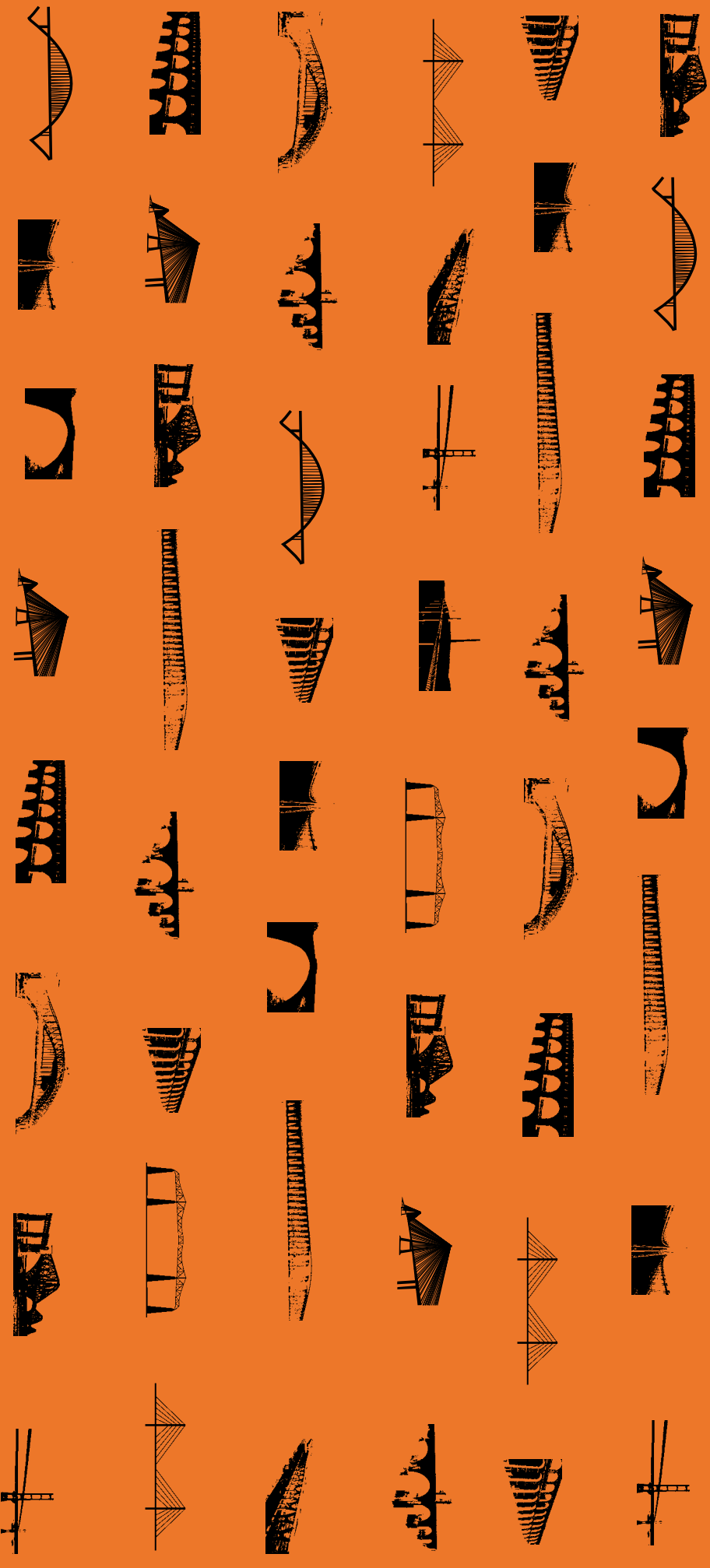


» BRIDGES //

Spanning the gap between
construction and materials



BRIDGES

Spanning the gap between construction and materials

This folder of information cards and posters forms the resource for schools joining or renewing their membership of the Institute of Materials, Minerals and Mining Schools Affiliate Scheme in the 2009-2010 academic year. It has been designed as a reference guide for teachers to link in with the materials, minerals and mining topics in the secondary science and technology curricula, though some sections will also be very relevant to geology and geography.

This resource has been written by Dr Diane Aston, Education Co-ordinator and Mr Toby White, Education Co-ordinator (Minerals and Mining) from the Institute of Materials, Minerals and Mining.



1 » THE DESIGNS

» History of Bridges



<http://static.panoramio.com/photos/original/301678.jpg>

THE HISTORY OF BRIDGES

Over the centuries bridges have played an enormous and valuable part in bringing communities together and allowing easier trade routes to develop. They are portrayed in books and films as romantic spots where couples meet, or the middle ground where the final stand-off takes place. Bridges have evolved from simple logs across streams to massive and complex engineering structures and every few years another bridge comes along to beat records and sparks our imaginations.

The very first bridges were built by Mother Nature and were the result of falling trees spanning streams or canyons. Man used these accidental crossings to reach new areas for settlement and new sources of food. The first man-made bridges copied this and were made from logs and then later stones. These very early designs relied on the log or stone being long enough to cross the gap in a single span. Later designs used simple crossbeams and support to cross larger gaps.



Figure 1 Bronze Age Arkadiko Bridge in Greece. Built by the Myceneans on the road from Tiryns to Epidaurus it dates from 1300 BC and is still used today. (<http://www.panoramio.com/photo/13255844>)

The oldest surviving bridge in the world is a simple corbelled stone arch bridge in Greece made from limestone boulders (Figure 1). The Arkadiko Bridge, built by the Myceneans is thought to date from around 1300BC and it is still used by local people today. It is 22 metres long, 5.6 metres wide and 4 metres high, though the width of the culvert through the arch is only one metre. The roadway, which is 2.5 metres wide and has curb stones, is thought to have been built specifically to carry chariots and there are four other similar Bronze Age bridges in the surrounding area.

Chinese history shows that complex wooden bridges were being built 3000 years ago but the oldest surviving Chinese bridge is made from stone and dates to the Sui Dynasty (Figure 2). It was built between 596AD and 605AD and is the oldest example in the world of an open-spandrel segmented arch bridge. The bridge was designed by Li Chun and it has a total length of 50.82 metres with the longest arch spanning 37.37 metres. The centre of the arch is 7.3 metres tall and the bridge is 9 metres wide. Over the last 1400 years the bridge

has withstood ten major floods and many earthquakes, not to mention at least eight wars! Only the decorative railings have needed replacing. The bridge is built from limestone cut into curved slabs and the central arch is comprised of 28 of these joined together with iron dovetails. These joints allow the arch to shift with movements in the earth or traffic and prevent it from collapsing if one segment breaks. The central arch is framed by two smaller arches on either side. These side arches dramatically reduce the weight of the bridge and they allow water to pass through the bridge during a flood.

The Romans were master bridge builders, constructing complex arch bridges, sometimes on many levels, to carry roads and water courses. Many of these structures still stand such as the Aqueduct of Segovia on the Iberian Peninsula in Spain which was constructed between the first and second century (Figure 3). This tremendous feat of engineering consists of two tiers of arches, 167 arches in total, and at its tallest point, stands 28.5 metres above ground level. It was made from granite carved into bricks and required no mortar to hold it together.

Over the centuries wooden bridges became more complex and large wooden structures were commonly used in America to carry early railroad tracks.

The Industrial Revolution helped to change the materials that were used in the construction of bridges. Iron and steel became affordable alternatives to wood, brick and stones and the properties of these new materials allowed for new designs and larger bridges. Truss and cantilever bridges made from iron became increasingly popular. These designs allowed large distances to be crossed using a number of spans and tall structures to be built to span deep canyons.

Modern suspension and cable-stayed bridges rely on the excellent properties of concrete in compression and steel in tension to span great distances and create breathtaking structures. For example, the Juscelino Kubitschek Bridge over Lake Paranoá in Brazil is a work of art as well as a crossing (Figure 4). The bridge comprises three asymmetrical steel arches which criss-cross and support the suspended concrete deck. The bridge carries a six lane road, footpath and cycle way and has won a number of awards for its designer, Mário Vial Verde.



Figure 2 Zhaozhou Bridge in China, built 1400 years ago (<http://www.chinapicturespub.com/north-china/shijiazhuang-china/shijiazhuang-zhaozhou-bridge.html>)



Figure 3 Roman aqueduct at Segovia in Spain (http://en.wikipedia.org/wiki/Aqueduct_of_Segovia)



Figure 4 Juscelino Kubitschek Bridge over Lake Paranoá in Brazil (http://en.wikipedia.org/wiki/Juscelino_Kubitschek_bridge)



Figure 5 The Second Severn Crossing
(<http://www.flickr.com/photos/beimages/175286033/>)

In many cases modern bridges use a combination of designs to successfully span large distances. Suspension and cable-stayed bridges often have approach sections consisting of beam, truss or cantilever bridges. These include the second Severn Crossing (Figure 5), completed in 1996, which consists of a central cable-stayed section with approach viaducts on both the English and Welsh sides. The approach viaduct consists of a total of 49 spans supported on 37 pillars which are just less than 100 metres apart. Each span is made from 27 segments which were manufactured off-site from reinforced concrete and floated into place. The central cable-stayed section has a span on 456 metres and provides the shipping route along the deepest channel in the river, the Shoots Channel.

Where can I find out more?

<http://www.severnbridge.co.uk>

<http://en.wikipedia.org/wiki/Bridge>

http://en.wikipedia.org/wiki/Arkadiko_bridge

BRIDGE DESIGNS

Looking around it is evident that there are a large number of different possibilities when it comes to the design of a bridge. The choice of design will depend on a number factors including the length of the gap which must be crossed, the material preference, the ground on to which the bridge is to be built and the load it must carry. Generally speaking a bridge can be described by four factors:

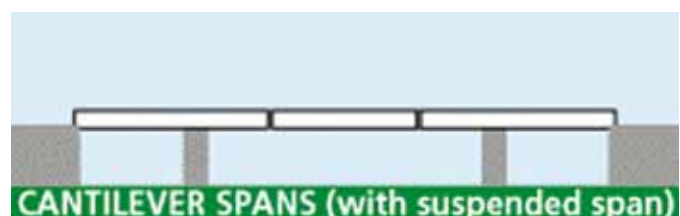
- 1// **THE SPAN.** This could be a simple span where each deck section is supported by either the ground or a pier, a continuous span where a continuous deck is supported by multiple piers, a cantilever span where the centre of each deck section is supported but the ends are free or a cantilever span with a suspended central section. These alternatives are shown schematically in Figure 1.
- 2// **THE MATERIALS.** A large number of materials can be used in the construction of bridges; these include bricks, stone, concrete and metal, usually iron or steel. In the future engineering composites (such as carbon fibre epoxy composite) and materials such as carbon nanotubes may allow larger, lighter, stronger structures to be constructed.
- 3// **THE DECK POSITION.** The placement of the travel surface in relation to the structure of the bridge varies across the designs. In a deck bridge the travel surface is on top of the bridge structure and this technique is commonly adopted in arch and beam designs. In a through bridge the travel surface is below the bridge structure, as in a suspension bridge or cable stayed bridge. In a pony bridge the travel surface passes through the bridge superstructure and the two sides of the

bridge are not cross-braced. All three of these configurations are commonly used for truss bridges and schematic diagrams are shown in Figure 2.

4// **THE FORM.** The bridge form described the general design of the bridge and these include the simple beam bridge, the truss bridge, arch bridge, suspension bridge and cable-stayed bridge. Each of these forms is discussed in greater detail below but in many cases a bridge is a complex combination of a number of these configurations.

Where can I find out more?

<http://www.pghbridges.com/basics.htm>



BEAM BRIDGES

Beam bridges are the simplest type of bridge and are the modern day equivalent of the fallen tree. A beam bridge is characterised by one or more horizontal beams which span the gap and rest on supports at either end. The road or walkway may be the beam itself or it could be attached in sections to multiple beams to create a simple but effective crossing. The size of a beam bridge is limited by the length and strength of the beams as these must carry the weight of the bridge and its load without sagging. Stiff materials are required to resist bending as the bridge is effectively put into three-point bend when it is loaded (i.e. its top surface is put into compression and its lower surface tension). This stiffness can be achieved by varying the geometry of the beams as well as the materials. Therefore beam bridges are often described by the shape of the beams, for example, box girder or tubular bridges and girder bridges which use plates to create an I-beam.

Individual beam bridges do not tend to be longer than about 75 metres so in order to span greater distances a number of individual beam bridges may be connected together to create a continuous span. The height of the bridge can be varied by increasing and decreasing the height of the piers to allow traffic to flow under the bridge. The President Costa e Silva Bridge (commonly known as the Rio-Niterói Bridge) which connects Rio de Janeiro and Niterói in Brazil, is a box girder beam bridge (Figure 2). It utilises piers of increasing height to raise the central span 72 metres above the water in order to allow ships to pass in and out of the bay below. The bridge is 13.29 kilometres (8.25 miles) long, 72 metres wide and comprises an eight lane expressway which carries around 140,000 vehicles every day.

The longest bridge in the world was completed in 2000. The Bang Na Expressway in Bangkok (Figure 3) is an elevated

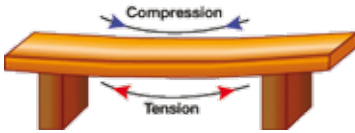


Figure 1 Simple beam bridge showing forces during loading (<http://science.howstuffworks.com/bridge2.htm>)



Figure 3 The Bang Na Bridge in Bangkok, the longest bridge in the world. (http://4.bp.blogspot.com/_U3GDyUM-C15I/SjGIJXPrHyI/AAAAAAAAAZw/KC3D0TPv6Kg/s1600-h/bang-na-expressway.gif)



Figure 4 Lake Pontchartrain Causeway Bridge in Louisiana, USA (<http://www.creativesuite.com/cities-landscapes/5-longest-bridges-in-the-world>)

Figure 2 The Rio-Niterói Bridge in Brazil, a box girder beam bridge carrying 140,000 vehicles every day. (http://en.wikipedia.org/wiki/File:Ponte_Rio-Niteroi01_2005-03-15.jpg)

six-lane road which runs for a total of 54 kilometres (just over 33 miles) entirely over land. The viaduct is 27 metres wide and the distance between supporting pillars is approximately 42 metres. The deck is made up of concrete box girders and 1.8 million cubic metres of concrete were used in its construction.

