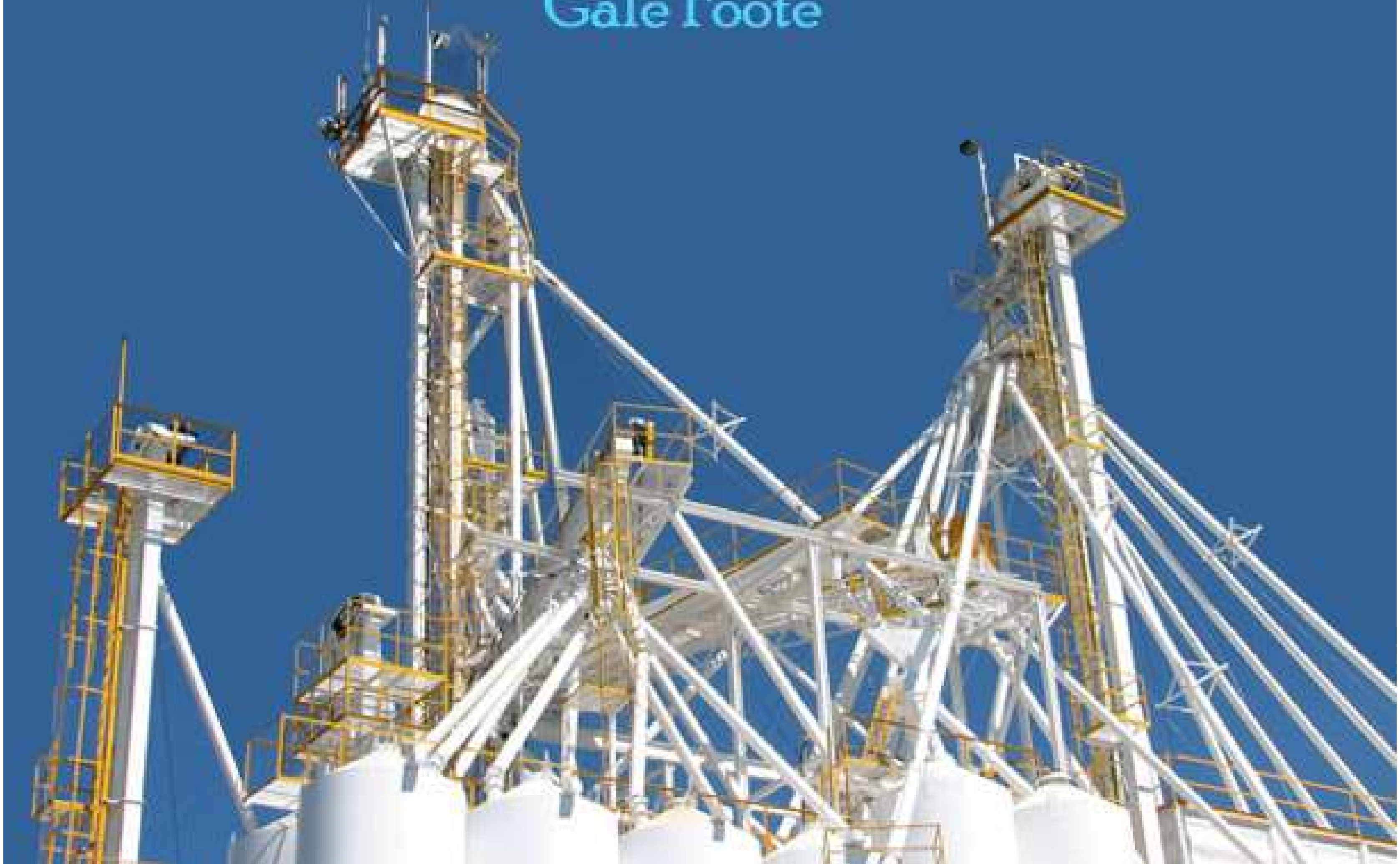
Encyclopedia of

Structural Materials

Gale Foote



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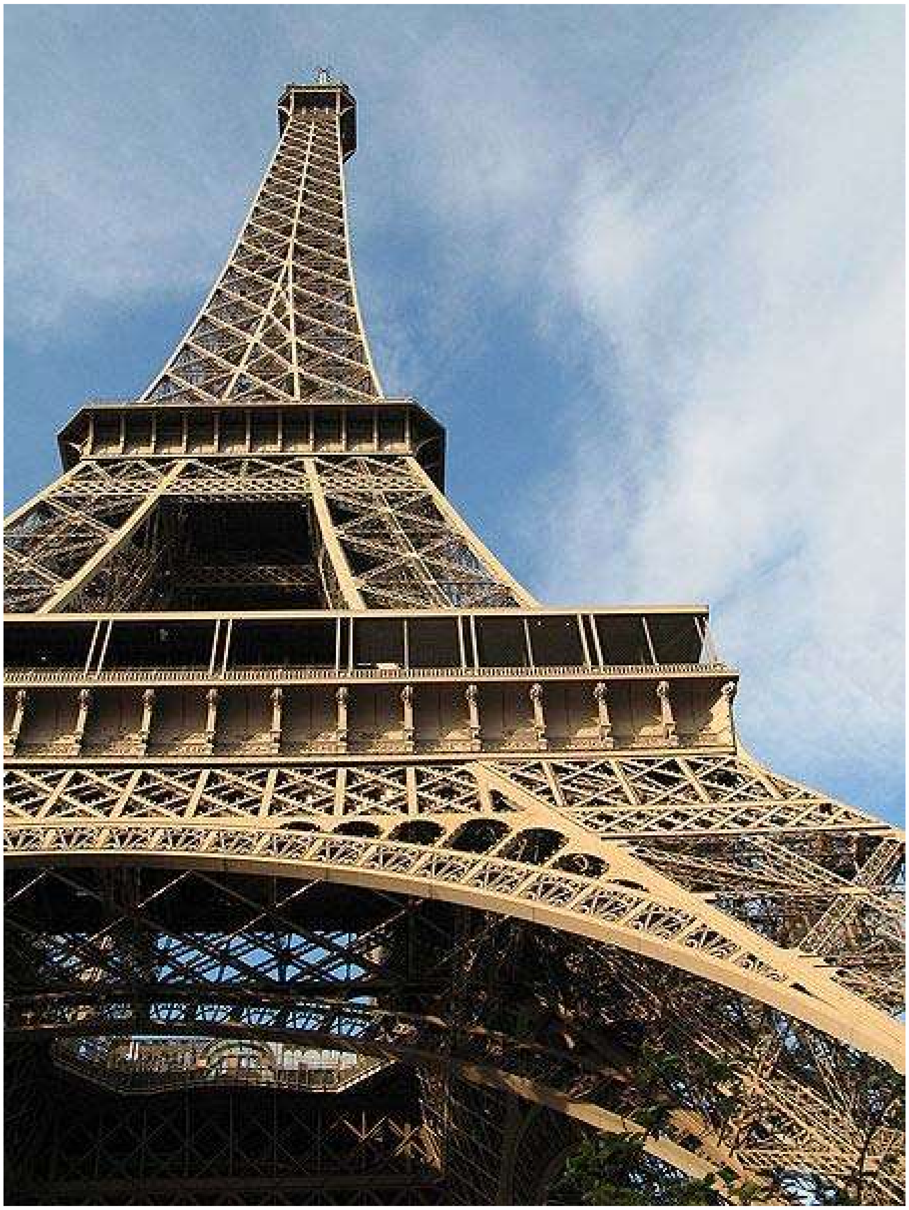


The Eiffel tower is constructed from puddle iron, a form of wrought iron

Iron pillar at Delhi, India, containing 98% wrought iron

Wrought iron is an iron alloy with a very low carbon content, in comparison to steel, and has fibrous inclusions, known as slag. This is what gives it a "grain" resembling wood, which is visible when it is etched or bent to the point of failure. Wrought iron is tough, malleable, ductile and easily welded. Historically, it was known as "commercially pure iron", however it no longer qualifies because current standards for commercially pure iron require a carbon content of less than 0.008 wt%.

Before the development of effective methods of steelmaking and the availability of large quantities of steel, wrought iron was the most common form of malleable iron. A modest amount of wrought iron was used as a raw material for manufacturing of steel, which was mainly to produce swords, cutlery and other blades. Demand for wrought iron reached its peak in the 1860s with the adaptation of ironclad warships and railways, but then declined as mild steel became more available.

Before they came to be made of mild steel, items produced from wrought iron included rivets, nails,wire, chains, railway couplings, water and steam pipes, nuts, bolts, horseshoes, handrails, straps for timber roof trusses, and ornamental ironwork.

Wrought iron is no longer produced on a commercial scale. Many products described as wrought iron, such as guard rails, garden furniture and gates, are made of mild steel. They retain that description because they were formerly made of wrought iron or have the appearance of wrought iron. True wrought iron is required for the authentic conservation of historic structures.

Terminology

Wrought iron is so named because it is worked from a bloom of porous iron mixed with slag and other impurities. The word "wrought" is an archaic past tense form of the verb "to work". "Wrought iron" literally means "worked iron".

