximum thickness of the plate? (Plate shear stress is 1MPa).
24. A bolt used in a bridge is subjected to a 40kN shear force perpendicular to its axis. Determine the shear stress if the bolt has a diameter of 18mm.
25. Explain engineering stress.
26. What is Hooke's law?
27. What is proof stress?

28. The ultimate shear strength for steel is 360 MPa. A mild steel pin is used in the coupling shown below to hold the joint of a truss together. If the diameter of the pin is 10 mm what will the maximum load permissible be if a factor of safety of 6 is used?



29. A coupling on a bridge is shown below. The device is subjected to a shear load of 20 kN, and the maximum shear stress allowed in the bolt is 500 MPa. What will the minimum diameter of the bolt be?



30. Explain the procedures of X-ray, dye penetration and ultrasonic testing.
31. Why is the critical crack length of a material important?
32. Why is cracking more likely to occur once a crack has started to form?
33. What is an interface in relation to cracking?
34. Define glass.
35. What materials are used to make glass?
36. What is toughened glass?
37. What is the difference between cement and concrete?
38. Explain what mortar is.
39. What is the reason for reinforcing concrete?
40. Describe the two types of pre-stressed reinforced concrete.
41. Explain what asphalt is.
42. How does laminated glass differ from normal glass?
43. What is a geotextile?
44. Describe what is meant by the term corrosion.
45. Explain the difference between oxidation and reduction.
46. Explain the three types of galvanic corrosion.
47. Describe what crevice corrosion is and explain why it is a problem for civil structures.
48. How may steel structures be protected from corroding?