The longest bridge over water is also a continuous span beam bridge and it is over 38 kilometres (24 miles) long. The Lake Pontchartrain Causeway Bridge consists of two, two-lane causeways running parallel to each other (Figure 4). The prestressed concrete deck sections are supported by over 9000 piers creating a southbound carriageway consisting of 2243 spans (opened in 1956) and a northbound carriageway consisting of 1500 spans (opened in 1969). There are seven crossover sections joining the carriageways, which are 24 metres apart, which can be used in emergencies. The bridge is not a true beam bridge though as each causeway has an opening section to allow boat traffic to pass.

Where can I find out more?

http://en.wikipedia.org/w/index.php?title=beam_bridge

<http://www.matsuo-bridge.co.jp/english/bridges/basics/index.shtm>

<http://www.design-technology.org/beambridges.htm>

http://en.wikipedia.org/wiki/Rio-Niter%C3%B3i_bridge

<http://www.pbs.org/wgbh/nova/bridge/meetbeam.html>

http://www.gnoec.net/causeway_new/default.html

<http://www.creativesuite.com/>

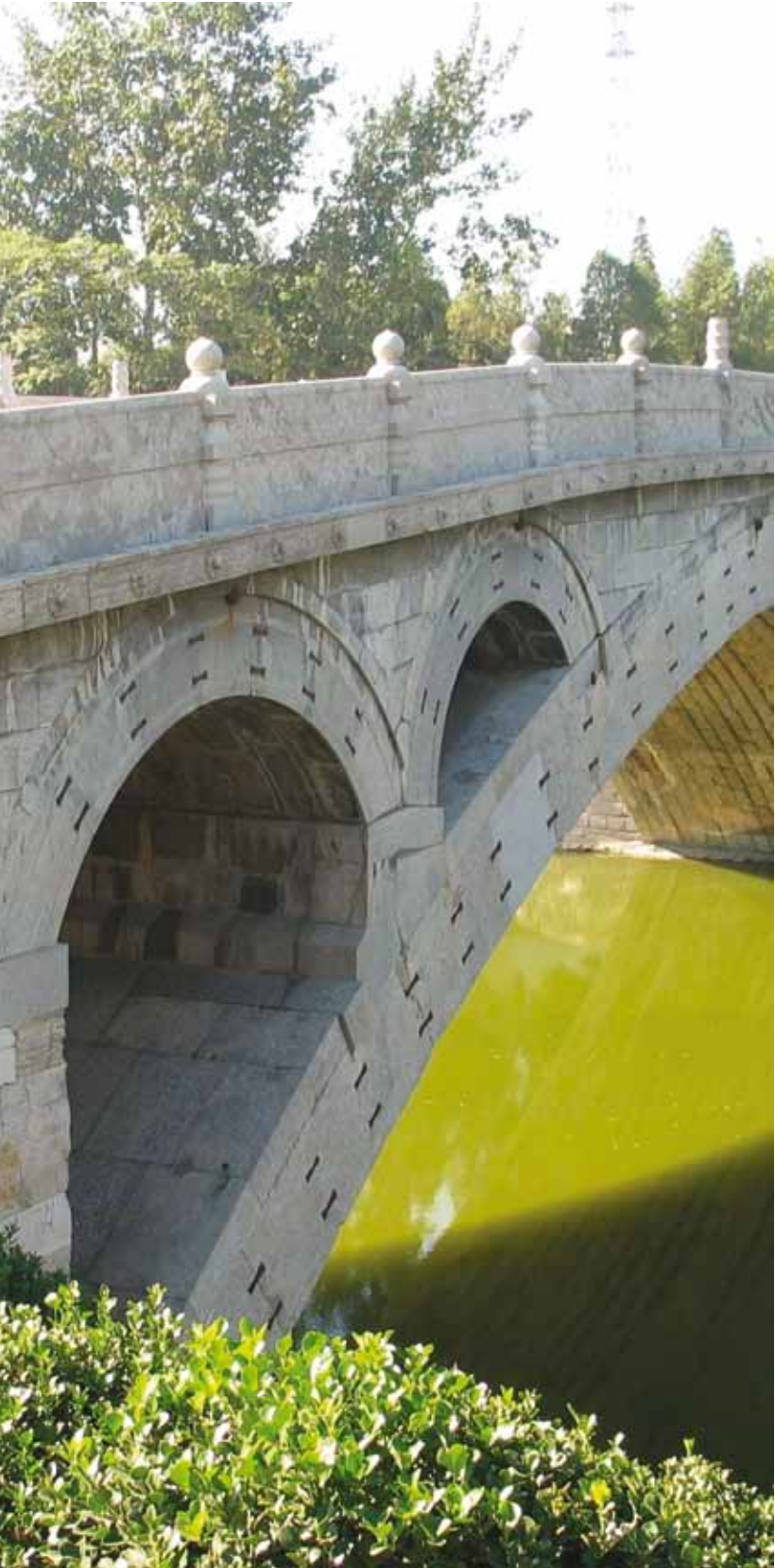
[cities-landscapes/5-longest-bridges-in-the-world](http://www.creativesuite.com/cities-landscapes/5-longest-bridges-in-the-world)

<http://science.howstuffworks.com/bridge2.htm>

http://en.wikipedia.org/wiki/Bang_Na_Expressway



» Arch Bridges



http://upload.wikimedia.org/wikipedia/commons/0/03/Zhaozhou_Bridge.jpg

ARCH BRIDGES



Figure 1 The Roman arch bridge at Alcantara constructed from concrete and clad in brick. (http://en.wikipedia.org/wiki/File:Bridge_Alcantara.JPG)



Figure 2 One of the now partially buried arches of the Limyra Bridge in Turkey, constructed by the Romans around the 3rd century BC. (http://upload.wikimedia.org/wikipedia/commons/1/1b/Bridge_near_Limyra_Pic_04.jpg)

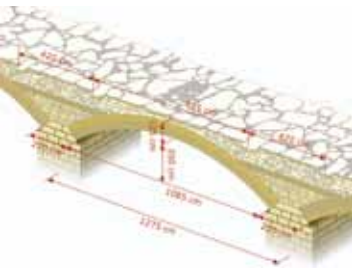


Figure 3 The Limyra Bridge has a particularly flat profile, with the arches having a span-to-rise ration of 5.3:1 (http://en.wikipedia.org/wiki/File:Limyra_Bridge_Arch.svg)

Arch bridges are amongst some of the oldest surviving examples of bridges around the world. The central span is supported by pillars or piers on either side and the curved shape allows the load to be transferred through to the piers making the structure very strong. The main disadvantage of the arch bridge is that complex false work must be built to support the arch during construction, limiting the size of the arches that can be built.

The Romans were great arch bridge builders. Their early bridges were made from circular or semicircular arches in which the arch shape formed a half circle. They constructed their bridges from stone that was precisely cut to fit to shape without the need for mortar. They were also the first to construct bridges from concrete, which they called *Opus caementicium*. The Alcantara Bridge in Spain, built by the Romans between 103 and 106AD was constructed from concrete and then clad with brick or ashlar (Figure 1).

The Romans were the first to introduce segmental arch bridges in which the arch consisted of an arc of a circle rather than a whole semicircle. This made them generally much flatter than semicircular arches and required the use of less material. The other advantage of this type of bridge was that larger spans could be built so that flood water could pass through easily, reducing the risk of the bridge being washed away.

They often used multiple arches built next to each other to span greater distances. The Limyra Bridge in Turkey (Figure 2) was built from 26 segmental arches and spanned a total distance of 360m. The bridge was built from two courses of radially laid bricks and today much of the structure is buried as the river has silted up. The other interesting feature of this bridge was the very flat profile, with the spans having an average span-to-rise ratio of 5.3 to 1 (Figure 3).

The Romans also spanned deep gorges by building an arch bridge on top of another arch bridge. In some cases three tiers were built in order to achieve the desired height. These immense structures were often aqueducts used to carry water. The Pont du Gard aqueduct in Southern France was constructed from three tiers of arches in order to span the Gardon River valley. In total the aqueduct stands 49 metres high and is 275 metres long. The bottom tier consists of 6 arches, is 142 metres long, 6 metres wide and 22 metres tall and carries a roadway. The middle tier has 11 arches and is 242 metres long, 4 metres wide and 20 metres tall. The upper arch has 35 arches, is 275 metres long, 3 metres wide and 7 metres tall and carries a covered water conduit 1.8 metres tall and 1.2 metres wide. The bridge was built from precisely cut stones, weighing up to 6 tonnes, which were hauled into place and required no mortar to hold them in place. A complex scaffold had to be built during construction and the scaffold supports are still evident on the faces of the stones.

Over the centuries arch bridges evolved and the shape of the arches changed to more pointed gothic arches. These arches were inherently stronger than the early Roman designs and thus required the use of less material in both the deck and supporting piers. In Medieval Europe bridge building advanced at a great pace and by the 14th century span lengths of over 40 metres could be achieved. The Pont du Diable or Devil's Bridge in France was built between 1321 and 1341. It spans 45.45 metres and is 22.3 metres tall at its highest point (Figure 5). This bridge is an example of a simple open spandrel bridge. The spandrel is the area between the arches of a bridge and in most early designs this was filled with material to create a solid structure. In an open spandrel bridge the space between the main arches is filled with smaller arches creating a more open structure.

The Chinese were building complex arch bridges at the same time as the Romans and many of these are still standing and in use. The Zhaozhou Bridge (Figure 6) was built between 595 and 605AD in Southern China. The bridge has a total length of over 50 metres, with the main span measuring 37.37 metres. The bridge is 9.6 metres wide and 7.3 metres tall at its highest point.



Figure 4 The Pont du Gard aqueduct in southern France constructed by the Romans around 19BC. (http://en.wikipedia.org/wiki/File:Pont_du_gard.jpg)



Figure 5 The Pont du Diable in France is an early example of an open spandrel bridge. (http://en.wikipedia.org/wiki/File:Pont_du_Diable_2.JPG)



Figure 6 The Zhaozhou Bridge in China is the oldest surviving example of an open spandrel segmental arch bridge. (http://en.wikipedia.org/wiki/Zhaozhou_bridge)



Figure 7 Sydney Harbour Bridge is a well known example of a through arch bridge. The main arch is 503 metres wide and 139 metres tall. The deck is 49 metres wide and has a clearance of 49 metres above the water. (http://en.wikipedia.org/wiki/File:Sydney_Harbour_Bridge_from_Circular_Quay.jpg)



Figure 8 The Lupu Bridge in China, built from steel and concrete and opened in 2003 was the longest through arch bridge in the world until 2009. (<http://en.wikipedia.org/wiki/File:LupuBridgeandBoats.jpg>)

It is an excellent example of an open spandrel segmental arch bridge. By using a segmental arch rather than a semicircular arch master craftsman Li Chun made a weight saving of about 40%. The open spandrels allowed even less material to be used and the open structure allows flood water to pass through without risking the bridge being washed away. The bridge has survived many earthquakes since its construction and part of the reason for this is the way that the bridge was built. The main arch consists of 28 thin, curved limestone slabs which are joined together using iron dovetails. These dovetails allow the bridge to move and flex and even allow it to stay standing if one of the stone slabs fails.

All of the arch bridges discussed so far are considered to be deck arch bridges in which the deck or road way sits entirely above the arches. In many modern designs the deck is suspended from the main arch by cables or tie bars and the Sydney Harbour Bridge, completed in 1932, is an example of this kind of through arch bridge. Modern materials such as steel and concrete have allowed much larger spans to be built and an excellent example is the Lupu Bridge in China which has a central span of 550 metres and an overall length of 3.9 kilometres (Figure 8). This bridge was opened in 2003 but the record for the longest arch bridge was beaten in 2009 by the steel built Chaotianmen Bridge, also in China which has a central arch span on 552 metres.

Where can I find out more?

http://en.wikipedia.org/wiki/Arch_bridges

<http://en.wikipedia.org/wiki/Arch>

http://en.wikipedia.org/wiki/Limyra_Bridge

http://en.wikipedia.org/wiki/Pont_du_Gard

[http://en.wikipedia.org/wiki/Pont_du_Diable_\(C%C3%A9ret\)](http://en.wikipedia.org/wiki/Pont_du_Diable_(C%C3%A9ret))

http://en.wikipedia.org/wiki/Zhaozhou_bridge

http://en.wikipedia.org/wiki/Through_arch_bridge

http://en.wikipedia.org/wiki/Sydney_Harbour_Bridge

http://en.wikipedia.org/wiki/Lupu_Bridge

» Truss Bridges



http://en.wikipedia.org/wiki/File:General_Hertzog_Bridge_over_Orange_River_at_Aliwal_North.jpg

TRUSS BRIDGES



Figure 1 The original Sioux Narrows Bridge in Ontario Canada. A wooden truss bridge built in 1936 from Douglas fir. (<http://www.flickr.com/photos/77136894@N00/2334314530/>)



Figure 2 Deck truss bridge where road sits on top of truss. (<http://www.interstate-guide.com/i-091.html>)



Figure 3 Through truss bridge where road sits under truss. (<http://www.historicbridges.org/truss/mckeowen/>)

Truss bridges evolved from simple beam bridges and use a series of beams and cross-braces to build truss work which stiffens the structure. As with beam bridges the structure may comprise just one span or be made up from a number of shorter spans in order to cross a greater distance. The use a series of vertical, horizontal and diagonal members which are in tension or compression allows the construction of a lighter bridge as not as much material is required compared to a similar beam bridge design.

Truss bridges were particularly popular in the United States in the nineteenth century as wood was in plentiful supply. Timber sections were used in compression and these were attached to iron rods in tension. The combination of these two materials proved successful for many years and a number of these bridges are still in operation today (Figure 1). As iron became more readily available it replaced wood in bridge construction and wrought iron truss bridges are still found all over the world.

Truss bridges can be characterised by the location of the deck or road bed. In some cases, as in Figure 2 it sits on the top of the truss (deck truss bridge), in others (Figure 3) the deck is below the truss (through truss bridge) and in some cases it is between the two trusses which are not joined together (pony truss).