Wrought iron is a general term for the commodity, but is also used more specifically for finished iron goods, as manufactured by a blacksmith or other smith. It was used in this narrower sense in British Customs records, such manufactured iron being subject to a higher rate of duty than what might be called "unwrought" iron.

In the 17th, 18th and 19th centuries, wrought iron went by a wide variety of terms according to its form, origin, or quality.

Form

- Bar iron—iron in bars, which are the usual product of the finery forge, but not necessarily made by that process. These might be square or flat, and flat bars might be narrow or broad.
- Rod iron—cut from flat bar iron in a slitting mill to provide the raw material for nails.
- Hoop iron—suitable for the hoops of barrels, made by passing rod iron through flat rolls.
- Plate iron—sheets of iron suitable for use as boiler plate.
- Blackplate—sheets of iron, perhaps thinner than plate iron, from the black rolling stage of tinplate production.
- Voyage iron—narrow flat bar iron, made or cut into bars of a particular weight, a commodity for sale in Africa for the Atlantic slave trade. The number of bars per ton gradually increased from 70 per ton in the 1660s to 75–80 per ton in 1685 and "near 92 to the ton" in 1731.

Origin

- Charcoal Iron — Until the end of the eighteenth century, wrought iron was made using charcoal, by the bloomery process, in a finery forge or from the industrial revolution in a Lancashire hearth. The resulting metal was highly variable, both in chemistry and slag content.

- Puddled Iron — By the late eighteenth century there was a demand for wrought iron to be refined with coal as fuel. This resulted in ‘puddled iron’. The iron was kept separate from the fire in a reverberatory furnace to prevent harmful sulphur and phosphorus from entering the finished iron. Puddled iron, although also variable in its properties, was generally more consistent than the earlier irons, and the method lent itself to the production of far greater quantities. By 1876, annual production of puddled iron in the UK alone was over 4 million tons.
- Oregrounds iron—a particularly pure grade of bar iron made ultimately from iron ore from the Dannemora mine in Sweden. Its most important use was as the raw material for the cementation process of steelmaking.
- Danks iron — originally iron imported to Great Britain from Danzig (now Gdansk), but in the 18th century more probably the kind of iron (from eastern Sweden) that once came from Danzig.
- Forest iron — iron from the Forest of Dean, where haematite ore enabled tough iron to be produced.
- Lukes iron — iron imported from Liège, whose Dutch name is "Luik."
- Ames iron or amys iron — another variety of iron imported to England from northern Europe. Its origin has been suggested to be Amiens, but it seems to have been imported from Flanders in the 15th century and Holland later, suggesting an origin in the Rhine valley. Its origins remain controversial.
- Botolf iron or Boutall iron — from Butow (Pommerania) or Beuthen (Silesia).
- Sable iron (or Old Sable) — iron bearing the mark (a sable) of the Demidov family of Russian ironmasters, one of the better brands of Russian iron.

Quality

Tough iron

Tough iron, also spelled "tuf", is not brittle and strong enough to be used for tools.

Blend iron

Blend iron is made using a mixture of different types of pig iron.

Best iron

Best iron is iron that had gone through several stages of piling and rolling, might reach the stage of being best iron (in the 19th century).

Marked bar iron

This is iron made by members of the Marked Bar Association and marked with the maker's brand mark as a sign of its quality.

Defects

Wrought iron is *redshort* if it contains sulfur in excess quantity. It has sufficient tenacity when cold, but cracks when bent or finished at a red heat. It is therefore useless for welding or forging.

Coldshort iron, also known as *coldshear*, *colshire* or *bloodshot*, contains excessive phosphorus. It is very brittle when it is cold. It cracks if bent. It may, however, be worked at high temperature. Historically, coldshort iron was considered good enough for nails.

Nevertheless, phosphorus is not necessarily detrimental to iron. Ancient Indian smiths did not add lime to their furnaces; the absence of CaO in the slag, and the deliberate use of wood with high phosphorus content during the smelting, induces a *higher P content* (> 0.1%, average 0.25%) than in modern iron. There is more phosphorus as solid solution throughout the metal than in the slags (one analysis gives 0.10% in the slags for .18% in the iron itself, for a total P content of 0.28% in the metal). This high P content and particular repartition are essential factors in the formation of a passive protective film of "misawite" (d-FeOOH), an amorphous iron oxyhydroxide that forms a barrier by adhering next to the interface between metal and rust. From this technology recently rediscovered by metallurgists at IIT Kanpur through the study of the Iron Pillar of Delhi, rust-proof iron is at the last stages of being commercialized. This 1600 years-old rust-proof pillar is also of a remarkable strength, having withstood the impact of a cannon ball in the 18th century. Copper has a similar effect as phosphate regarding the formation of a passive protection film. Furthermore, the presence of phosphorus (without carbon) produces a ductile iron suitable for wire drawing, for piano wire.

History

The puddling process of smelting iron ore to make wrought iron from pig iron, the right half of the illustration (not shown) displays men working a blast furnace, *Tiangong Kaiwu* encyclopedia published in 1637, written by Song Yingxing (1587–1666).

Wrought iron has been used for many centuries, and is the "iron" that is referred to throughout western history. The other form of iron, cast iron, was not introduced into Western Europe until the 15th century; even then, due to its brittleness, it could only be used for a limited number of purposes. Throughout much of the Middle Ages iron was produced by the direct reduction of ore in manually operated bloomeries, although waterpower had begun to be employed by 1104.

The raw material produced by all indirect processes is pig iron. It has a high carbon content and as a consequence it is brittle and could not be used to make hardware. The osmond process was the first of the indirect processes, developed by 1203, but bloomery production continued in many places. The process depended on the development of the blast furnace, of which medieval examples have been discovered at Lapphyttan, Sweden and in Germany.

The bloomery and osmond processes were gradually replaced from the 15th century by finery processes, of which there were two versions, the German and Walloon. They were in turn replaced from the late 18th century by puddling, with certain variants such as the Swedish Lancashire process. These too are now obsolete, and wrought iron is no longer manufactured commercially.

Bloomery process

Wrought iron was originally produced by a variety of smelting processes, all described today as bloomeries. Different forms of bloomery were used at different places and times. The bloomery was charged with charcoal and iron ore and then lit. Air was blown in through a tuyere to heat the bloomery to a temperature somewhat below the melting point of iron. In the course of the smelt, slag would melt and run out, and carbon monoxide from the charcoal would reduce the ore to iron, which formed a spongy mass. The iron remained in the solid state. If the bloomery was allowed to become hot enough to melt the iron, carbon would dissolve into it and form pig or cast iron, but that was not the intention.

After smelting was complete, the bloom was removed, and the process could then be started again. It was thus a batch process, rather than a continuous one. The spongy mass contained iron and also silicate (slag) from the ore; this was iron bloom from which the technique got its name. The bloom had to be forged mechanically to consolidate it and shape it into a bar, expelling slag in the process.

During the Middle Ages, water-power was applied to the process, probably initially for powering bellows, and only later to hammers for forging the blooms. However, while it is certain that water-power was used, the details of this remain uncertain. This was the culmination of the direct process of ironmaking. It survived in Spain and southern France as Catalan Forges to the mid 19th century, in Austria as the *stuckofen* to 1775, and near Garstang in England until about 1770; it was still in use with hot blast in New York State in the 1880s.

Osmond process

Osmond iron consisted of balls of wrought iron, produced by melting pig iron and catching the droplets on a staff, which was spun in front of a blast of air so as to expose as much of it as possible to the air and oxidise its carbon content. The resultant ball was often forged into bar iron in a hammer mill.

Finery process

In the 15th century, the blast furnace spread into what is now Belgium and was improved. From there, it spread via the Pays de Bray on the boundary of Normandy and then to the Weald in England. With it, the finery forge spread. These remelted the pig iron and (in effect) burnt out the carbon, producing a bloom, which was then forged into a bar iron. If rod iron was required, a slitting mill was used.