The structure and geometry of truss can also vary between bridges. The simplest design is the Warren Truss (Figure 4a) in which the two horizontal beams are separated by diagonal struts which form a series of equilateral triangles. No individual strut, beam or tie experiences bending or twisting forces; the diagonal struts alternate in tension and compression towards the centre of the bridge. This design is suitable for relatively short spans of up to 100m and offers a relatively lightweight solution. This design was patented by James Warren and Willoughby Theobald Monzani in 1848. The Pratt and Howe Truss designs include vertical supports between the diagonal struts which provide additional stiffening. The Pratt Truss (Figure 4b) was invented in 1840 by Thomas and Calab Pratt and it



(a) (b) (c)
 Figure 4 Three types of truss bridge design: (a) Warren Truss, (b) Pratt Truss and (c) Howe Truss (<http://www.matsuo-bridge.co.jp/english/bridges/basics/truss.shtml>)

was commonly adopted for railway bridges. In this design all the diagonal struts (with the exception of the two on the ends) face downwards towards the centre of the bridge, and these experience tensile forces. The vertical supports are in compression and help to support the horizontal beams and prevent them from bending. This type of truss bridge is also suitable for spans up to about 100m. The Howe Truss (Figure 4c) is the opposite of the Pratt Truss and in this case all of the diagonal struts face away from the centre of the bridge. The diagonal struts are in compression and the vertical supports are in tension. This type of design is relatively rare as it is very uneconomic for steel bridges. The Howe Truss was named after its designer, William Howe, and was also patented in 1840.

There are many other variations of truss bridge design, most named after their inventor and many designed for specific crossings. Other more common truss designs are shown schematically in Figure 5.

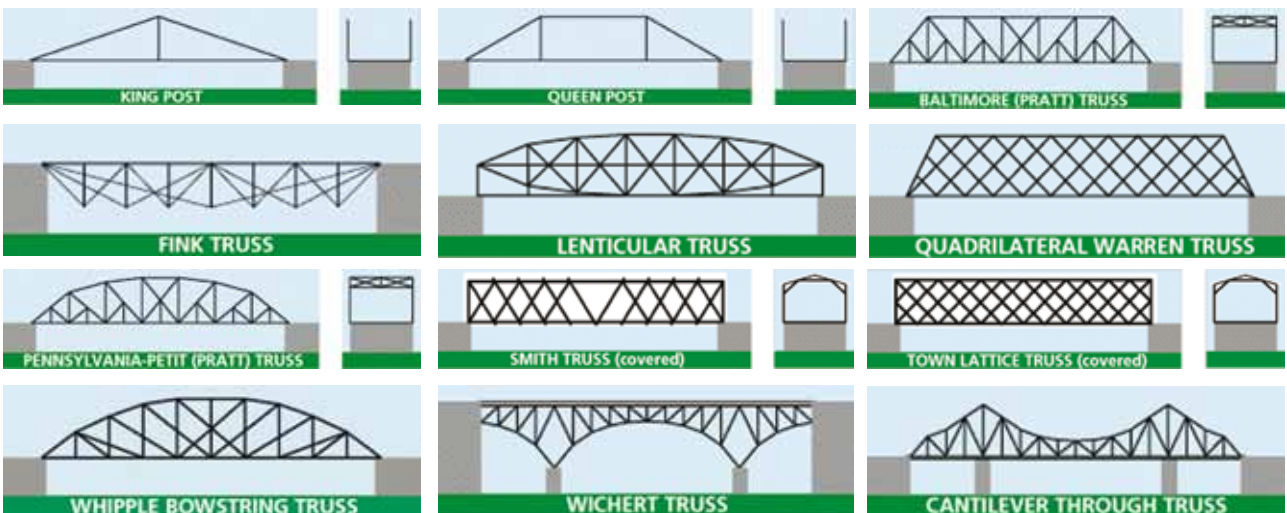


Figure 5 A selection of truss bridge design variations (<http://www.pghbridges.com/basics.htm>)



Figure 6 The Quebec Bridge over the Saint Lawrence River in Canada – the longest truss bridge in the world (<http://www.creativesuite.com/cities-landscapes/the-quebec-bridge>)

The longest truss bridge in the world also holds the record for the longest cantilever span. The Quebec Bridge crosses the lower Saint Lawrence River in Canada (Figure 6). The structure is 987 metres long, 29 metres wide, 104 metres high and the central span is 549m. The bridge, made from riveted alloy steel, was opened in 1917 after two disasters during construction in 1907 and 1916 in which many lives were lost. It was originally designed purely as a railway bridge but today carries a road, railway and footpath.

Where can I find out more?

<http://www.saintanthonymain.com/bridges/engineering.php>

http://en.wikipedia.org/wiki/Truss_bridge

http://en.wikipedia.org/wiki/Sioux_Narrows_Bridge

http://en.wikipedia.org/wiki/Quebec_Bridge

CANTILEVER BRIDGES

A cantilever bridge is a bridge which utilises a number of cantilevers to support the deck. A cantilever is a beam which is supported on one end and free at the other. In the simplest form of cantilever bridge two cantilever arms project out over the region to be crossed and are joined in the middle. The other ends of the arms are supported by pillars at either side of the obstacle. A further suspended span may be included in between the two cantilever arms to further increase the possible span distance (Figure 1). The cantilever arms may consist of simple beams, however, trusses are commonly used to improved the stiffness of the deck and allow greater distances to be spanned.

Construction of a cantilever bridge usually starts with the construction of the main support pillars. The cantilever arms are then constructed and extended on site. In order to balance the structure two cantilever arms are often projected from either side of the support pillar. Once opposing cantilever arms meet they are joined together to complete the span. A suspended span may be raised into position and joined between two cantilever arms.

The concept of the cantilever was first explored in the mid-nineteenth century and Heinrich Gerber was the first to obtain a patent to build a 'hinged girder' in 1866. His Hassfurt Bridge in Germany was completed in 1867 and is recognised as the first example of a modern cantilever bridge.

One advantage of the cantilever design was that scaffolding or false work was not needed to support the span during construction. This allowed deep gorges and other difficult obstacles to be able to be crossed. The Kentucky River Bridge spanned a gorge which was 84 metres deep and had previously been uncrossable.

The Forth Railway Bridge (Figure 2), constructed entirely from steel girders and opened in 1890 held the record for the longest cantilever span for 17 years and was considered an engineering marvel of its time. It is still standing and carries rail traffic from Edinburgh to the north of Scotland. It still holds the

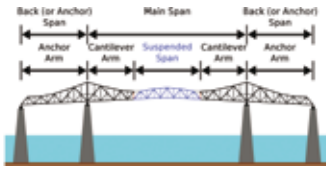


Figure 1 Schematic diagram showing parts of a suspended span cantilever bridge with the deck composed of truss sections (<http://en.wikipedia.org/wiki/File:CooperRiverBridge.svg>)



Figure 2 Forth Railway Bridge in Scotland constructed entirely from steel and holding the record for the longest cantilever bridge for 17 years. (<http://www.edinburghvilla.com/EdinburghForthRailBridgecrop2.jpg>)



Figure 3 Construction of the Pierre Pflimlin Bridge on the border between Germany and France began in the late 1990s and the crossing was opened in 2002.. (http://en.wikipedia.org/wiki/File:Pierre_Pflimlin_Bridge_UC_Adjusted.jpg)

record for the second longest cantilever span in the world with two spans each 521 metres long).

Although early cantilever bridges were constructed from iron or steel girders formed into trusses, many modern cantilever bridges take advantage of the properties of pre-stressed concrete. Sections of the bridge deck can be cast off-site and then joined together in-situ to extend the cantilever arms. The Pierre Pflimlin Bridge shown under construction in Figure 3 crosses the River Rhine between Germany and France. It was opened in 2002 and was constructed from reinforced concrete. The sections of the road deck were cast in position and joined together to form a balanced cantilever. The central span is 205 metres long and carries two lanes of traffic along with pedestrian and cycle ways.

Where can I find out more?

http://en.wikipedia.org/wiki/Cantilever_bridges

http://en.wikipedia.org/wiki/Forth_Railway_Bridge

http://en.wikipedia.org/wiki/Pierre_Pflimlin_bridge

» Suspension Bridges



http://en.wikipedia.org/wiki/File:Great_Belt_Bridge_JvdC.jpg

SUSPENSION BRIDGES

Suspension bridges differ to most other types of bridges in that a large amount of the structure is under tension rather than compression. The cables and ties from which the deck is suspended are placed in tension and the support pillars experience compressive forces. The load is transferred vertically down through the pillars and laterally through the cables. They require little or no false work to support the structure during construction and as such can be used to span wide or difficult spaces.

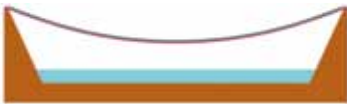


Figure 1 Simple suspension bridge in which the deck is supported on the main cables (<http://en.wikipedia.org/wiki/File:Bridge-suspension-simple.svg>)



Figure 2 The Capilano Bridge in Canada is an example of a simple suspension bridge in which the deck is supported by the hand rail cables. (<http://en.wikipedia.org/wiki/File:CapilanoBridge.jpg>)



Figure 3 The Arroyo Cangrejillo Bridge in Argentina is the longest simple suspension bridge in the world with a span of 337 metres. (<http://www.ketchum.org/Cangrejillo/fig15-700x470.jpg>)

Suspension bridges can be divided into three types. In simple suspension bridges the deck is placed directly on the main cables. These cables are only anchored at either end and thus the bridge takes on a hyperbolic shape. In some cases the deck is suspended from raised cables which also serve as hand rails. Since the deck is curved and the load bearing capacity is limited these bridges are restricted to pedestrian traffic, but can be built quickly in difficult areas.

The Capilano Suspension Bridge in Canada is 136 metres long and stands 70 metres above the river. It is a simple suspension bridge in which the hand rail acts as a support for the suspended deck. The original bridge was built using hemp ropes and cedar planks in 1888.

The longest simple suspension bridge in the world is the Arroyo Cangrejillo Pipeline Bridge in Argentina. The bridge was built between September 1997 and October 1998 to carry a 1 metre wide footpath and 0.2 metre diameter copper concentrate pipeline 337 metres across a 90 metre deep valley on the way from a nearby copper mine to a railway facility. Construction of the bridge preserved the natural environment as it meant that the pipeline did not have to be buried. The open steel deck is only supported by the main cables and sags by 7.85 metres at its mid-point. The main cables, made from 57 tonnes of steel, were made by encasing seven galvanised wires in a wax-filled sheath (for corrosion protection) to create a strand and then combining thirty seven of these 15 millimetre diameter strands together in a hexagonal arrangement. In addition to the main cables, 129 tonnes of structural steel and 250 cubic metres of reinforced concrete were used in the construction of the deck and abutments.

The second and third types of suspension bridge are very similar. In a traditional suspension bridge, also known as a suspended-deck suspension bridge, the main cables are anchored in the ground on either side of the structure (Figure 4a). In the less common self-anchored suspension bridge (Figure 4b) the main cables are anchored to the deck.

Construction of a suspension bridge generally follows a specific sequence:

- 1// **BUILDING OF THE TOWER SUPPORTS.** If the towers are to be located in a channel of water underwater piers must be constructed, ensuring that solid foundations are made in the river or sea bed. If the towers are on land then deep foundations must be sunk.
- 2// **CONSTRUCTION OF THE TOWERS.** Towers were traditionally built from stone, as in the Menai Suspension Bridge (Figure 5). The deck is suspended 30 metres above the straits, allowing ships to pass beneath and the bridge has a total length of 417 metres with a central suspended section of 176 metres. It has undergone some modification since its construction; in 1893 the wooden road deck was replaced with steel and between 1938 and 1940 the iron chains were replaced with steel. In some cases the towers are built from steel, as in the Golden Gate Bridge (Figure 6) which crosses San Francisco Bay. This bridge was completed in 1937 and has a central suspended span of 1.28 kilometres. Today steel reinforced concrete is the material of choice for building the towers as it offers excellent mechanical properties at a relatively low cost.
- 3// **SADDLES,** usually made from cast steel are attached to the top of the towers to eventually support the main cables.
- 4// **ANCHOR POINTS** are built to hold the main cables in place. These may be built into the bedrock if it is sufficiently strong; alternatively they are built from massive reinforced concrete blocks.
- 5// **GUIDE WIRES** are used to erect temporary catwalks between the towers which will be used to hold the gantries used for cable spinning.
- 6// **IN OLDER BRIDGES** the main suspension cables were made from iron or steel chains, such as those on the Clifton Suspension Bridge in Bristol (Figure 7). On modern bridges many thousands of miles of high strength steel

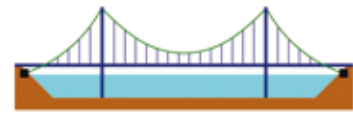


Figure 4a Traditional suspended-deck suspension bridge in which the main cables are anchored in the ground. (<http://en.wikipedia.org/wiki/File:Bridge-suspension-anchorage.svg>)

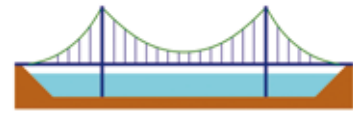


Figure 4b Self-anchored suspension bridge in which the main cables are anchored to the deck. (<http://en.wikipedia.org/wiki/File:Bridge-self-anchored.svg>)



Figure 5 Menai Suspension Bridge between Anglesey and mainland Wales, was designed by Thomas Telford and finished in 1826. It is one of the earliest examples of a modern suspension bridge. (<http://static.panoramio.com/photos/original/5219787.jpg>)



Figure 6 The south tower of the Golden Gate bridge constructed from steel. (http://en.wikipedia.org/wiki/File:Golden_Gate_bridge_pillar.jpg)



Figure 7 The cables of the Clifton Suspension Bridge are made from wrought iron. The Bridge was designed by Isambard Kingdom Brunel and was opened in 1864. (http://upload.wikimedia.org/wikipedia/commons/3/3a/Uk_bristol_csbchains.jpg)



Figure 8 The longest suspension bridge in the world today is the Akashi-Kaikyo Bridge in Japan, opened in 1998. (<http://www.msm.cam.ac.uk/pha-setrans/2004/Bridges/Bridges-Pages/Image0.html>)

wire is strung between the anchorage points and over the towers to spin the main cables. Each cable consists of many strands, each made up from individual wires. A corrosion resistant coating is applied to the wires.

7// **AT SPECIFIC POINTS ALONG** the main cables suspender cables or rods are attached to support the road deck.

8// **THE ROAD DECK IS BUILT IN SECTIONS** and attached to the suspender cables. Where possible the deck sections are lifted from the river below, otherwise they are carefully pushed out from the towers. The shape of the deck is particularly important as the bridge must be able to survive winds and vibration from the load travelling across the bridge. Open truss decks made from steel are very popular, but in many cases reinforced concrete sections with an aerodynamic profile are used for constructing the deck.

The longest suspension span today is part of the Akashi-Kaikyo Bridge which carries a six lane motorway and connects Kobe and Iwaya in Japan. The bridge was built between 1988 and 1998 and has a total length of 3.9 kilometres. The central suspended span is 1.99 kilometres long and is 65.72 metres above the Akashi Strait. The towers, made from steel are the tallest of any suspension bridge, standing 282.8 metres tall. In total the bridge used 700,000 tonnes of reinforced concrete in the two anchorage points, and 181,000 tonnes of steel. Each main cable, made from 36,830 individual strands, is 1.12 metres in diameter and used 300,000 kilometres of wire. The bridge has an open truss deck structure designed to be able to withstand wind speeds of up to 286 kilometres per hour and it is also designed to be able to withstand an earthquake measuring 8.5 on the Richter Scale!

Even longer suspension bridges have been suggested for future construction and modern materials may eventually allow these designs to be turned into reality.

Where can I find out more?

http://en.wikipedia.org/wiki/Suspension_bridge_types

http://en.wikipedia.org/wiki/Simple_suspension_bridge

http://en.wikipedia.org/wiki/Capilano_Suspension_Bridge

<http://www.ketchum.org/Cangrejillo/Cangrejillo.html>

http://en.wikipedia.org/wiki/Suspension_bridge

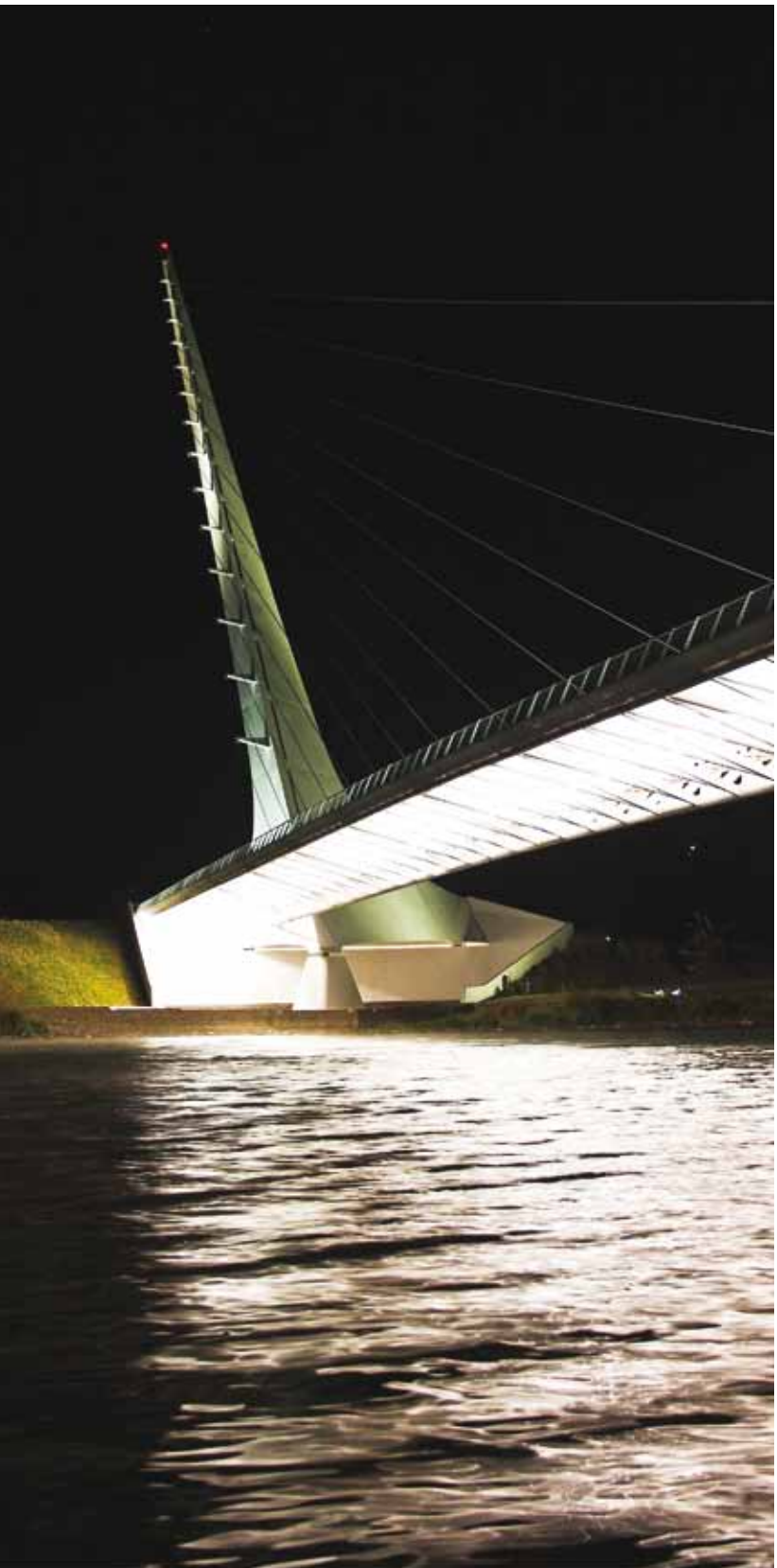
http://en.wikipedia.org/wiki/Menai_Suspension_Bridge

http://en.wikipedia.org/wiki/Golden_Gate_Bridge

http://en.wikipedia.org/wiki/Clifton_Suspension_Bridge

http://en.wikipedia.org/wiki/Akashi-Kaikyo_Bridge

» Cable-Stayed Bridges



<http://en.wikipedia.org/wiki/File:Sundialbridge2.jpg>

CABLE-STAYED BRIDGES

Cable-stayed bridges are closely related to suspension bridges in that they are comprised of one or more towers in compression and a deck suspended from cables which are in tension. They are not capable of spanning such large distances as suspension bridges, but can be used for larger single spans than cantilever or arch bridges.

The most important difference between a cable-stayed bridge and a suspension bridge is the primary load bearing component. In a suspension bridge this is the main cables which are held in tension and transfer the load to the anchorage points. In a cable-stayed bridge the primary load bearing structures are the towers to which the supporting cables are attached. The cables may be attached to the deck and tower in two different configurations. In a cable-stayed bridge with a fan or radial design all of the supporting cables originate from the top of the towers. In a cable-stayed bridge with a harp or parallel design the supporting cables are distributed down the length of the tower and run parallel to each other. The other distinguishing feature of a cable-stayed bridge is that the deck is also held in compression by the cables creating a structure which is inherently stiffer than a suspension bridge. This increased stiffness means that the deck deforms less under live loading (i.e. when the bridge is in use).

As with suspension bridges, cable-stayed bridges can be built without the need for false work. Once the towers have been constructed the deck can be cantilevered out from the desired height in pieces and the sections held in place by the supporting cables until they meet. Alternatively the individual sections may be raised and attached to the cables.

Cable-stayed bridges come in a variety of shapes and sizes, allowing crossings to be created which are as much a work of art as a functional structure.

The traditional cable-stayed bridge consists of two support towers with a central cable-stayed span and approach bridges on either side. A good example of this is the second Severn Crossing which carries the M4 motorway across the river between England and Wales (Figure 2). The bridge was opened in 1996 and has a total length of 5.13 kilometres. The



Figure 1a Fan design of cable-stayed bridge in which the supporting cables all originate from the top of the tower. (<http://en.wikipedia.org/wiki/File:Bridge-fan-cable-stayed.svg>)



Figure 1b Harp design of cable-stayed bridge in which the supporting cables are situated down the length of the tower. (<http://en.wikipedia.org/wiki/File:Bridge-harp-cable-stayed.svg>)



Figure 2 Second Severn Crossing comprises two approach bridges separated by a cable-stayed section over the shipping channel. (http://en.wikipedia.org/wiki/File:New_severn_bridge_best_750pix.jpg)

cable-stayed section is 900 metres long in total with a central span of 456 metres. The central span rises above the Shoots Channel – the main shipping lane. The approach viaducts are slender segmental arch bridges and are supported by 37 piers. The twin leg towers of the cable-stayed section are 149 metres tall and made from prestressed concrete. They support the 240 cables which hold the deck in place. The deck is made from steel plate girders and reinforced concrete and is designed so that the effect of high winds is minimal.

In some cases only one support tower is used and this may or may not be located in the centre of the span. The Rama VIII Bridge over the Chao Phraya River in Bangkok was opened in 2002 (Figure 3). It has a total length, including approaches, of 2.45 kilometres and the longest cable-stayed section is 300 metres long. The only tower of a single leg construction is positioned one third of the distance from one end. In this bridge the deck is supported by only one set of cables, running up the centre of the roadway and the cables are arranged in a harp design.

Somewhat more dramatic is the cantilever-spar cable-stayed design in which only one tower is used again. However, rather than being located towards the centre of the span, this tower is positioned at one end of the bridge and only one set of cables are used to support the deck. In this instance the cable forces are not balanced and the supporting tower must resist the huge bending forces exerted by the cables and have very strong foundations to resist overturning. The Sundial Bridge (Figure 4), opened in 2004, crosses the Sacramento River in California and has a 7 metre wide deck for pedestrians and cyclists. The bridge has one 36 metre tall tower inclined at 42° which supports the 213 metre long deck.

The longest single tower cable-stayed bridge in the world is the Surgut Bridge across the River Ob in Siberia. The single steel tower supports a cable-stayed span of 408 metres. The bridge, opened in 2000, has a total length of 2.11 kilometres.

It is possible to construct cable-stayed bridges with multiple spans in order to cross greater distances. These structures are generally less stiff than single spans but they can be quite spectacular.



Figure 3 The Rama VIII Bridge in Thailand has only one supporting tower located to one side of the centre of the span. (http://en.wikipedia.org/wiki/File:Rama_VIII_Bridge_at_night.jpg)



Figure 4 The Sundial Bridge in California is an example of a cantilever-spar cable-stayed bridge. (http://en.wikipedia.org/wiki/File:Sundial_Bridge_at_Turtle_Bay.jpg)



Figure 5 The Millau Viaduct across the Tarn Valley in France is a multiple span cable-stayed consisting of eight spans supported by seven towers. (<http://dannyoigrady.com/images/millau-viaduct-france.jpg>)



Figure 6 The Sutong Bridge over the Yangtze Rver in China has the longest cable-stayed span in the world at 1.088 kilometres. (<http://www.lqgcs.com/uploads/allimg/200909/1-0Z919141537.jpg>)

The Millau Viaduct in France is an excellent example of a multiple span cable-stayed bridge (Figure 5). It was designed by architect Norman Foster and structural engineer Michel Virlogeux and opened to traffic in late 2004. It consists of seven towers of varying height which support eight spans. The concrete towers are topped with 87 metre tall masts, each weighing 700 tonnes, which house eleven cables on each side that support the deck. The deck has a total length of 2.46 kilometres. It is 32 metres wide, 4.2 metres deep and is made from 36,000 tonnes of steel. The deck has an inverse aerofoil cross section in order to resist the high winds which blow down the valley. The bridge also holds the record for the tallest supporting towers with the largest standing at 343 metres.

The bridge with the longest cable-stayed span in the world is the Sutong Bridge in China (Figure 6). The bridge crosses the Yangtze River and was built between 2003 and 2008. The bridge has a total length of 8.2 kilometres and consists of a central cable-stayed span 1.088 kilometres long. On either side of the central span are a 300 metre long and then two 100 metre long cable-stayed spans and concrete segmental arch approach viaducts. The support pillars rise to 306 metres tall and there is a clearance of 62 metres between the deck and river. The steel deck of the central cable-stayed section was built off-site in 16 metre long sections, each weighing 450 tonnes. Like the Millau Viaduct the deck has been designed to resist strong winds.

As with suspension bridges, advances in modern materials will no doubt lead to the construction of even more impressive designs.

Where can I find out more?

http://en.wikipedia.org/wiki/Cable-stayed_bridge

<http://www.pbs.org/wgbh/nova/bridge/meetcable.html>

http://www.brantacan.co.uk/cable_stayed.htm

http://en.wikipedia.org/wiki/Second_Severn_Crossing

http://en.wikipedia.org/wiki/Rama_VIII_Bridge

http://en.wikipedia.org/wiki/Sundial_Bridge

http://en.wikipedia.org/wiki/Surgut_Bridge

http://en.wikipedia.org/wiki/Millau_Viaduct

http://en.wikipedia.org/wiki/Sutong_Bridge

2 >> MATERIALS



http://commons.wikimedia.org/wiki/File:Hope_Cement_Works.jpg

» Industrial Minerals

INDUSTRIAL MINERALS

Although the UK has almost no economically viable metal deposits, a significant number of other resources, including energy minerals (coal, oil & gas) and industrial minerals do occur in workable quantities as shown in Figure 1.

	Self sufficiency (%)	Consumption per person (kg)	Total consumption (Mt)
Primary Aggregates	100	3900	232
Cement	90	210	12.3
Limestone/Dolomite/Chalk	100	178	10.5
Brick Clay	100	118	7.0
Salt	100	96	5.7
Silica Sand	100	65	3.8
Gypsum	90	62	3.7
Potash	100	12	0.728
Kaolin	100	4.5	0.264
Ball Clay	100	2.7	0.158
Bentonite	25	3	0.178
Barytes	55	1.8	0.104
Fluorspar	70	1.4	0.080

Figure 1 UK self-sufficiency in industrial minerals, 2002 (from The Economic Importance of Minerals to the UK, BGS)

As well as limestone for cement, industrial minerals cover a wide range of resources and can be considered any resource that is not a metal or fuel. Building materials form a sub-group within this, and include building stone, clays for bricks and tiles, slates for roofs and the components of concrete.

CEMENT

The UK has a number of quarries and processing plants that produce cement, so the UK is almost self-sufficient.

Cement comprises three essential ingredients: calcite (CaCO_3) from limestone or chalk, silica (SiO_2) and alumina (Al_2O_3) which can both be obtained from shale or mudstone. This means that cement can be produced by mixing the right proportions of these two rocks (limestone/chalk and shale).