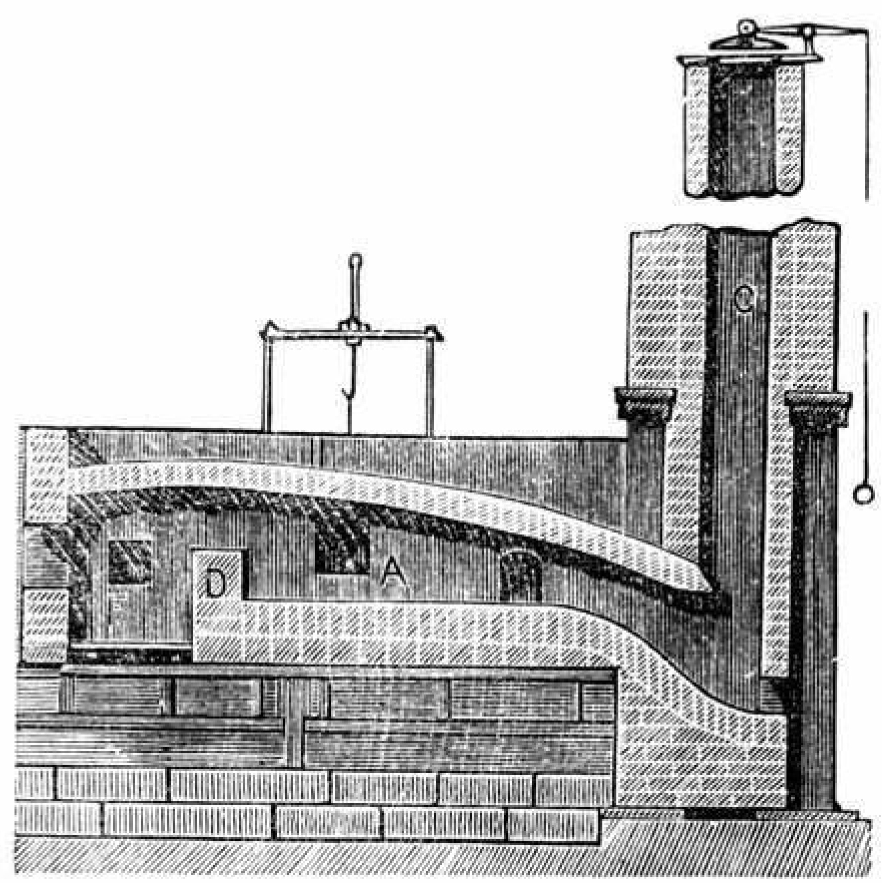
The finery process existed in two slightly different forms. In Great Britain, France, and parts of Sweden, only the Walloon process was used. This employed two different hearths, a finery hearth for fining the iron and a chafery hearth for reheating it in the course of drawing the bloom out into a bar. The finery always burnt charcoal, but the chafery could be fired with mineral coal, since its impurities would not harm the iron when it was in the solid state. On the other hand, the German process, used in Germany, Russia, and most of Sweden used a single hearth for all stages.

The introduction of coke for use in the blast furnace by Abraham Darby in 1709 (or perhaps others a little earlier) initially had little effect on wrought iron production. Only in the 1750s was coke pig iron used on any significant scale as the feedstock of finery forges. However, charcoal continued to be the fuel for the finery.

Potting and stamping

From the late 1750s, ironmasters began to develop processes for making bar iron without charcoal. There were a number of patented processes for this, which are referred to today as potting and stamping. The earliest were developed by John Wood of Wednesbury and his brother Charles Wood of Low Mill at Egremont, patented in 1763. Another was developed for the Coalbrookdale Company by the Cranage brothers. Another important one was that of John Wright and Joseph Jesson of West Bromwich.

Puddling process



Schematic drawing of a puddling furnace

A number of processes for making wrought iron without charcoal were devised as the Industrial Revolution began during the latter half of the 18th century. The most successful of these was puddling, using a puddling furnace (a variety of the reverberatory furnace). This was invented by Henry Cort in 1784. It was later improved by others including Joseph Hall. In this type of furnace, the metal does not come into contact with the fuel, and so is not contaminated by impurities in it. The flame from the fire is reverberated or sent back down onto the metal on the fire bridge of the furnace.

Unless the raw material used is white cast iron, the pig iron or other raw material first had to be refined into refined iron or finers metal. This would be done in a refinery where raw coal is used to remove silicon and convert carbon from a graphitic form to a combined form.

This metal was placed into the hearth of the puddling furnace where it was melted. The hearth was lined with oxidizing agents such as haematite and iron oxide. This mixture is subjected to a strong current of air and stirred with long bars, called puddling bars or rabbles, through working doors. The air, stirring, and "boiling" action of the metal help the oxidizing agents to oxidize the impurities and carbon out of the pig iron to their maximum capability. As the impurities oxidize, the retaining material solidifies into spongy wrought iron balls, called puddle balls.

Shingling

There is still some slag left in the puddle balls, so while they are still hot they must be shingled to remove the remaining slag and cinder. It may be achieved by forging the balls under a power hammer, or by squeezing the bloom in a machine. The material obtained at the end of shingling is known as bloom and it is still red-hot. The blooms are not useful in this form, so they must be rolled into a final product.

Sometimes European ironworks would skip this step completely and roll the puddle balls. The only drawback to this is that the edges of the rough bars are not as well compressed. When the rough bar is reheated, the edges may separate and be lost into the furnace.

Rolling

The bloom is passed through grooved rollers and flat bars were produced. These bars of wrought iron were of poor quality, called muck bars or puddle bars. To improve the quality of wrought iron, these bars were cut up, piled and tied together by wires, a process known as faggoting or piling. They were then reheated and rolled again in merchant rolls. This process may be repeated several times to get wrought iron of desired quality. Wrought iron that has been rolled multiple times is called merchant bar or merchant iron.

Lancashire process

The advantage of puddling was that it used coal, not charcoal as fuel. However this was little advantage in Sweden, which lacks coal. Gustaf Ekman observed charcoal fineries at Ulverstone, which were quite different from any in Sweden. After his return to Sweden in the 1830s, he experimented and developed a process similar to puddling but using forewood and charcoal, which was widely adopted in the Bergslagen in the following decades.

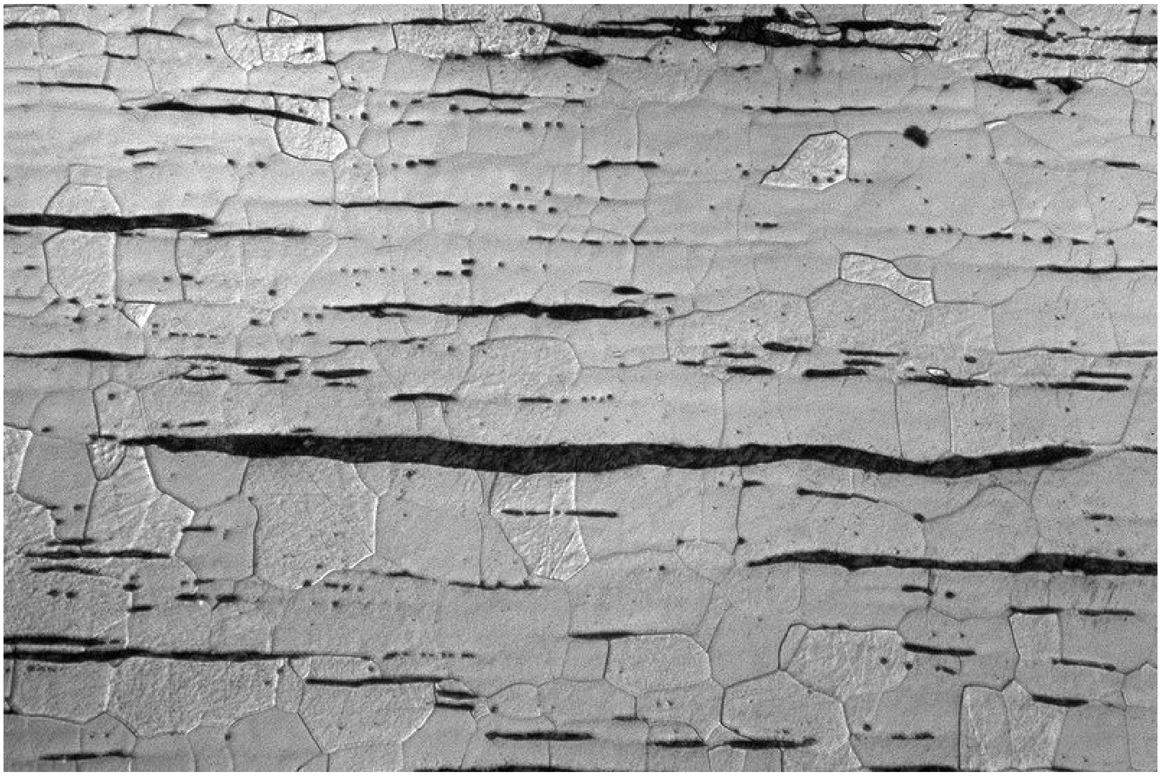
The Aston process

In 1925, James Aston of the United States developed a process for manufacturing wrought iron quickly and economically. It involves taking molten steel from a Bessemer converter and pouring it into cooler liquid slag. The temperature of the steel is about 1500 °C and the liquid slag is maintained at approximately 1200 °C. The molten steel contains a large amount of dissolved gases so when the liquid steel hits the cooler surfaces of the liquid slag the gases are liberated. The molten steel then freezes to yield a spongy mass having a temperature of about 1370 °C. This spongy mass must then be finished by being shingled and rolled as described under puddling (above). Three to four tons can be converted per batch with this method.

The end of wrought iron

In the 1960s the price of steel production was dropping due to recycling and even using the Aston process wrought iron production was a labor-intensive process. It has been estimated that the production of wrought iron costs approximately twice as much as the production of low carbon steel. In the United States the last plant closed in 1969. The last in Great Britain (and the world) was the Atlas Ironworks of Thomas Walmley Ltd in Bolton, which closed in 1973. Its equipment, of a type dating from the 1860s, was moved to the Blists Hill site of Ironbridge Gorge Museum for preservation. Some wrought iron is still being produced for heritage restoration purposes, but only by recycling scrap.