Cement manufacture is primarily based on Carboniferous limestones and Cretaceous chalk. These are relatively

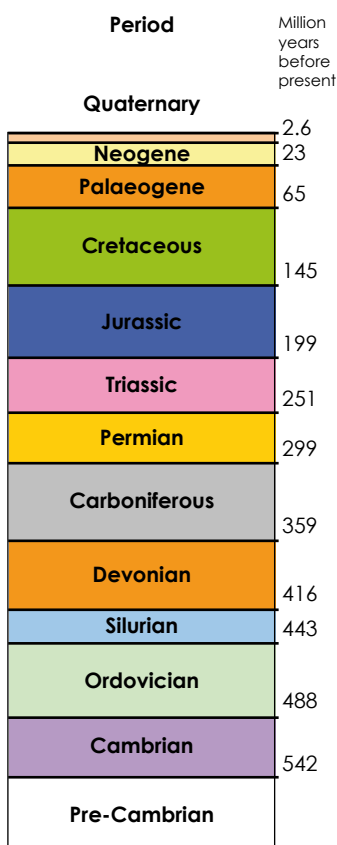


Figure 2 A simplified geologic time scale (the height of the periods are not drawn to scale)

extensive and so are worked in a number of locations across the UK. Figure 2 shows the relative positions of these periods in geological time.

A happy coincidence in the manufacture of cement from limestone is that the limestone and shale required often occur in the same sequence of sedimentary rocks, so both raw materials can be extracted from the same (or nearby) quarries.

Cement production

The raw materials are extracted from quarries and crushed in similar ways to hard rock aggregate quarries. However, in this case the aim is to get everything down to a very small particle size, so the material has to be finely ground in a ball mill after the initial crushing. It is at this point that the limestone or chalk is carefully mixed with the shale or clay to ensure a completely homogenous mixture. This grinding and mixing can either take place dry or wet. Limestone (3% moisture content) is usually processed dry, whereas chalk (12-16% moisture) is usually processed wet.

Whether it is wet or dry, the material is then heated (roasted) in a rotary kiln to a temperature of about 1400°C, where firstly water and then CO₂ are driven off, indicating the decomposition of first the shale and then the limestone.

Decomposition of the limestone takes the form of:



This process is known as calcination and the products of burning limestone are quicklime and carbon dioxide. This reaction has been known for millennia and was one of the first chemical reactions discovered by humankind. Left to its own devices, quicklime will reabsorb CO₂ from the atmosphere and convert back to calcium carbonate.

The kiln is tilted so that as the material rotates it passes through the kiln at a controlled rate. Burning fuel consisting of powdered coal or natural gas is forced into the lower end of the kiln. The remaining materials react and fuse to form a cement clinker which is then cooled.

At this point a further material is added to control the initial rate of reaction when the cement is mixed with water. Either gypsum or anhydrite can be used for this purpose, and usually makes up 5% of the final cement. This mixture is then finely ground (to less than 75 microns in size) to produce what is known as Ordinary Portland Cement.

CONSTRUCTION AGGREGATES

The term aggregate is the collective word for sand, gravel and crushed rock. Aggregates are extracted in very significant amounts, far in excess of all other industrial minerals combined, and so they are sometimes considered as a separate group.

Aggregates are normally defined as being hard, granular, materials which are suitable for use either on their own (compacted to a firm mass to fill a space) or with the addition of cement, lime or bituminous binder (for roads) in construction. About 35% of the aggregates used in the UK each year goes into concrete.

The value of aggregate is relatively low, so a significant proportion of the total cost is made up of the transport costs. This is one reason why there are so many quarries scattered around the UK, as wherever possible, demand will probably be met by local resources. However, there is a particular problem around London and the south-east, where demand is extremely high but the available natural resources are low. Concerns at minimising environmental impact and at maximising our natural resources, mean that Primary, Secondary and Recycled Aggregates are now defined in addition to considering the different sources of Primary aggregate. Figure 3 gives the amounts of aggregate produced in each of these groups.

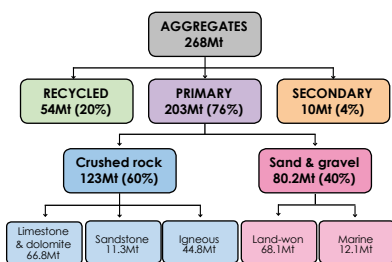


Figure 3 The tonnage of aggregate produced in 2003 from each source (from Construction aggregates, Mineral Planning Factsheet, BGS)

PRIMARY AGGREGATES

These are produced from naturally occurring mineral deposits, extracted specifically for use as aggregate and used for the first time. The source material can be a wide variety of hard rocks (e.g. limestone, sandstone, basalt, granite) which are then crushed to the appropriate sizes, or sand and gravel deposits recovered from a land or marine environment. The UK can be considered self-sufficient in aggregate as we only import a very small amount into the south east of England.

The UK has large resources of the different materials suitable for use as primary aggregates which are distributed quite widely. They can be divided into crushed rock aggregate and sand & gravel deposits.

Crushed rock aggregate

The suitability of a rock to be crushed as an aggregate depends on its physical characteristics, such as crushing strength, porosity, and resistance to impact, abrasion and polishing. Aggregates range from low to high quality, and concrete requires a reasonably high quality. This type of material is commonly derived from hard, dense and cemented sedimentary rock (most

limestones and certain sandstones) and the tougher, crystalline igneous rocks.

Quarries that excavate hard rock deposits are often large and deep and require large scale equipment to extract up to five million tonnes of rock a year (Figures 4 & 5). Sites are usually active for many years and therefore usually have fixed processing plant on site (Figure 6).

The method of working is to blast the rock to produce a good muckpile that can then be loaded into a dump truck by an excavator or a wheeled vehicle called a front-end loader. The quarry works down in a series of benches that are usually between 10 – 15 m high.

The objective of processing of the rock is to gain a range of different sized fractions which will be used for different purposes. Typically, a quarry will produce material with a diameter of 40mm, 28mm, 20mm, 14mm, 10mm and 6mm.

LIMESTONES Limestones are sedimentary rocks composed mainly of calcium carbonate (CaCO_3). Limestones are common rock types and are hard and durable and therefore suitable for aggregate. The main resource and extraction areas are in the Peak District of Derbyshire, the Mendip Hills, parts of North & South Wales, parts of the northern Pennines and Lakes District, and in Northern Ireland.

IGNEOUS AND METAMORPHIC ROCK Igneous rocks are particularly important where other materials are not widespread. Most igneous rock is used as roadstone or rail ballast, so is not as relevant to the production of concrete. Resources of igneous and metamorphic rocks are mainly concentrated in Scotland and Northern Ireland, mostly in remote upland areas.

However, there are some small outcrops of Cambrian/ Precambrian igneous rock (slightly metamorphosed diorite and granodiorite intrusions) in Leicestershire. These are a source not only for the Midlands, but they also serve London and the South East by good rail links, thus keeping traffic off the roads.

There is one very large granite quarry in Scotland, in the Strontian Granite on Loch Linne. Glensanda produces about 5 Mt per year, all of which is transported by ship to London, the south east of England and north west Europe.

SANDSTONE The term sandstone covers a wide range of different rock types, all of which are predominantly comprised of quartz, but with various amounts of feldspar and rock fragments in a fine-grained matrix or cement.

The most extensively worked sandstones are those of Upper Carboniferous age in the Pennines, but they are generally



Figure 4 - Typical hard rock quarry



Figure 5 - Large scale equipment is necessary to extract the rock.



Figure 6 - On-site processing plants are often built alongside quarries.

low quality. Sandstones known as greywackes occur across Britain and often make very good roadstone because of their resistance to abrasion and polishing.

SAND AND GRAVEL

These deposits have been formed by the erosion of rocks, mainly by glacial and river action, which produces fragments that then accumulate into a sedimentary deposit. Most sand and gravel is composed of particles that are durable and silica rich (e.g. quartz and flint), as softer material will degrade rapidly to produce silt which is of limited use.

LAND-WON SAND AND GRAVEL Sand and gravel resources extracted from land can be conveniently divided into two major categories. The bedrock (or "solid") deposits are geologically older deposits ranging from Permian to Palaeogene in age and are bedded deposits, often fairly thick, laid down as part of a sedimentary sequence. The sandy pebble beds that make up the Triassic Sherwood Sandstone Group (found in the Midlands and Devon) are conglomerates that are important as coarse aggregate for concrete. Others are made entirely of sand (e.g. Permian Yellow Sands of Durham).

The superficial (or "drift") deposits comprise all sediments laid down in the last 200 million years as fluvial (river) deposits or glaciofluvial (glacial meltwater) deposits.

The fluvial deposits commonly occur along the floors and sides of major river valleys and usually range between 1m and 10m thick. The Thames, Trent and Severn rivers are all important sources and the composition of each deposit reflects the upstream geology (the source of the sand and gravel). For example, the River Trent deposits contain a high proportion of well sorted quartzite pebbles from the Triassic Sherwood Sandstone Group.

The glaciofluvial deposits were laid down by the action of glacial meltwaters. These are often complex in shape and structure and are not confined to river systems. They can reach over 30m in thickness, although they may not be very laterally extensive and may also have a considerable thickness of glacial till (primarily a clay deposit) lying over them.

Sand and gravel quarries tend to be much shallower than hard rock quarries, but can be more significant in the area they cover. Extraction can be by small dragline (Figure 7) if the quarries are wet and the water is not pumped during extraction, however the usual method is by hydraulic excavator. Long field conveyors are often used to reduce the fuel bill of using dump trucks.

Sand and gravel is normally washed and screened over several different sizes of aperture, with crushing used to varying degrees depending on the size of the pebbles and boulders in the deposit, and on the product required. As the deposit is the result of rivers and glacial meltwaters, it is possible that it may contain some organic material (wood or lignite). This usually needs to be removed before the material is screened into various size ranges – 20mm, 14mm, 10mm and 6mm.

The sand is classified into coarse and fine sands, but the main issue here is separating the sand from the very fine silts and clays which are not required. The method of separation of sand and silt uses the effect of moving water and the different densities of the material.

Sand and gravel processing plants tend to use a lot of water, which quickly becomes contaminated with silt. The water is re-circulated as much as possible, and the silt rich waters taken to settling lagoons.

MARINE SAND AND GRAVEL These are very important to the UK as they are an important source of materials for London and the South East, where terrestrial sources are limited. While some of the off-shore deposits are modern marine tidal sand banks, most of them are directly comparable to the land-won fluvial and glaciofluvial deposits. These were originally deposited in a terrestrial environment, but subsequent subsidence and sea-level rise has resulted in them being located on the sea-floor.

There are approximately 25 vessels used for extracting marine sand and gravel from specific locations around the shores of Britain. It is usually extracted using a technique called trailer dredging, which is shown schematically in Figure 8. As the vessel proceeds at up to 3 km/h, it sucks up the sand and gravel at a rate of up to 1,500 t/h into the hold. The overall operational cycle of leaving port, traveling to dredge site, dredging, returning to port and discharging, usually takes between 12 and 37 hours, depending on where the material has to be delivered.

SECONDARY AGGREGATES

These are usually defined as either aggregates obtained as a by-product of other quarrying and mining operations (e.g. waste from china clay or slate), or aggregates obtained as a by-product of other industrial processes (e.g. blast furnace / steel slag, coal-fired power station ash).



Figure 7 - Typical dragline excavator used to extract sand and gravel.



Figure 8 - Diagram showing trailer dredging process for extraction of marine sand and gravel.

RECYCLED AGGREGATES

These arise from various sources including demolition or construction of buildings, structures and civil engineering works. Asphalt plantings from resurfaced roads and railway track ballast can also be used.

AGGREGATES AND THE ENVIRONMENT

There is no doubt that the extraction of primary aggregate causes an environmental impact. All quarries are strictly controlled by local authorities, and have to operate to high standards and meet a large number of conditions that will have been attached to the condition to work. The companies themselves realise they have an obligation to be good neighbours and to minimise impact, but there will often be residual noise or dust from a site, or an increase in local traffic.

The problem is exacerbated because many of the resources form the basis of some of the valued regions of our islands. Many of the limestones are found in National Parks or Areas of Outstanding Natural Beauty, and so there can often be a conflict between the materials required for modern living and the desire to protect special areas.

However, quarries are often a great opportunity for environmental and amenity enhancement, particularly in relation to biodiversity, habitats and nature parks. This applies to areas owned by the quarry company but not currently being worked, and to the restoration schemes after the quarry has finished, which are amongst the best in the world.

While the local effects of the aggregates industry are well understood and controlled, it is also true that the global effects (i.e. CO₂ emissions) also monitored and reduced at every opportunity. This is even more important in the cement industry which uses a significant amount of fuel during processing, and where CO₂ is released in significant quantities as part of the cement manufacture process.

» Concrete



CONCRETE



Figure 1 – The Roman baths at Caesarea built from Roman concrete which would set underwater. (http://en.wikipedia.org/wiki/File:Caesarea_Concrete_Bath.jpg)

INTRODUCTION

Concrete is a manufactured product and is produced by combining cement with a mixture of coarse and fine aggregate and water. Concrete can be placed in-situ or cast in moulds, where cement and added water undergo a number of reactions that produce new “minerals” that set hard and bind the aggregate in place. This produces a highly versatile building material which is valued for its high compressive strength, fire resistance, mouldability, impermeability and durability.

Concrete is the most widely used man-made material around the world. Enough concrete is made each year for every individual on the planet to have their own cubic metre – that amounts to about 7.5 cubic kilometres! Fortunately, the materials needed to make concrete can all be found in the UK, which means the extraction and processing takes place here and we are self-sufficient.

HISTORY OF CONCRETE

Concrete is not the modern material that it might appear to be. Evidence in Egypt suggests that concrete was used in the construction of the pyramids and the Romans were pioneers in concrete construction. Opus caementicium (Roman concrete) was widely used in the late Roman period for the construction of buildings, bridges and even underwater structures. Roman builders often thought the concrete unsightly so many structures had brick or stone cladding applied to a concrete core.

Roman concrete was made by mixing quicklime with pozzolana and aggregate. Pozzolana is a volcanic ash rich in silica and alumina minerals. These react with the calcium hydroxide when water is added to create a cementitious mixture capable of setting under water (Figure 1)

The type of aggregate used depended on the nature of the construction. In major structural applications such as walls and foundations heavy stone such as travertine was used giving a

material with a density of around 2200kgm⁻³. However, where weight was an important consideration the aggregate used was pumice reducing the density of the material to 1350kgm⁻³.

The Pantheon in Rome (Figure 2) still has the largest unsupported, unreinforced concrete dome in the world. The dome is 43.3 metres in diameter and at its highest point stands 43.3 metres above the floor. It contains an estimated 4535 tonnes of concrete and varies in thickness from 6.4 metres where it sits on the supporting walls to just 1.2 metres in the centre around the oculus (the opening in the centre of the dome which with the door provides the only source of light). The building has now been in continuous use for over 2000 years.

Roman concrete was used in a different manner to today. The Romans first laid down the aggregate and then packed a virtually dry mix of quicklime and pozzolana in to the gaps between the blocks.

The Romans used additives in their concrete to impart particular properties:

- » Volcanic ash such as pozzolana was added to allow the mix to set underwater.
- » Horsehair was added to the mix to reduce cracking during hardening.
- » Blood was added to make the concrete resistant to frost.

These innovations demonstrate that the Romans researched their material in order to design a concrete with the properties required for the job, much like the materials scientists and engineers of today.

MODERN CONCRETE

Modern day concrete is similar to its Roman predecessor though its properties are much improved. Concrete consists of three key ingredients, cement, water and aggregate. By varying the relative proportions of these and using additives a material with the desired properties can be made.

CEMENT consists of a mixture of calcium, silicon and aluminium oxides. When mixed with water a number of chemical reactions take place to produce 'new' minerals. Portland



Figure 2 – The concrete dome of the Pantheon in Rome showing the exterior (top) and interior (bottom). (http://en.wikipedia.org/wiki/File:Pantheon_dome.jpg and http://upload.wikimedia.org/wikipedia/commons/8/88/Pantheon_chiesa%2C_Roma_fc07.jpg)

cement (OPC) is the most commonly used type of cement. The main source of the calcium compounds in Portland cement is limestone and obtaining this material can lead to controversy as it is quarried from areas of natural beauty. It is possible to replace some of the OPC with cementitious materials from other sources. Fly ash, a by-product of coal fired power stations and ground granulated blast furnace slag, a by-product from steel production, can be used to replace up to 60% and 80% of the OPC in concrete respectively.

WATER reacts with the cement to produce glue which binds the aggregate particles together. The amount of water used depends on the flow properties required. Adding more water allows the cement mixture to flow freely and fill voids between aggregate particles. Using less water produces a stiffer mix which gives a stronger more durable concrete, but it does not flow so easily.

AGGREGATE usually takes two forms: fine and coarse. The main fine aggregate used is sand and coarse aggregates include natural gravel and crushed rock. Recycled materials are increasingly being used in concrete and such materials include demolition rubble and blast furnace slag.

ADDITIVES are used to change the properties of the concrete and make it more suitable for the particular application. Accelerators and retarders are used to either speed up or slow down the hardening process. Plasticisers increase the workability of the concrete allowing less water to be used. Additives which entrap tiny air bubbles in the concrete help to increase durability by reducing frost damage but they have a detrimental effect on the compressive strength of the material. Pigments may be added to change the colour of the concrete to improve its appearance.

Properties of concrete

Concrete is a material that is good in compression but its tensile properties are significantly poorer; the tensile strength of concrete may be 10% to 15% lower than its compressive strength. The aggregate carries the compressive load very efficiently, however, the cement matrix holding the aggregate particle together is weak in tension and can crack leading to

failure. It is possible to overcome this problem by reinforcing the concrete with a material that is good in tension. The ultimate tensile strength is influenced by the ratio of water and cement (or other cementitious materials). In general the lower the water content the stronger the material.

Shrinkage and cracking can lead to problems in concrete structures. As the chemical reaction in the material proceeds the material shrinks and this process can continue for days, weeks or even many years. This shrinkage can lead to internal stresses in the material and surface cracking.

CONCRETE PROCESSING

The way in which concrete is produced and processed varies depending on how it is to be poured and formed to shape. The chemical reaction between the cement and water starts as soon as they are mixed so time is of the utmost importance as there is a limited window for pouring the concrete into position.

It is essential to ensure that all of the ingredients in the concrete are mixed thoroughly and that they continue to be mixed up until the concrete is poured (Figure 3).

The concrete may be poured directly to where it is needed or cast and individual components assembled on site.

The concrete can be poured on to the ground to create foundations or the floor raft for a building (Figure 4). It may also be pumped into place (Figure 5).

Once the concrete has been poured or pumped into place it must be allowed to cure and this can be a critical stage. During the initial few days after pouring the moisture level, temperature, circulation of air and carbon dioxide level are very important. The concrete requires a moist environment in order for the chemical reactions to proceed and allow the cement to harden and gain strength. If the cement hardens too quickly internal stresses can be generated which can lead to cracking. Temperature must also be controlled as the curing process is highly exothermic. Curing is not a fast process; it may take around three weeks for the cement to achieve 90% of its final strength and potentially decades to get its full strength. It is thought that very large concrete structures such as dam walls



Figure 3 – Mobile cement mixer used to keep concrete moving until it is poured. (<http://upload.wikimedia.org/wikipedia/commons/2/20/CementMixerM2439.jpg>)



Figure 4 – Pouring a concrete raft for the floor of a building. (http://upload.wikimedia.org/wikipedia/commons/5/58/Concrete_pouring_0020.jpg)



Figure 5 – A pump may be used to move concrete to an elevated position or a difficult to reach area. (http://upload.wikimedia.org/wikipedia/commons/a/a0/Concrete_Pump_At_Works_Site.jpg)



Figure 6 – The Three Gorges Dam in China holds the world record for the largest concrete pour in a single project. (http://upload.wikimedia.org/wikipedia/commons/7/7c/Dreischluchtdamm_hauptwall_2006.jpg)

could take hundreds of years to cure fully.

The largest continuously poured concrete raft was built in 2007 in Abu Dhabi and formed part of the foundations for the Landmark Tower. It comprised 16,000 cubic metres of concrete poured in two days. In 2009 concrete was pumped to a height of 715 metres during the construction of the Parbati hydro-electric power project in India, this still holds the world record for the highest vertical concrete pump. These records pale into insignificance when the largest concrete pour in a single project is considered. The Three Gorges Dam in China is comprised of 16 million cubic metres of concrete poured over a period of 17 years (Figure 6).

STEEL REINFORCED CONCRETE

Reinforcing concrete with materials such as steel produces a composite material with the best properties of both constituents: concrete offers excellent properties in compression and steel offers excellent properties in tension. Steel is a suitable reinforcing material as it has a similar coefficient of thermal expansion to concrete. This means that internal stresses resulting from temperature changes are eliminated reducing the risk of cracking. In addition concrete forms an excellent bond with steel allowing stresses to be transmitted between the two materials efficiently and the alkaline nature of the concrete causes a passivating film to develop on the surface of the steel thus improving its corrosion resistance. However, it is still vital to ensure that water cannot penetrate the concrete and reach the steel rebar. One of the main causes of failure in reinforced concrete is failure of the steel rebar through corrosion.

The steel reinforcement may take various forms such as bars (rebar), grids, fibres or plates and reinforced concrete can be classified as either precast or cast in-situ.

PRECAST REINFORCED CONCRETE is made by making a mould in the shape of the desired component and then placing the desired reinforcement in place before casting the concrete. The reinforcing bars may be placed under tension prior to casting and the load removed once the concrete has solidified. This produces concrete which is pre-stressed in

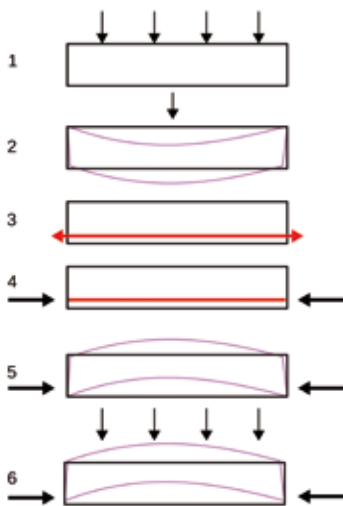


Figure 7 – Diagram showing the effect of pre-stressed steel reinforcement on the behaviour of a concrete bar. 1 & 2 shows how the concrete bar deflects (pink) when a load is applied to its top surface. 3 & 4 show how the concrete can be placed in compression by incorporating a steel bar in tension into the casting. 5 & 6 show how the pre-stressed concrete bar deflects when a load is applied to its top surface. The load must first overcome the internal compressive stress before causing further deflection. (http://en.wikipedia.org/wiki/Prestressed_concrete)

compression to limit the effect of tensile loads applied during use. Figure 7 shows how pre-stressing concrete affects the material during loading. Pre-stressing is used in the manufacture of beams, lintels and posts which are used for building high-rise buildings and bridges amongst other things. The main drawback with making precast sections is size; the components must be able to be transported to site for assembly.

When **CASTING CONCRETE IN-SITU** the reinforcement can be added in two ways. The first option is by far the simplest and can be used when making floor rafts. Once the concrete is poured rebar frames are placed and a further layer of concrete added (Figure 8). When more complex shapes are required a cage of rebar is constructed and then wooden shuttering is assembled around this to form a temporary mould into concrete is poured (Figure 9). Large structures can be built using this method as the wooden shuttering can be slowly moved and additional rebar frame constructed. Tall buildings and bridge pylons are built using this technique.

OTHER REINFORCING MATERIALS

In some applications it is not possible to use steel as the reinforcing material. For example, MRI scanners are built from concrete but steel cannot be used for the reinforcement as it would interact with the large magnets.

It is possible to add glass or plastic fibres or rebar made from fibre reinforced plastic (FRP) to concrete to offer reinforcement. These materials are all less dense than steel and so will not produce such a heavy material. This is of particular importance when trying to minimise weight. The advantage of using fibre reinforcement is that it stabilises the concrete during the initial stages of the curing process thus helping to prevent cracking. It does not add strength to the concrete in the same way as steel rebar. Steel and polymer or glass fibres may be used together to give the best overall properties.



Figure 8 – Installing a steel mesh in to a wet concrete floor raft to provide reinforcement. (http://upload.wikimedia.org/wikipedia/commons/0/04/Concrete_rebar_0030.jpg)



Figure 9 – Complex network of rebar in the roof of the Sagrada Familia in Barcelona prior to concrete pouring. (<http://en.wikipedia.org/wiki/File:SagradaFamiliaRoof2.jpg>)

SUMMARY

We have been using concrete for over 2000 years to build sustainable and enduring structures. It is an ideal choice in the construction of bridges and buildings, particularly when steel reinforcement is added and it is little wonder that it is the most commonly used man-made structural material

Where can I find out more?

<http://en.wikipedia.org/wiki/Concrete>

http://en.wikipedia.org/wiki/Roman_concrete

<http://en.wikipedia.org/wiki/Pozzolana>

http://en.wikipedia.org/wiki/Pantheon,_Rome

<http://www.romanconcrete.com>

http://en.wikipedia.org/wiki/Properties_of_concrete

http://en.wikipedia.org/wiki/Portland_cement

http://en.wikipedia.org/wiki/reinforced_concrete

http://en.wikipedia.org/wiki/Prestressed_concrete

http://en.wikipedia.org/wiki/Fibre_reinforced_concrete

BRICKS



HISTORY OF BRICKS

Bricks have been used in construction for over ten thousand years and it is thought that these bricks were made from the mud left in dry riverbeds. After being moulded by hand the bricks were left to dry in the sun, but they were not fired.

Sun dried bricks dating back to 4000BC have been found in Mesopotamia (modern day Iraq) and the ancient Egyptians were also brick makers. These early sun-dried bricks are referred to as adobe (adobe meaning mud brick) and they are generally made by mixing sand (50%) and clay (35%) with organic matter such as straw or dung. The purpose of the straw is to help bind the brick together and help the clay to dry out evenly in the sun. Adobe was also used as a construction material in Europe and the Americas and the largest adobe structure in the world was the citadel of Arg-é Bam in the south east of Iran, constructed around 500BC (Figure 1). Unfortunately the spectacular structure was almost entirely destroyed by an earthquake in 2003.

In China bricks were being made as far back as 3800 years ago. The Chinese were the first to stamp the bricks with the name of the maker, a practice continued to this day.

The Mayans traditionally used cut limestone to build their cities. However, in Comalcalco they used bricks made from fired clay as there was no stone available locally (Figure 2). Many of the stamped symbols found on the bricks at Comalcalco are very similar to Roman stamps found elsewhere, suggesting that the Romans travelled to the Americas.

Although many Roman structures were made from stone, they were also master brick makers (Figure 3). Roman legions operated mobile kilns to fire the bricks and thus introduced bricks to many parts of the Empire.

Over the past thousand years bricks went in and out of fashion. For example during the Renaissance and Baroque brickwork was often covered in plaster.

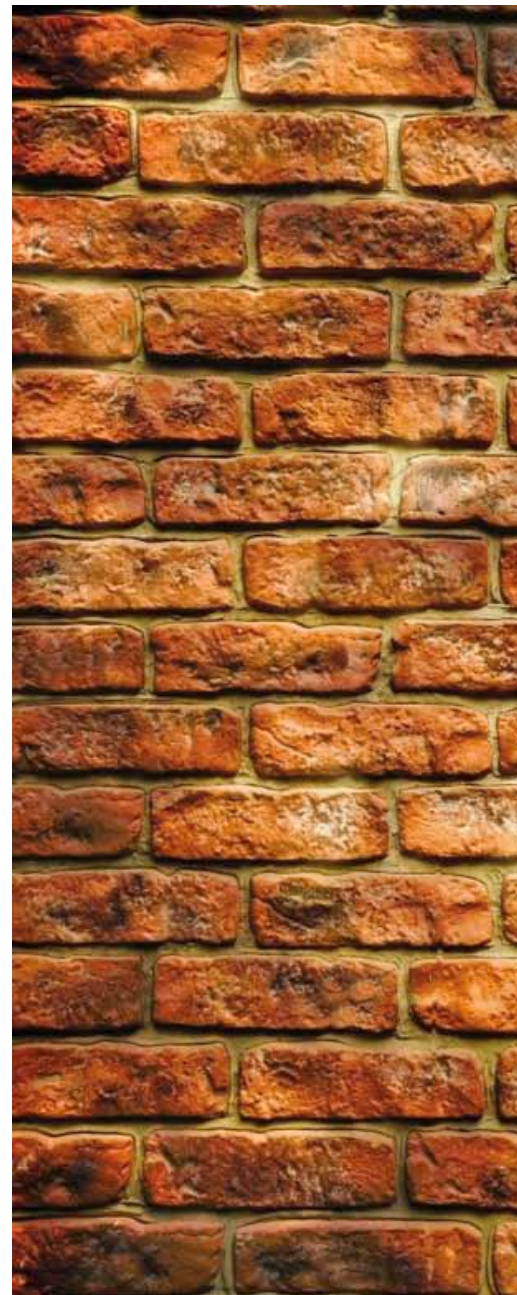




Figure 1 - The Arg-e Bam citadel in Iran was the largest adobe structure in the world until it was destroyed by an earthquake in 2003. This is just one small part of the huge, sprawling complex that was built 2500 years ago. (http://en.wikipedia.org/wiki/File:Arge_Bam_Arad_edit.jpg)



Figure 2 The Mayans used fired bricks made from clay to build the city of Comalcalco as no stone was available locally. (<http://www.mexconnect.com/articles/1241-did-you-know-mayan-pyramid-in-tabasco-mexico-has-possible-roman-links>)



Figure 3 - The Romans used mobile kilns to make bricks where ever they went. This is a fine example of a Roman brick wall with embedded arches. (http://www.architectureweek.com/2005/0803/images/surfaces_B129).