Properties



The microstructure of wrought iron, showing dark slag inclusions in ferrite

The slag inclusions in wrought iron give it properties not found in other forms of ferrous metal. There are approximately 250,000 inclusions per square inch. A fresh fracture shows a clear bluish color with a high silky luster and fibrous appearance.

Wrought iron lacks the carbon content necessary for hardening through heat treatment, but in areas where steel was uncommon or unknown, tools were sometimes cold-worked (hence cold iron) in order to harden them. An advantage of its low carbon content is its excellent weldability. Furthermore, sheet wrought iron cannot bend as much as steel sheet metal (when cold worked). Wrought iron can be cast, however there is no engineering advantage as compared to cast iron; cast iron is much easier to produce and thus cheaper, so it is exclusively chosen over wrought iron.

Due to the variations in iron ore origin and iron manufacture, wrought iron can be inferior or superior in corrosion resistance compared to other iron alloys. There are many mechanisms behind this corrosion resistance. Chilton and Evans found that nickel enrichment bands reduce corrosion. They also found that in puddled and forged and piled the working over of the iron spread out copper, nickel and tin impurities, which produce electrochemical conditions that slow down corrosion. The slag inclusions have been shown to disperse corrosion in to an even film to resist pitting. Another study has shown that slag inclusions are pathways to corrosion. Other studies show that sulfur impurities in the wrought iron decrease corrosion resistance, but phosphorus increase corrosion resistance. Environments with a high concentration of chlorine ions also decreases wrought iron's corrosion resistance.

Wrought iron has a rough surface so it can hold platings and coatings better. For instance, a galvanic zinc finish is approximately 25–40% thicker than the same finish on steel.

In Table 1, the chemical composition of wrought iron is compared to that of pig iron and carbon steel. Although it appears that wrought iron and plain carbon steel have similar chemical compositions, this is deceiving. Most of the manganese, sulfur, phosphorus, and silicon are incorporated into the slag fibers present in the wrought iron, so wrought iron really is purer than plain carbon steel.

Table 1: Chemical composition comparison of pig iron, plain carbon steel, and wrought iron

Material	Iron	Carbon	Manganese	Sulfur	Phosphorus	Silicon
Pig iron	91–94	3.5–4.5	0.5–2.5	0.018–0.1	0.03–0.1	0.25–3.5
Carbon steel	98.1–99.5	0.07–1.3	0.3–1.0	0.02–0.06	0.002–0.1	0.005–0.5
Wrought iron	99–99.8	0.05–0.25	0.01–0.1	0.02–0.1	0.05–0.2	0.02–0.2

All units are percent weight

Table 2: Properties of wrought iron

Property	Value
Ultimate tensile strength [psi (MPa)]	34,000–54,000 (234–372)
Ultimate compression strength [psi (MPa)]	34,000–54,000 (234–372)
Ultimate shear strength [psi (MPa)]	28,000–45,000 (193–310)
Yield point [psi (MPa)]	23,000–32,000 (159–221)
Modulus of elasticity (in tension) [psi (MPa)]	28,000,000 (193,100)
Melting point [°F (°C)]	2,800 (1,540)
Specific gravity	7.6–7.9 7.5–7.8

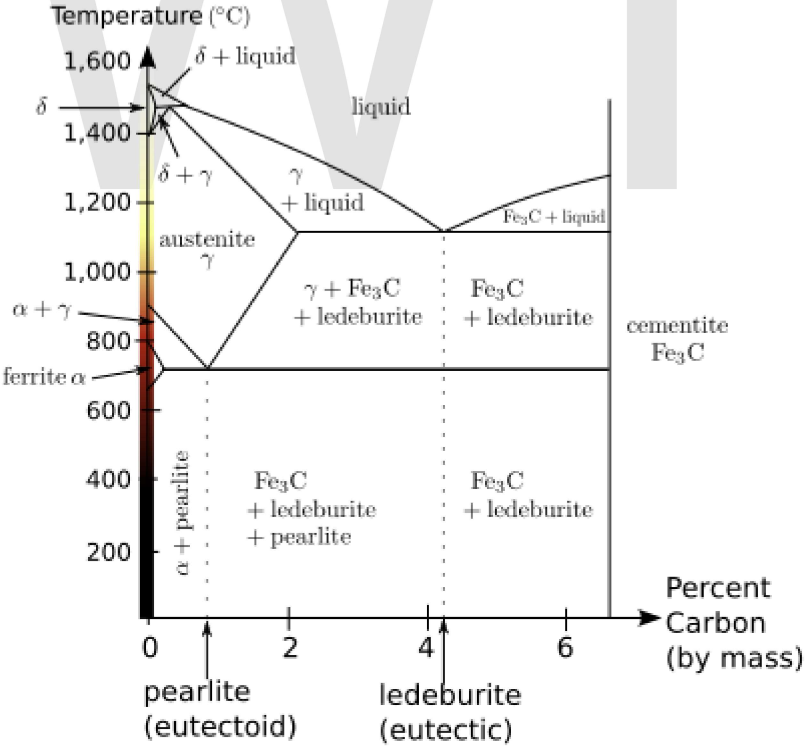
Amongst its other properties, wrought iron becomes soft at red heat, and can be easily forged and forge welded. It can be used to form temporary magnets, but cannot be magnetized permanently, and is ductile, malleable and tough.

Applications

One application is furniture. It has a long history, dating back to Roman times. There are Thirteenth century wrought iron gates in Westminster Abbey in London, but the Seventeenth century, and the reign of William and Mary in Great Britain, appears to have brought its popularity to a peak. However the coming of cast iron and cheaper steel caused a gradual decline in wrought iron manufacture, with the last wrought ironworks in Britain closing in 1974.

It is also used to make home decor items such as baker's racks, wine racks, pot racks, etageres, table bases, desks, gates, beds, candle holders, curtain rods, bars and bar stools.

Cast iron



Iron-cementite meta-stable diagram

Cast iron usually refers to grey iron, but also identifies a large group of ferrous alloys, which solidify with a eutectic. The colour of a fractured surface can be used to identify an alloy. **White cast iron** is named after its white surface when fractured, due to its carbide impurities which allow cracks to pass straight through. **Grey cast iron** is named after its grey fractured surface, which occurs because the graphitic flakes deflect a passing crack and initiate countless new cracks as the material breaks.

Carbon (C) and silicon (Si) are the main alloying elements, with the amount ranging from 2.1 to 4 wt% and 1 to 3 wt%, respectively. While this technically makes these base alloys ternary Fe-C-Si alloys, the principle of cast iron solidification is understood from the binary iron-carbon phase diagram. Since the compositions of most cast irons are around the eutectic point of the iron-carbon system, the melting temperatures closely correlate, usually ranging from 1,150 to 1,200 °C (2,102 to 2,192 °F), which is about 300 °C (572 °F) lower than the melting point of pure iron.

Cast iron tends to be brittle, except for malleable cast irons. With its relatively low melting point, good fluidity, castability, excellent machinability, resistance to deformation, and wear resistance, cast irons have become an engineering material with a wide range of applications, and are used in pipes, machines, and automotive industry parts, such as cylinder heads (declining usage), cylinder blocks, and gearbox cases (declining usage). It is resistant to destruction and weakening by oxidisation (rust).

Production

Cast iron is made by remelting pig iron, often along with substantial quantities of scrap iron and scrap steel, and taking various steps to remove undesirable contaminants such as phosphorus and sulfur. Depending on the application, carbon and silicon content are reduced to the desired levels, which may be anywhere from 2 to 3.5% and 1 to 3% respectively. Other elements are then added to the melt before the final form is produced by casting.

Iron is sometimes melted in a special type of blast furnace known as a cupola, but more often melted in electric induction furnaces. After melting is complete, the molten iron is poured into a holding furnace or ladle.

Types

Cast iron drain, waste and vent piping

Alloying elements

Cast iron's properties are changed by adding various alloying elements, or alloyants. Next to carbon, silicon is the most important alloyant because it forces carbon out of solution. Instead the carbon forms graphite which results in a softer iron, reduces shrinkage, lowers strength, and decreases density. Sulfur, when added, forms iron sulfide, which prevents the formation of graphite and increases hardness. The problem with sulfur is that it makes molten cast iron sluggish, which causes short run defects. To counter the effects of sulfur, manganese is added because the two form into manganese sulfide instead of iron sulfide. The manganese sulfide is lighter than the melt so it tends to float out of the melt and into the slag. The amount of manganese required to neutralize sulfur is 1.7×sulfur content+0.3%. If more than this amount of manganese is added, then manganese carbide forms, which increases hardness and chilling, except in grey iron, where up to 1% of manganese increases strength and density.