The speed of construction in brick meant that it was the preferred building material for factories built during the Industrial Revolution, even though stone was easily available. Many cotton mills in the North West were built from bricks and brick bridges helped the extensive rail network to develop during this time of rapid industrial expansion. The 27-arch Stockport Viaduct over the River Mersey was completed in 1840 and was the largest viaduct in the world when it was built (Figure 4). The structure took just 21 months to erect and contains over 11 million common bricks!

Although bricks are still used extensively for domestic dwellings, their use for commercial buildings has decreased over the past 200 years. Materials such as concrete and steel are more suited to high rise structures as they are stronger and allow more open designs to be built.

BRICK MAKING

A variety of techniques and materials are used in the manufacture of bricks, but in each case roughly the same procedure is followed.

Obtaining and preparing the raw materials

Bricks can be made from a wide range of materials but clay is by far the most common. Clay is a mixture of fine-grained (particles less than $2\mu\text{m}$) minerals generated by the long-term chemical erosion of silicate-bearing rocks. These minerals may be deposited at their erosion site but are often transported from their site of origin and laid down elsewhere. Clays deposits found at the formation site are known as primary clays or kaolins. Secondary clays are those which are located away from the site of formation. Many types of pure clay exist, with subtle differences in mineral content, but most clay deposits contain a mixture of different types producing a range of colours ranging from a deep red to dull grey.

The clay is dug out of the ground, either by hand or with machinery, depending on the size of the operation, and prepared prior to moulding into bricks. Preparation involves allowing the clay to dry out slightly and then grinding the material to achieve the desired grain size. The water content of the clay is carefully controlled to ensure that the material is

the correct consistency for moulding. Sand may be added to the clay to reduce shrinkage of the bricks during drying and firing.

Moulding the bricks

A number of techniques may be used to mould the clay into bricks. The method chosen depends on the consistency of the clay and the type of brick. Features such as frogs (an indent in the surface of the brick), holes and stamps are introduced during the moulding process.

HANDMADE BRICKS. The traditional method of brick making involves taking a piece of clay, known as a clot, and throwing it into a wooden frame. This is a skilled operation as the clay must completely fill the frame in order to produce a uniform brick. The soft bricks are removed from the moulds prior to drying and firing.

SOFT MUD. This process is similar to the hand-made method, but in this case clay with a higher water content is dropped between two rollers. As the rollers rotate they throw the clay into a metal mould. Excess clay is removed and the brick released from the mould giving a similar finish to a hand-made brick.

SEMI-DRY. This method allows more than one brick to be made simultaneously, with a mould containing several individual cells. Ground clay is fed into a machine which presses it into the mould.

STIFF PLASTIC. The clay used in this case has a relatively low moisture content and extra water is added before the clay is pressed into the mould by a machine. This technique produces a dense, uniform brick.

EXTRUDED AND WIRE-CUT. Most types of clay can be used in this process which involves forcing it through a metal die to produce a continuous extruded column. This column has the correct length and width and a wire is used to cut the desired depth of brick. The extruded column can be textured or coloured prior to cutting and it may contain holes or perforations. Extruded bricks do not contain frogs.



Figure 4 - The Stockport Viaduct over the River Mersey, completed in 1840, carries the Manchester to Birmingham railway. The M60 motorway now also passes beneath this spectacular structure. (<http://en.wikipedia.org/wiki/File:Stockportviaduct.jpg>)



Figure 5 - Clay deposit on the surface, ideally located for easy extraction. (<http://www.sheffield-pottery.com/vspfiles/assets/images/clay-pit.jpg>)

Drying the bricks

Once the bricks have been moulded it is important to let them dry out to reduce the water content before firing. At this stage some shrinkage will occur and the dried bricks have a leathery surface layer, allowing them to be handled without causing damage. The bricks can be dried outdoors or in an oven and at this stage are known as 'green' bricks.

Firing the bricks

Once the bricks have dried out they are stacked in a kiln and fired to a temperature of over 1100°C. During this process the bricks are heated slowly until the desired temperature is reached, held at this temperature for several days and then allowed to cool at a controlled rate. As the temperature increases the remaining water is driven off, once up to temperature the material undergoes a sintering process in which the edges of the clay particles melt and fuse together. During firing the chemical composition of the bricks changes and this results in a change in their properties and appearance.

Where can I find out more?

<http://en.wikipedia.org/wiki/Brick>

<http://en.wikipedia.org/wiki/Adobe>

<http://www.myanmars.net/myanmar-history/mayan-civilization.htm>

<http://www.mexconnect.com/articles/1241-did-you-know-mayan-pyramid-in-tabasco-mexico-has-possible-roman-links>

<http://science.jrank.org/pages/1025/Brick.html>

<http://www.shol.com/agita/thespiel.htm>

<http://www.penmorfa.com/bricks/history.html>

» Iron



IRON



Figure 1 – Metallic meteorite comprising an iron-nickel alloy. (http://www.meteorites.wustl.edu/id/gibeon_slice_rk_12851.jpg)

INTRODUCTION

Iron is the sixth most abundant element in the Universe and the most common element in the Earth as a whole, as the core of the planet is thought to be comprised mainly of an iron and nickel alloy. Iron is only the fourth most abundant element in the crust and it rarely occurs in its native form as it oxidises readily to form minerals such as haematite and magnetite.

Man has been using iron for many thousands of years and the first iron artefacts were probably made from iron occurring in metallic meteorites. Spear tips, daggers and ornaments made from iron have been found dating back to 4000BC and it is mentioned in both the Bible and Qur'an. Smelted iron objects appeared in Mesopotamia as far back as 3500BC. These can be distinguished from meteoric iron by the lack of nickel (metallic meteorites are generally composed of an iron-nickel alloy). It is thought that early iron production occurred as a by-product of copper refining which was being carried out for bronze production and deliberate smelting of iron started in the Middle Bronze Age. The iron produced was very impure, containing a large amount of carbon. The Chinese developed early blast furnace technology towards the end of the Zhou Dynasty in around 550BC. They produced furnaces which would reach temperatures of over 1000°C and produced carbon-rich pig iron.

Today iron is the most commonly used metal, but it is not often used in its elemental form. Iron alloys, chiefly steel, have helped to shape the modern world and their wide range of properties has led to their use in vast number of applications.

Structure and properties of iron

Iron is a grey lustrous metal with atomic number 26 and relative atomic mass 55.8 and it sits in the first transition series in the Periodic Table between manganese and cobalt. Some of the key properties of iron are presented in Figure 2.

Iron can exist in a number of allotropic forms (Figure 3) and indeed on solidification undergoes phase transformations through these various structures before settling on a body-centred cubic (bcc) structure at room temperature. On solidification from the melt iron adopts a bcc structure and this form is known as δ -iron. At 1394°C iron undergoes a solid

Physical properties

Density	7874kgm ³
Melting point	1536°C
Boiling point	2861°C

Atomic properties

Crystal structure at RT	Body centred cubic
Electronegativity (Pauling Scale)	1.83
Atomic radius	126pm

Mechanical properties

Ultimate tensile strength	Pure Fe single crystal	10MPa
	Cold worked Fe	690MPa
	Fe whisker	11000MPa
Young's modulus		211GPa
Mohs hardness		4.0

Figure 2 – Some key properties of iron

state phase transformation and the structure becomes face-centred cubic (fcc). This phase or allotrope is known as γ -iron or austenite. At 912°C the structure reverts to a bcc arrangement and the resulting phase is known as ferrite or α -iron. This is the most stable structure for pure iron, however, other phases may be stabilised by the addition of alloying elements.

Iron is one of only three naturally occurring ferromagnetic elements (the other two being nickel and cobalt) and many of its applications use this unusual property.

The main disadvantage of iron is its poor corrosion resistance. Iron will readily oxidise forming a surface layer of rust (iron II oxide). This corrosion product occupies a larger volume than the underlying iron and so spalls off revealing more bare metal for reaction. Alloying and surface coating both offer solutions to this costly problem.

OCCURRENCE, EXTRACTION AND PROCESSING OF IRON

Iron accounts for about 95% of worldwide metal production and its use is on the increase. World production of iron ore rose by 16% in 2006 to 1,810 million tonnes, mainly driven by high demand in China.

Iron ore extraction

The extraction of iron ore is done on a massive scale. The most economically important iron ore deposits are the banded iron formations in Western Australia and around Lake Superior, although the largest reserves are held in the Ukraine, Russia and China, with China being currently the biggest producer (Figure 4). Economic deposits have usually been enriched to grades of around 65% iron, although this will vary with the market price of iron and the location and accessibility of the resource.

Bedded iron ore deposits can be found in the Carboniferous and Jurassic periods, but the most important are the banded iron formations of the Pre-Cambrian. These deposits can be vast, extending for hundreds of kilometres and sometimes up to 500 metres thick. The formation of these is still rather uncertain, but it is thought they are related to the lower level of oxygen in the atmosphere that existed in Pre-Cambrian times.

Nearly all iron ore is extracted from surface mines, otherwise known as open-pits, because of the nature of the deposits and the vast amount that is mined. Equipment on a huge scale is used to dig the rock (Figure 5) and haul it up to the processing plant.

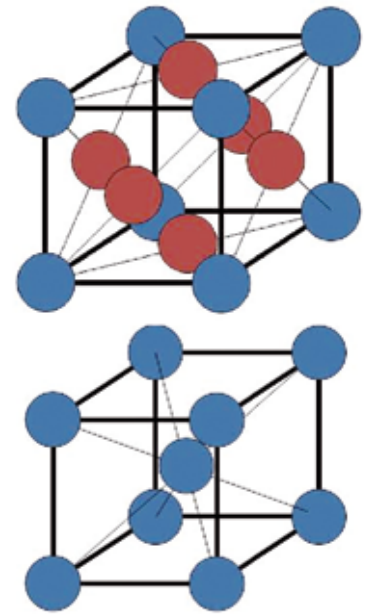


Figure 3 – Diagram showing face-centred cubic crystal structure of austenite (top) and body-centred cubic structure of ferrite (bottom)



Figure 4 - Iron output in 2006 shown as a percentage of the top producer – China: 420 Mt (from Wikipedia, based on data from the BGS)

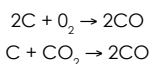


Figure 5 – The equipment used in the extraction of iron ore is massive. The person (outlined in red) is dwarfed by the enormous machine!

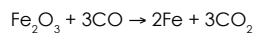


Figure 6 – Blast furnace used to extract iron from its ore. (http://commons.wikimedia.org/wiki/File:Blast_furnace_at_Corus_IJmuiden.jpg)

Production of reducing agent:



Reduction of iron ore:



Slag forming reactions:

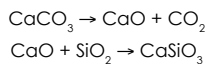


Figure 7 – Summary of main chemical reactions occurring in blast furnace

Pig iron Liquid tapped off from the blast furnace. So called because the ingots cast looked like piglets suckling a sow.

Cast iron This is a specific type of alloy with a carbon content of 2-4wt%. Cast irons are described as being white, grey, malleable or ductile depending on their composition and microstructure.

Steel This is an iron alloy containing 0.2-2.0wt% of carbon and other alloying additions

Wrought iron This used to be known as commercially pure iron as it has a very low carbon content. However, it does contain significant slag inclusions.

Figure 8 – Some definitions associated with iron and its alloys

Iron processing

The blast furnace (Figure 6) is used to extract iron from its ore using a simple reduction chemical reaction on a massive scale. Iron ores such as haematite and magnetite, coke (the reducing agent) and limestone (a flux to aid in slag removal) are continuously fed in to the top of the furnace. Heated air is blasted through tuyeres towards the bottom of the furnace at a rate of about 4 tonnes of air per tonne of iron.

The chemical reactions taking place in the furnace are shown in Figure 7. The main reduction chemical reaction is highly exothermic and the heat generated raises the temperature of the blast furnace to over 2,000°C. As the temperature rises burning coke generates carbon dioxide and carbon monoxide. The CO₂ from the burning coke reacts with more coke to produce more carbon monoxide (CO) and it is this that is the main reducing agent.

However, this is not the only reaction going on, as the original ore will contain impurities such as silica (SiO₂). This is where the limestone comes in because when it is heated it gives off CO₂ and forms quicklime (CaO), which then reacts with the silica to form a molten slag of material like calcium silicate.

The molten slag is less dense than the molten iron, so it floats on the surface and can be drained away separately.

The molten iron is tapped from the bottom of the furnace but this is not pure iron by any means. The liquid metal, known as pig iron, has a carbon content of 4 to 5 percent by weight (wt%) and may also contain other impurities such as sulphur, silicon and phosphorus. This is the starting point for further processing in to cast irons, steels or other alloys.

NOMENCLATURE

A number of names are used to describe iron and its alloys and these can often be quite confusing. A brief summary of some of the terms is presented in Figure 8.

Where can I find out more?