Nickel is one of the most common alloyants because it refines the pearlite and graphite structure, improves toughness, and evens out hardness differences between section thicknesses. Chromium is added in small amounts to the ladle to reduce free graphite, produce chill, and because it is a powerful carbide stabilizer; nickel is often added in conjunction. A small amount of tin can be added as a substitute for 0.5% chromium. Copper is added in the ladle or in the furnace, on the order of 0.5 to 2.5%, to decrease chill, refine graphite, and increase fluidity. Molybdenum is added on the order of 0.3 to 1% to increase chill and refine the graphite and pearlite structure; it is often added in conjunction with nickel, copper, and chromium to form high strength irons. Titanium is added as a degasser and deoxidizer, but it also increases fluidity. 0.15 to 0.5% vanadium are added to cast iron to stabilize cementite, increase hardness, and increase resistance to wear and heat. 0.1 to 0.3% zirconium helps to form graphite, deoxidize, and increase fluidity.

In malleable iron melts, bismuth is added, on the scale of 0.002 to 0.01%, to increase how much silicon can be added. In white iron, boron is added to aid in the production of malleable iron; it also reduces the coarsening effect of bismuth.

Grey cast iron

Grey cast iron is characterized by its graphitic microstructure, which causes fractures of the material to have a grey appearance. It is the most commonly used cast iron and the most widely use cast material based on weight. Most cast irons have a chemical composition of 2.5 to 4.0% carbon, 1 to 3% silicon, and the remainder is iron. Grey cast iron has less tensile strength and shock resistance than steel, however its compressive strength is comparable to low and medium carbon steel.

White cast iron

With a lower silicon content and faster cooling, the carbon in *white cast iron* precipitates out of the melt as the metastable phase cementite, Fe_3C, rather than graphite. The cementite which precipitates from the melt forms as relatively large particles, usually in a eutectic mixture, where the other phase is austenite (which on cooling might transform to martensite). These eutectic carbides are much too large to provide precipitation hardening (as in some steels, where cementite precipitates might inhibit plastic deformation by impeding the movement of dislocations through the ferrite matrix). Rather, they increase the bulk hardness of the cast iron simply by virtue of their own very high hardness and their substantial volume fraction, such that the bulk hardness can be approximated by a rule of mixtures. In any case, they offer hardness at the expense of toughness. Since carbide makes up a large fraction of the material, white cast iron could reasonably be classified as a cermet. White iron is too brittle for use in many structural components, but with good hardness and abrasion resistance and relatively low cost, it finds use in such applications as the wear surfaces (impeller and volute) of slurry pumps, shell liners and lifter bars in ball mills and autogenous grinding mills, balls and rings in coal pulverisers, and the teeth of a backhoe's digging bucket (although cast medium-carbon martensitic steel is more common for this application).

It is difficult to cool thick castings fast enough to solidify the melt as white cast iron all the way through. However, rapid cooling can be used to solidify a shell of white cast iron, after which the remainder cools more slowly to form a core of grey cast iron. The resulting casting, called a *chilled casting*, has the benefits of a hard surface and a somewhat tougher interior.

High-chromium white iron alloys allow massive castings (for example, a 10-tonne impeller) to be sand cast, i.e., a high cooling rate is not required, as well as providing impressive abrasion resistance.

Malleable cast iron

Malleable iron starts as a white iron casting that is then heat treated at about 900 °C (1,650 °F). Graphite separates out much more slowly in this case, so that surface tension has time to form it into spheroidal particles rather than flakes. Due to their lower aspect ratio, spheroids are relatively short and far from one another, and have a lower cross section vis-a-vis a propagating crack or phonon. They also have blunt boundaries, as opposed to flakes, which alleviates the stress concentration problems faced by grey cast iron. In general, the properties of malleable cast iron are more like mild steel. There is a limit to how large a part can be cast in malleable iron, since it is made from white cast iron.

Ductile cast iron

A more recent development is *nodular* or *ductile cast iron*. Tiny amounts of magnesium or cerium added to these alloys slow down the growth of graphite precipitates by bonding to the edges of the graphite planes. Along with careful control of other elements and timing, this allows the carbon to separate as spheroidal particles as the material solidifies. The properties are similar to malleable iron, but parts can be cast with larger sections.

Table of comparative qualities of cast irons

Comparative qualities of cast irons

Name	Nominal composition [% by weight]	Form and condition	Yield strength [ksi (0.2% offset)]	Tensile strength [ksi]	Elongation [% (in 2 inches)]	Hardness [Brinell scale]	Uses
Grey cast iron (ASTM A48)	C 3.4, Si 1.8, Mn 0.5	Cast	—	25	0.5	180	Engine cylinder blocks, flywheels, gears, machine-tool bases
White cast iron	C 3.4, Si 0.7, Mn 0.6	Cast (as cast)	—	25	0	450	Bearing surfaces
Malleable iron (ASTM A47)	C 2.5, Si 1.0, Mn 0.55	Cast (annealed)	33	52	12	130	Axle bearings, track wheels,

							automotive crankshafts
Ductile or nodular iron	C 3.4, P 0.1, Mn 0.4, Ni 1.0, Mg 0.06	Cast	53	70	18	170	Gears, camshafts, crankshafts
Ductile or nodular iron (ASTM A339)	—	cast (quench tempered)	108	135	5	310	—
Ni-hard type 2	C 2.7, Si 0.6, Mn 0.5, Ni 4.5, Cr 2.0	Sand-cast	—	55	—	550	High strength applications
Ni-resist type 2	C 3.0, Si 2.0, Mn 1.0, Ni 20.0, Cr 2.5	Cast	—	27	2	140	Resistance to heat and corrosion

Historical uses

A cast iron wagon wheel

Because cast iron is comparatively brittle, it is not suitable for purposes where a sharp edge or flexibility is required. It is strong under compression, but not under tension. Cast Iron was first invented in China and poured into molds to make weapons and figurines. Historically, its earliest uses included cannon and shot. Henry VIII initiated the casting of cannon in England. Soon, English iron workers using blast furnaces developed the technique of producing cast iron cannons, which, while heavier than the prevailing bronze cannons, were much cheaper, and enabled England to arm her navy better. The ironmasters of the Weald continued producing cast irons until the 1760s, and armament was one of the main uses of irons after the Restoration.

Cast iron pots were made at many English blast furnaces at the time. In 1707, Abraham Darby patented a method of making pots (and kettles) thinner, and hence cheaper than his rivals could. This meant that his Coalbrookdale furnaces became dominant as suppliers of pots, an activity in which they were joined in the 1720s and 1730s by a small number of other coke-fired blast furnaces.

The development of the steam engine by Thomas Newcomen provided further market for cast irons, since cast irons were considerably cheaper than the brass of which the engine cylinders were originally made. John Wilkinson was a great exponent of cast iron, who, amongst other things, cast the cylinders for many of James Watt's improved steam engines until the establishment of the Soho Foundry in 1795.

Cast iron bridges

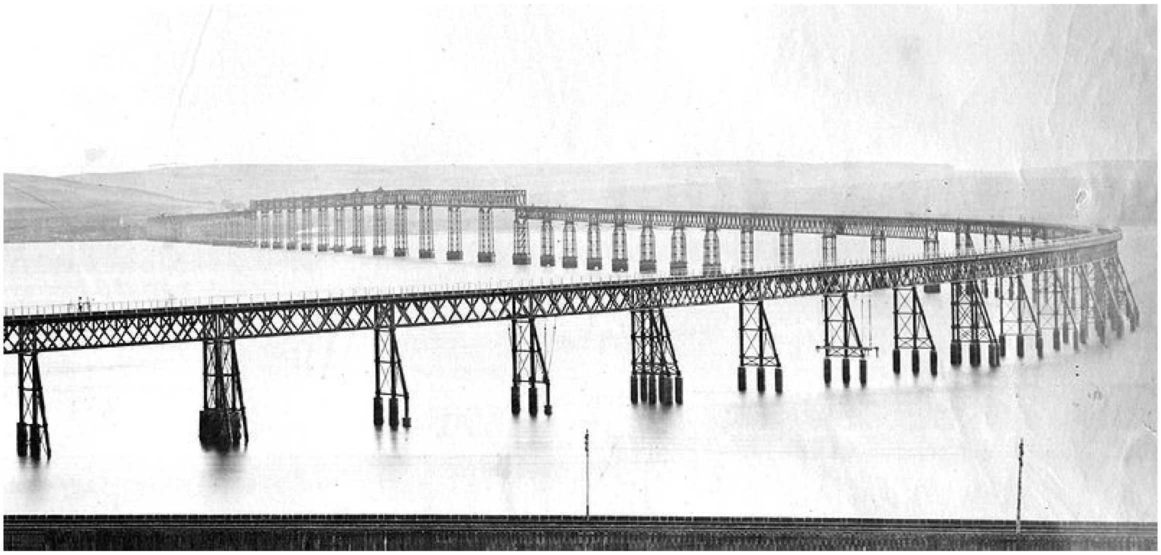
The use of cast iron for structural purposes began in the late 1770s, when Abraham Darby III built the Iron Bridge, although short beams had already been used, such as in the blast furnaces at Coalbrookdale. Other inventions followed, including one patented by Thomas Paine. Cast iron bridges became commonplace as the Industrial Revolution gathered pace. Thomas Telford adopted the material for his bridge upstream at Buildwas, and then for a canal trough aqueduct at Longdon-on-Tern on the Shrewsbury Canal.