<http://en.wikipedia.org/wiki/Iron>

http://en.wikipedia.org/wiki/Iron_Age

http://en.wikipedia.org/wiki/History_of_ferrous_metallurgy

http://en.wikipedia.org/wiki/Blast_furnace

http://en.wikipedia.org/wiki/Cast_iron

<http://en.wikipedia.org/wiki/steel>

http://en.wikipedia.org/wiki/wrought_iron



» Steel

STEEL



Figure 1 – Steel production by country in 2007. (http://en.wikipedia.org/wiki/File:Steel_production_by_country_map.PNG)



Figure 2 – Charging a BOS furnace. An idea of the scale of the furnace is given by the size of the two people. (http://www.wrhs.org/index.php/crawford/Online_Exhibit/Clev_Steel/Part3)



Figure 3 – Schematic diagram of a BOS vessel showing the lance blowing oxygen through the liquid iron. (<http://www.coruselearn.com/images/bos.gif>)

THE STEEL INDUSTRY

The manufacture of steel has helped to shape the world we live in today. It is used in the construction of our transport network, buildings, and cars and it is used at some point in the machinery used to make almost everything we use every day.

The steel industry is still growing; between 2000 and 2005 production grew by 6%, mainly due to increased production in rapidly developing countries like China and India. Figure 1 shows steel production by country in 2007 and it can be seen that China is by far the biggest producer, followed by India, Russia and the USA.

STEELMAKING

The majority of the steel produced today is made via the Basic Oxygen Steelmaking (BOS) route; this is known as primary steelmaking. In 2000 BOS accounted for 60% of steel production worldwide. However, secondary steelmaking using recycled steel accounts for a significant quantity so the Electric Arc Furnace (EAF) will also be discussed.

Primary steelmaking

The BOS process was introduced in the 1950s and is used to convert pig iron from the blast furnace into steel. A modern furnace (Figure 2) may take a charge of up to 350 tonnes of iron and is capable of converting this to steel in less than 40 minutes. The reaction vessel is lined with refractories such as calcium oxide and magnesium oxide which have a basic pH. Molten pig iron with a carbon content of 4-5wt% is poured in to the vessel and a water-cooled lance is then lowered into it (Figure 3). Pure oxygen is then blown through the lance at high pressure and the gas reacts with the carbon in the liquid producing carbon monoxide and carbon dioxide. Oxygen blowing is controlled to achieve the desired carbon content in the resulting steel. Burnt lime or dolomite may also be added to act as a flux and aid slag formation. The furnace is tipped to pour the steel from the vessel into a ladle after oxygen blowing is completed (Figure 4). The resulting steel may go on for further refinement of the

composition or to a continuous casting machine to cool and solidify. The typical composition of steel on exit from the BOS furnace is 0.3-0.6wt% C, 0.05-0.1% Mn, 0.01-0.03wt% Si, 0.01-0.03wt%S and 0.01-0.03wt%P.

Secondary steelmaking

Over the past century secondary steelmaking techniques, such as the electric arc furnace have become increasingly popular as they allow steel scrap to be recycled. A typical furnace (Figure 5) may take around an hour to make 80 tonnes of steel. The furnace consists of a large lidded vessel, lined with refractory material, which has a spout on one side for tapping and holes in the roof for the graphite electrodes to pass through. During operation the furnace is charged with a mixture of scrap steel and pig iron. Once loaded the roof is swung back across the furnace and the graphite electrodes lowered. An arc is struck to melt the charge and oxygen may be blown into the furnace to speed up the melting process and burn off some impurities. Slag forming minerals are added with the charge to help reduce impurities in the steel that will not burn away. Once the steel is melted and the desired composition has been achieved the electrodes are removed and the furnace tilted to first allow the slag and then the liquid steel to be tapped. The main advantages of the EAF are that it can operate on 100% scrap thus reducing the specific energy of making the steel and that it is flexible in terms of start-up and shut-down time allowing production to be varied with demand. The main disadvantages of the EAF are the amount of electricity consumed and the dust produced, though both of these issues can be overcome.

As with BOS steel, the steel from the EAF can go on for further compositional control or casting.

Steel processing

The first stage in steel processing involves producing slab. This may be done in a batch process but in many cases now a continuous casting (concast) machine is used (Figure 7). Liquid metal from the ladle flows into the tundish and is released into the water-cooled mould at a controlled rate. A thin skin of solid steel forms and gradually thickens as the slab is moved downwards. A series of rollers support the slab as it rotates from vertical to horizontal. By the time it is on the horizontal run-out



Figure 4 – Tapping a BOS furnace. (http://www.wrhs.org/images/uploaded_images/caam/Cleveland%20Steel/Making%20Steel/WarrenBOFTapping.jpg)



Figure 5 – Electric arc furnace for secondary steelmaking. (www.scienceinpublic.com)

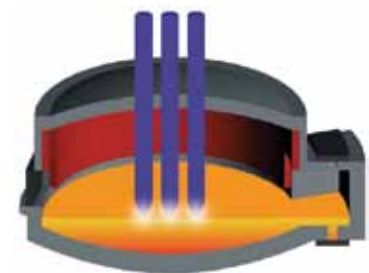


Figure 6 – Schematic diagram of an EAF. (http://www.corusgroup.com/file_source/Images/Functions/Education/PictureGallery/ElectricArcFurnace3D.jpg)

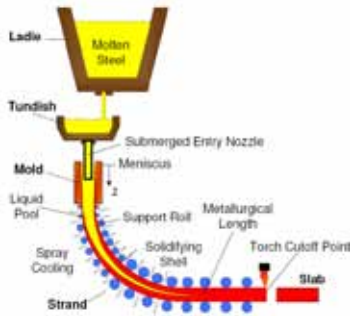


Figure 7 – Schematic diagram showing the continuous casting process used to make steel slabs. (<https://agora.cs.illinois.edu/download/attachments/20587553/cc.PNG>)



Figure 8 – Hot rolling steel slab in a reversing mill. (<http://web.srv.cmes.utah.edu:8080/metal/galleries/photo.2006-08-16.5298623956/variant/medium>)



Figure 9 – Rolls of cold rolled strip steel. (http://www.nskamericas.com/cps/nsk/eu_en/p/images/content/CS_7003_ImageR_square_rdx_95.jpg)

table it is completely solid. A gas torch is used to cut the slab to the desired length for subsequent processing.

The type of further processing will depend on the type of product, but generally speaking processing can be split into two types, which may be used in conjunction with each other:

- 1 **HOT PROCESSING** takes place above the recrystallisation temperature of the material which for steel is typically around 1000°C. Hot processing techniques include rolling (Figure 8) and forging.
- 2 **COLD PROCESSING** is defined as taking place below the recrystallisation temperature of the material but this generally means processing at room temperature. Cold rolling is used to produce sheet or strip material (Figure 9) and cold working can be used to strengthen a material by introducing defects into the structure.

By employing these methods steel can be processed into a wide variety of shapes and sizes and these plates, sheets, bars and billets may be processed further by deep drawing, stretch forming, bending and machining.

The steel may also undergo a heat treatment to modify the structure and control the properties. The most common heat treatments are:

- » **ANNEALING.** This involves heating the steel to above its recrystallisation temperature and then allowing it to cool slowly. A full annealing treatment has a very slow cooling rate, and involves leaving the material in the furnace to cool; a normalising treatment involves air cooling which gives a slightly faster cooling rate. Annealing relieves internal stresses in the steel and it is used to soften and induce ductility in the material. It may be carried out at regular intervals during a cold forming process to make it easier to deform the material.
- » **QUENCHING AND TEMPERING.** This process is used to harden the steel and involves heating it to a relatively high temperature and then cooling it quickly by quenching in oil, water or forced air. The rapid cooling produces a hard, brittle non-equilibrium microstructure

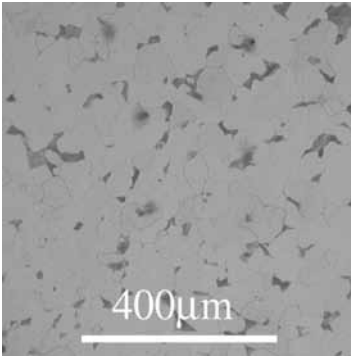


Figure 11 – Optical micrograph of a steel containing 0.1wt% carbon showing primary ferrite grains (light coloured regions) and pearlite (darker regions). (<http://www.doitpoms.ac.uk//miclib/micrograph.php?id=17>)

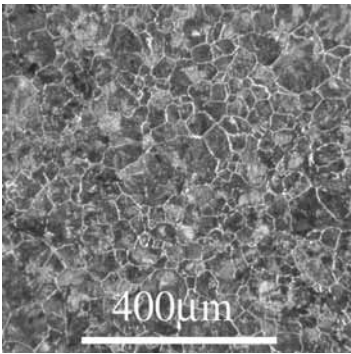


Figure 12 – Optical micrograph of a steel containing 0.1wt% carbon showing primary cementite on the grain boundaries and pearlite in the grain centres. (<http://www.doitpoms.ac.uk//miclib/micrograph.php?id=21>)

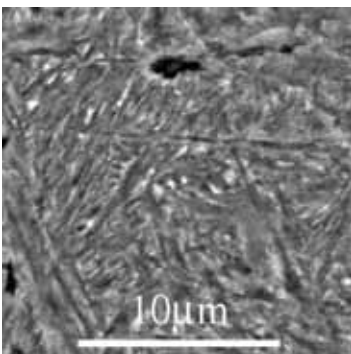


Figure 13 – Scanning electron micrograph showing the non-equilibrium structure generated in a 0.9wt% C steel on quenching from 800°C. (<http://www.doitpoms.ac.uk//miclib/micrograph.php?id=28>)

The cooling rate also affects the final microstructure of the steel. Figures 11 and 12 show equilibrium structures where the steel has been allowed to cool slowly. However if a steel is rapidly cooled or quenched through the austenite to ferrite transformation temperature (also known as the eutectoid transformation) there is not time for diffusion to occur and a non-equilibrium structure is produced. Martensite is a hard, brittle phase comprised of needle-like laths which can be seen in Figure 13. It is worth noting that this micrograph is at a much higher magnification than figures 11 & 12.

The strength of steel can be controlled in a number of different ways. In plain carbon steels strength may be increased by increasing the carbon content but this also makes the material more brittle and more difficult to form. Microalloyed steels were developed to achieve a higher strength without the detrimental effect on toughness. Strengthening is achieved by a number of different mechanisms which operate across a range of temperatures and typical alloying additions include titanium, niobium and vanadium.

Particular alloying elements may be used to stabilise either the austenite phase or the ferrite phase. Austenite stabilisers include nickel and manganese and silicon; molybdenum and chromium are ferrite stabilisers. By controlling the addition of elements such as these the desired microstructure may be achieved.

USES OF STEEL

Steels are used in a vast number of applications and perhaps the easiest way to consider where they are used is to look at the various types of steels in turn.

Plain carbon steels

In these steels the main alloying addition is carbon, though small amounts of other elements may be present in trace amounts. They can be split into subgroups based on carbon content, thus:

LOW CARBON STEELS containing 0.05 – 0.15wt% C are produced in the form of hot and cold rolled strip for a wide range of applications. They are also used for stampings, fasteners (such as rivets and nails) and wire.

MILD STEELS containing 0.16 – 0.29wt% C are the most commonly used steels as they are relatively cheap and malleable, though they do have a relatively low tensile strength. They are used in structural applications including RSJs (Figure 14), along with drop forgings, and gears.

MEDIUM CARBON STEELS containing 0.3 – 0.59wt% C are wear resistant and have a good balance between ductility and strength. They are typically used for large parts, forgings and automotive components such as crankshafts, axels and gears.

HIGH CARBON STEELS containing 0.6 – 0.99wt% C are very strong and can be used for high tensile wire (Figure 15) and springs. They may also be used for tools such as screwdrivers, hammers and chisels.

ULTRA-HIGH CARBON STEELS containing 1.0 – 2.0wt% C can be heat treated to be extremely hard and wear resistant and as such they tend to be used in a wide variety of tooling applications.

Alloy steels

Alloy steels are considered to be those in which other elements are added to control the structure or impart a particular property and again they can be split into sub groups. The main disadvantage of alloy steels over plain carbon steels is their high cost.

MICROALLOYED STEELS are the newest group of alloyed steels in which additions of as little as 0.005wt% of an element can have a significant effect on properties. For example, additions of 23ppm niobium, 6ppm nitrogen and 6ppm titanium can have a significant effect on the development of microstructure during processing resulting in a material with excellent strength and toughness suitable for a range of structural applications including bridges, pipelines and off-shore platforms.

LOW ALLOY STEELS typically contain small amounts of alloying additions such as manganese, silicon, chromium, nickel, vanadium, and molybdenum. These elements are added to improve the strength of the steel without having the detrimental effect on toughness that a higher carbon content would impart. They are used in a wide range of structural applications and their properties may be modified by heat treatment.



Figure 14 – Mild steel used in the construction of buildings. (http://www.davisiron.com/graphics/Texas_Land_Bank.jpg)



Figure 15 – High tensile steel wire made from a high carbon steel. (<http://imgs.tootoo.com/07/24/0724bf2225bf066307cf3e3b6adc86c3.jpg>)

HIGHLY ALLOYED STEELS typically contain alloying additions in quantities greater than 5% and in this case particular elements are chosen to impart particular properties such as corrosion resistance (chromium and nickel added to give stainless steels) or wear resistance (tungsten, molybdenum or cobalt added to make high speed steels).

SUMMARY

Steels continue to play a vital role in our society and the broad range of materials available, both in terms of properties and cost, means that there is usually a steel capable of doing the job.

Where can I find out more?

<http://en.wikipedia.org/wiki/Steel>

<http://en.wikipedia.org/wiki/Steelmaking>

http://en.wikipedia.org/wiki/Basic_oxygen_steelmaking

http://en.wikipedia.org/wiki/Electric_arc_furnace

<http://www.steeluniversity.org>

http://www.wrhs.org/index.php/crawford/Online_Exhibit/Clev_Steel/Part3

<http://resources.schoolscience.co.uk/Corus/11-14/index.html>

<http://resources.schoolscience.co.uk/corus/14-16/steel/index.html>

http://en.wikipedia.org/wiki/Continuous_casting

<http://www.calphad.com/iron-carbon.html>

http://en.wikipedia.org/wiki/Heat_treatment

http://en.wikipedia.org/wiki/Carbon_steels

http://en.wikipedia.org/wiki/Alloy_steel