It was followed by the Chirk Aqueduct and the Pontcysyllte Aqueduct, both of which remain in use following the recent restorations. Cast-iron beam bridges were used widely by the early railways, such as the Water Street Bridge at the Manchester terminus of the Liverpool and Manchester Railway. Problems arose when a new bridge carrying the Chester and Holyhead Railway across the River Dee in Chester collapsed in May 1847, less than a year after it was opened. The Dee bridge disaster was caused by excessive loading at the centre of the beam by a passing train, and many similar bridges had to be demolished and rebuilt, often in wrought iron. The bridge had been erroneously designed, being trussed with wrought iron straps, which were wrongly thought to reinforce the structure. The centres of the beams were put into bending, with the lower edge in tension, where cast iron, like masonry, is very weak.

The best way of using cast iron for bridge construction was by using arches, so that all the material is in compression. Cast iron, again like masonry, is very strong in compression. Wrought iron, like most other kinds of iron and indeed like most metals in general, is strong in tension, and also tough - resistant to fracturing. The relationship between wrought iron and cast iron, for structural purposes, may be thought of as analogous to the relationship between wood and stone.

Nevertheless, cast iron continued to be used in inappropriate structural ways, until the Tay Rail Bridge disaster of 1879 cast serious doubt on the use of the material. Crucial lugs for holding tie bars and struts in the Tay Bridge had been cast integral with the columns, and they failed in the early stages of the accident. In addition, the bolt holes were also cast and not drilled, so that all the tension from the tie bars was placed on a corner, rather than being spread over the length of the hole. The replacement bridge was built in wrought iron and steel.

Further bridge collapses occurred, however, culminating in the Norwood Junction rail accident of 1891. Thousands of cast iron rail underbridges were eventually replaced by steel equivalents.



Original Tay Bridge from the north

The iron bridge over the River Severn at Coalbrookdale, England

The Pontcysyllte Aqueduct, Llangollen, Wales, viewed from the ground

Buildings

Cast iron columns enabled architects to build tall buildings without the enormously thick walls required to construct masonry buildings of any height. Such flexibility allowed tall buildings to have large windows. In urban centres like SoHo Cast Iron Historic District in New York City, manufacturing buildings and early department stores were built with cast iron columns to allow daylight to enter. Slender cast iron columns could also support the weight that would otherwise require thick masonry columns or piers, opening up floor spaces in factories, and sight lines in churches and auditoriums. The historic Iron Building in Watervliet, New York, is a cast iron building.

Textile mills

Another important use was in textile mills. The air in the mills contained flammable fibres from the cotton, hemp, or wool being spun. As a result, textile mills had an alarming propensity to burn down. The solution was to build them completely of non-combustible materials, and it was found convenient to provide the building with an iron frame, largely of cast iron, replacing flammable wood. The first such building was at Ditherington in Shrewsbury, Shropshire. Many other warehouses were built using cast iron columns and beams, although faulty designs, flawed beams or overloading sometimes caused building collapses and structural failures.

During the Industrial Revolution, cast iron was also widely used for frame and other fixed parts of machinery, including spinning and later weaving machines in textile mills. Cast iron became widely used, and many towns had foundries producing industrial and agricultural machinery.

Cast-iron architecture

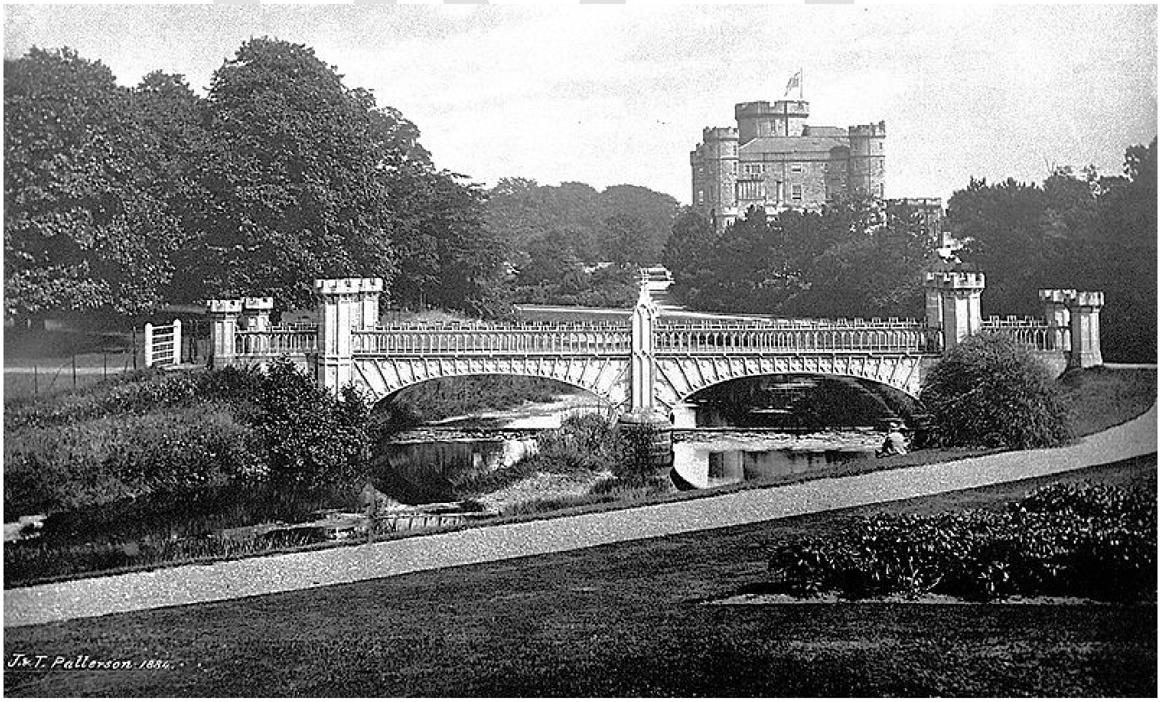
A street in SoHo in New York City showing a number of nineteenth century industrial structures with cast-iron facades.

Cast-iron architecture is a form of architecture where cast iron plays a central role. It was a prominent style in the Industrial Revolution era when cast iron was relatively cheap and modern steel had not yet been developed.

Structural use

Cast iron has been used for centuries, and was used occasionally in architecture in the pre-modern period. It was in eighteenth century Britain that new production methods first allowed cast iron to be produced cheaply enough and in large enough quantities to regularly be used in large building projects. One of the first important projects was The Iron Bridge in Shropshire, a precedent setting structure made almost entirely of cast iron. However, it was grossly over-designed, and the makers (principally Abraham Darby) suffered financially as a result. The quality of the iron used in the bridge is not high, and nearly 80 brittle cracks are visible in the present structure. Later designers and engineers, such as Thomas Telford improved both the design and quality of the material in his bridges (for example, at Buildwas upstream of Coalbrookdale) and aqueducts (such as the world-famous Pontcysyllte Aqueduct in North Wales.)

Architectural use



The highly decorative, Gothic style, cast iron Eglinton Tournament Bridge

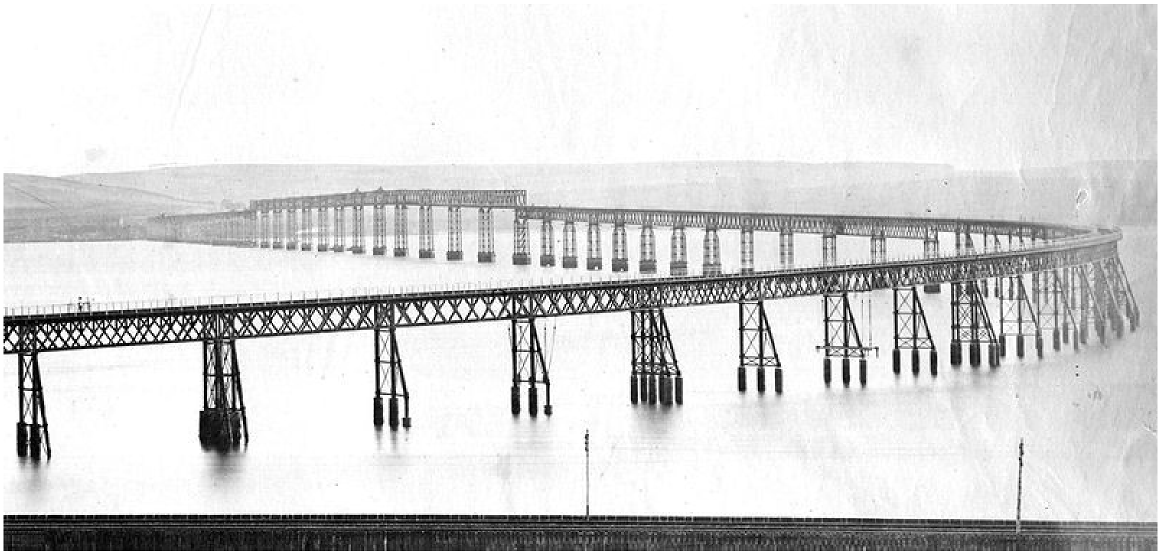
The Commissioner's House of the Royal Naval Dockyard, Bermuda designed by Edward Holl and built in the 1820s is considered to be the first residence that used cast iron in its structural framework. In the 1850s the cheapness and availability of cast iron led James Bogardus of New York City to advocate and design buildings using cast iron components. Cast iron could be forged into a wide array of shapes and designs, allowing elaborate facades that were far cheaper than traditional stone carved ones. These facades could also be painted a wide array of colours. Many of these buildings had elaborate neo-classical or Romanesque designs. Mostly used on commercial and industrial buildings there are many surviving examples, especially in the SoHo and Tribeca areas of New York and the western downtown area of Louisville, Ky. One of the most intact ensembles in the American West can be seen in the Skidmore/Old Town Historic District, a National Historic Landmark in Portland, Oregon. In Europe the best preserved examples of Victorian cast-iron warehouses can be viewed in Glasgow, Scotland, a city which experienced an enormous expansion in the late 1800s.

Cast iron columns had the advantage of being slender, compared with masonry columns capable of supporting similar weight. That saved space in factories and other kinds of buildings, and enabled architects of theaters, churches and synagogues to improve sight lines when supporting balconies.

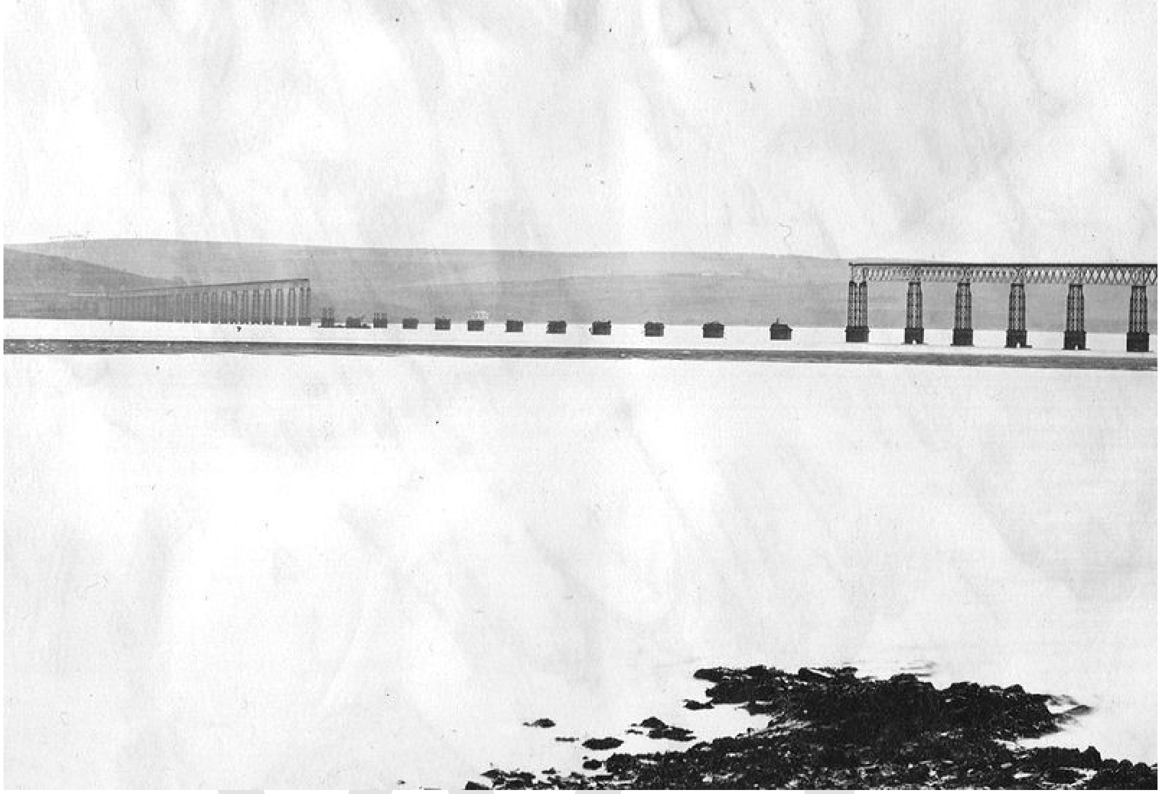
Cast iron also became the standard support structure in the construction of greenhouses, and this type of design led to the monumental Crystal Palace built in London in 1851. Designed by Joseph Paxton, the glass and cast iron structure was much imitated around the world.

In the late nineteenth century modern steel was developed, and it proved far more suitable than cast iron for structural and support purposes. The fashion for forged cast iron facades also faded in this era. Many of the innovations of the cast iron period were carried over to the new steel frame buildings, and were essential to the development of the modern skyscraper.

Catastrophic Failures



Original Tay Bridge from the north



Fallen Tay Bridge from the north

Cast iron has some architectural advantages, and some weaknesses. It is strong in compression, but weak in tension and bending. Its strength and stiffness deteriorate when subjected to high heat, such as in a fire. In the early era of the industrial revolution cast iron was often used in factory construction, in part owing to the misconception that such structures would be fireproof. William Strutt pioneered this innovation, building a number of industrial buildings using cast iron supports. Cast iron was strong enough to support the heavy machinery but was vulnerable to the frequent fires that would occur in such factories. There were also numerous building collapses caused by fracture of brittle cast iron beams. These often occurred when the bottom side of the beam was in tension, often from defects such as blow holes within the beams. Such internal defects were common in large beams.

Cast iron was also used widely in bridge construction for the new railway system, sometimes with horrific results, especially when cast iron girders were used instead of arches. The first use was at the Water Street terminus of the Liverpool and Manchester Railway in 1830 to a design by William Fairbairn, a successful design which was demolished about 1900 owing to the widespread concern about cast iron under bridges on the rail network in Britain. Robert Stephenson built a longer bridge over the river Dee, mistakenly adding wrought iron trusses to strengthen the structure. This led to the Dee bridge disaster of 1847, which killed five when the bridge collapsed.

Following the disaster such trussed bridges were demolished and cast-iron was replaced with wrought iron composite beams formed by riveting sheets together, and then steel rolled beams when steel became available in the late 1860s and 1870s. Cast iron continued to be used in railway under bridges, and there were a number of serious failures involving loss of life. The most serious accident occurred in 1879 with the Tay Bridge disaster when the centre part of the bridge collapsed in a storm as an express train was passing over. The whole train was lost with more than 75 passengers and crew. The weakest parts of the bridge were cast iron lugs holding tie bars in place, and cast iron in new bridges was effectively abandoned after the disaster. Most small cast iron beam structures were demolished and replaced after the Norwood Junction rail accident of 1891.

Chapter- 2

Steel

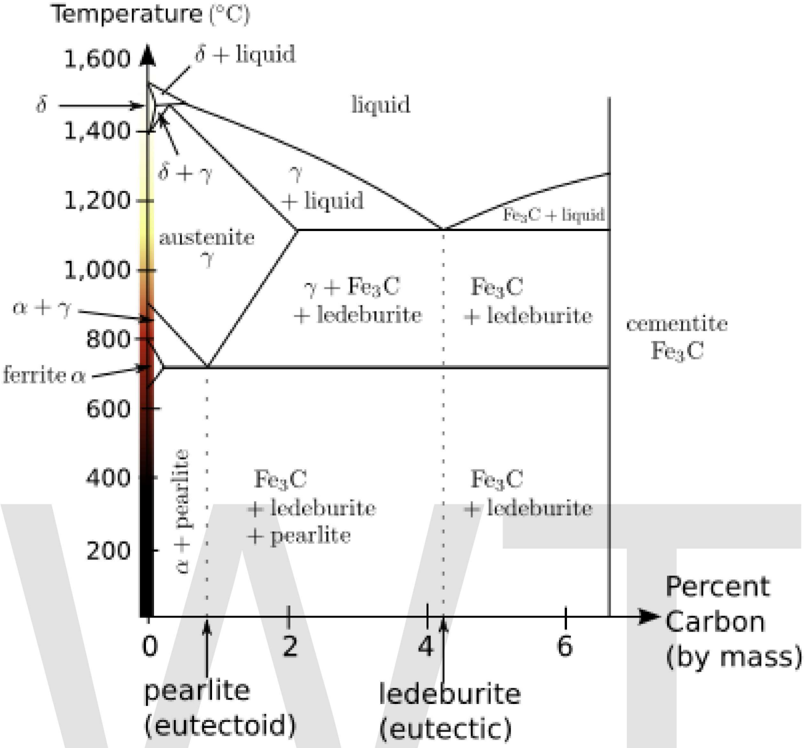
Steel is an alloy that consists mostly of iron and has a carbon content between 0.2% and 2.1% by weight, depending on the grade. Carbon is the most common alloying material for iron, but various other alloying elements are used, such as manganese, chromium, vanadium, and tungsten. Carbon and other elements act as a hardening agent, preventing dislocations in the iron atom crystal lattice from sliding past one another. Varying the amount of alloying elements and the form of their presence in the steel (solute elements, precipitated phase) controls qualities such as the hardness, ductility, and tensile strength of the resulting steel. Steel with increased carbon content can be made harder and stronger than iron, but such steel is also less ductile than iron.

Alloys with a higher than 2.1% carbon content are known as cast iron because of their lower melting point and castability. Steel is also distinguishable from wrought iron, which can contain a small amount of carbon, but it is included in the form of slag inclusions. Two distinguishing factors are steel's increased rust resistance and better weldability.

Though steel had been produced by various inefficient methods long before the Renaissance, its use became more common after more-efficient production methods were devised in the 17th century. With the invention of the Bessemer process in the mid-19th century, steel became an inexpensive mass-produced material. Further refinements in the process, such as basic oxygen steelmaking, further lowered the cost of production while increasing the quality of the metal. Today, steel is one of the most common materials in the world, with more than 1.3 billion tons produced annually. It is a major component in buildings, infrastructure, tools, ships, automobiles, machines, appliances, and weapons. Modern steel is generally identified by various grades defined by assorted standards organizations.

The steel cable of a colliery winding tower

Material properties



Iron-carbon phase diagram, showing the conditions necessary to form different phases

Iron, like most metals, is found in the Earth's crust only in the form of an ore, i.e., combined with other elements such as oxygen or sulfur. Typical iron-containing minerals include Fe_2O_3—the form of iron oxide found as the mineral hematite, and FeS_2—pyrite (fool's gold). Iron is extracted from ore by removing oxygen and combining the ore with a preferred chemical partner such as carbon. This process, known as smelting, was first applied to metals with lower melting points, such as tin, which melts at approximately 250 °C (482 °F) and copper, which melts at approximately 1,000 °C (1,830 °F). In comparison, cast iron melts at approximately 1,370 °C (2,500 °F). All of these temperatures could be reached with ancient methods that have been used since the Bronze Age. Since the oxidation rate itself increases rapidly beyond 800 °C, it is important that smelting take place in a low-oxygen environment. Unlike copper and tin, liquid iron dissolves carbon quite readily. Smelting results in an alloy (pig iron) containing too much carbon to be called steel. The excess carbon and other impurities are removed in a subsequent step.

Other materials are often added to the iron/carbon mixture to produce steel with desired properties. Nickel and manganese in steel add to its tensile strength and make austenite more chemically stable, chromium increases hardness and melting temperature, and vanadium also increases hardness while reducing the effects of metal fatigue. To prevent corrosion, at least 11% chromium is added to steel so that a hard oxide forms on the metal surface; this is known as stainless steel. Tungsten interferes with the formation of cementite, allowing martensite to form with slower quench rates, resulting in high speed steel. On the other hand, sulfur, nitrogen, and phosphorus make steel more brittle, so these commonly found elements must be removed from the ore during processing.

The density of steel varies based on the alloying constituents, but usually ranges between 7.75 and 8.05 g/cm^3 (0.280–0.291 lb/in^3).

Even in the narrow range of concentrations which make up steel, mixtures of carbon and iron can form a number of different structures, with very different properties. Understanding such properties is essential to making quality steel. At room temperature, the most stable form of iron is the body-centered cubic (BCC) structure α-ferrite. It is a fairly soft metallic material that can dissolve only a small concentration of carbon, no more than 0.021 wt% at 723 °C (1,333 °F), and only 0.005% at 0 °C (32 °F). If the steel contains more than 0.021% carbon then it transforms into a face-centered cubic (FCC) structure, called austenite or γ-iron. It is also soft and metallic but can dissolve considerably more carbon, as much as 2.1% carbon at 1,148 °C (2,098 °F)), which reflects the upper carbon content of steel.

When steels with less than 0.8% carbon, known as a hypoeutectoid steel, are cooled from an austenitic phase the mixture attempts to revert to the ferrite phase, resulting in an excess of carbon. One way for carbon to leave the austenite is for cementite to precipitate out of the mix, leaving behind iron that is pure enough to take the form of ferrite, resulting in a cementite-ferrite mixture. Cementite is a hard and brittle intermetallic compound with the chemical formula of Fe_3C. At the eutectoid, 0.8% carbon, the cooled structure takes the form of pearlite, named after its resemblance to mother of pearl. For steels that have more than 0.8% carbon the cooled structure takes the form of pearlite and cementite.

Perhaps the most important polymorphic form is martensite, a metastable phase which is significantly stronger than other steel phases. When the steel is in an austenitic phase and then quenched it forms into martensite, because the atoms "freeze" in place when the cell structure changes from FCC to BCC. Depending on the carbon content the martensitic phase takes different forms. Below approximately 0.2% carbon it takes an α ferrite BCC crystal form, but higher carbon contents take a body-centered tetragonal (BCT) structure. There is no thermal activation energy for the transformation from austenite to martensite. Moreover, there is no compositional change so the atoms generally retain their same neighbors.

Martensite has a lower density than austenite does, so that transformation between them results in a change of volume. In this case, expansion occurs. Internal stresses from this expansion generally take the form of compression on the crystals of martensite and tension on the remaining ferrite, with a fair amount of shear on both constituents. If quenching is done improperly, the internal stresses can cause a part to shatter as it cools. At the very least, they cause internal work hardening and other microscopic imperfections. It is common for quench cracks to form when water quenched, although they may not always be visible.

Heat treatment

There are many types of heat treating processes available to steel. The most common are annealing and quenching and tempering. Annealing is the process of heating the steel to a sufficiently high temperature to soften it. This process occurs through three phases: recovery, recrystallization, and grain growth. The temperature required to anneal steel depends on the type of annealing and the constituents of the alloy.

Quenching and tempering first involves heating the steel to the austenite phase, then quenching it in water or oil. This rapid cooling results in a hard and brittle martensitic structure. The steel is then tempered, which is just a specialized type of annealing. In this application the annealing (tempering) process transforms some of the martensite into cementite or spheroidite to reduce internal stresses and defects, which ultimately results in a more ductile and fracture-resistant metal.

Steel production

Iron ore pellets for the production of steel

When iron is smelted from its ore by commercial processes, it contains more carbon than is desirable. To become steel, it must be melted and reprocessed to reduce the carbon to the correct amount, at which point other elements can be added. This liquid is then continuously cast into long slabs or cast into ingots. Approximately 96% of steel is continuously cast, while only 4% is produced as cast steel ingots. The ingots are then heated in a soaking pit and hot rolled into slabs, blooms, or billets. Slabs are hot or cold rolled into sheet metal or plates. Billets are hot or cold rolled into bars, rods, and wire. Blooms are hot or cold rolled into structural steel, such as I-beams and rails. In modern foundries these processes often occur in one assembly line, with ore coming in and finished steel coming out. Sometimes after a steel's final rolling it is heat treated for strength, however this is relatively rare.

History of steelmaking

Bloomery smelting during the Middle Ages

Ancient steel

Steel was known in antiquity, and may have been produced by managing bloomeries, iron-smelting facilities, where the bloom contained carbon.

The earliest known production of steel is a piece of ironware excavated from an archaeological site in Anatolia (Kaman-Kalehoyuk) and is about 4,000 years old. Other ancient steel comes from East Africa, dating back to 1400 BC. In the 4th century BC steel weapons like the Falcata were produced in the Iberian Peninsula, while Noric steel was used by the Roman military. The Chinese of the Warring States (403–221 BC) had quench-hardened steel, while Chinese of the Han Dynasty (202 BC – 220 AD) created steel by melting together wrought iron with cast iron, gaining an ultimate product of a carbon-intermediate steel by the 1st century AD.

Wootz steel and Damascus steel

Evidence of the earliest production of high carbon steel in the Indian Subcontinent was found in Samanalawewa area in Sri Lanka. Wootz steel was produced in India by about 300 BC. Along with their original methods of forging steel, the Chinese had also adopted the production methods of creating Wootz steel, an idea imported into China from India by the 5th century AD. In Sri Lanka, this early steel-making method employed the unique use of a wind furnace, blown by the monsoon winds, that was capable of producing high-carbon steel. Also known as Damascus steel, wootz is famous for its durability and ability to hold an edge. It was originally created from a number of different materials including various trace elements. It was essentially a complicated alloy with iron as its main component. Recent studies have suggested that carbon nanotubes were included in its structure, which might explain some of its legendary qualities, though given the technology available at that time, they were produced by chance rather than by design. Natural wind was used where the soil containing iron was heated up with the use of wood. The ancient Sinhalese managed to extract a ton of steel for every 2 tons of soil, a remarkable feat at the time. One such furnace was found in Samanalawewa and archaeologists were able to produce steel as the ancients did long ago.

Crucible steel, formed by slowly heating and cooling pure iron and carbon (typically in the form of charcoal) in a crucible, was produced in Merv by the 9th to 10th century AD. In the 11th century, there is evidence of the production of steel in Song China using two techniques: a "berganesque" method that produced inferior, inhomogeneous steel and a precursor to the modern Bessemer process that utilized partial decarbonization via repeated forging under a cold blast.

Modern steelmaking

A Bessemer converter in Sheffield, England

Since the 17th century the first step in European steel production has been the smelting of iron ore into pig iron in a blast furnace. Originally using charcoal, modern methods use coke, which has proven to be a great deal cheaper.

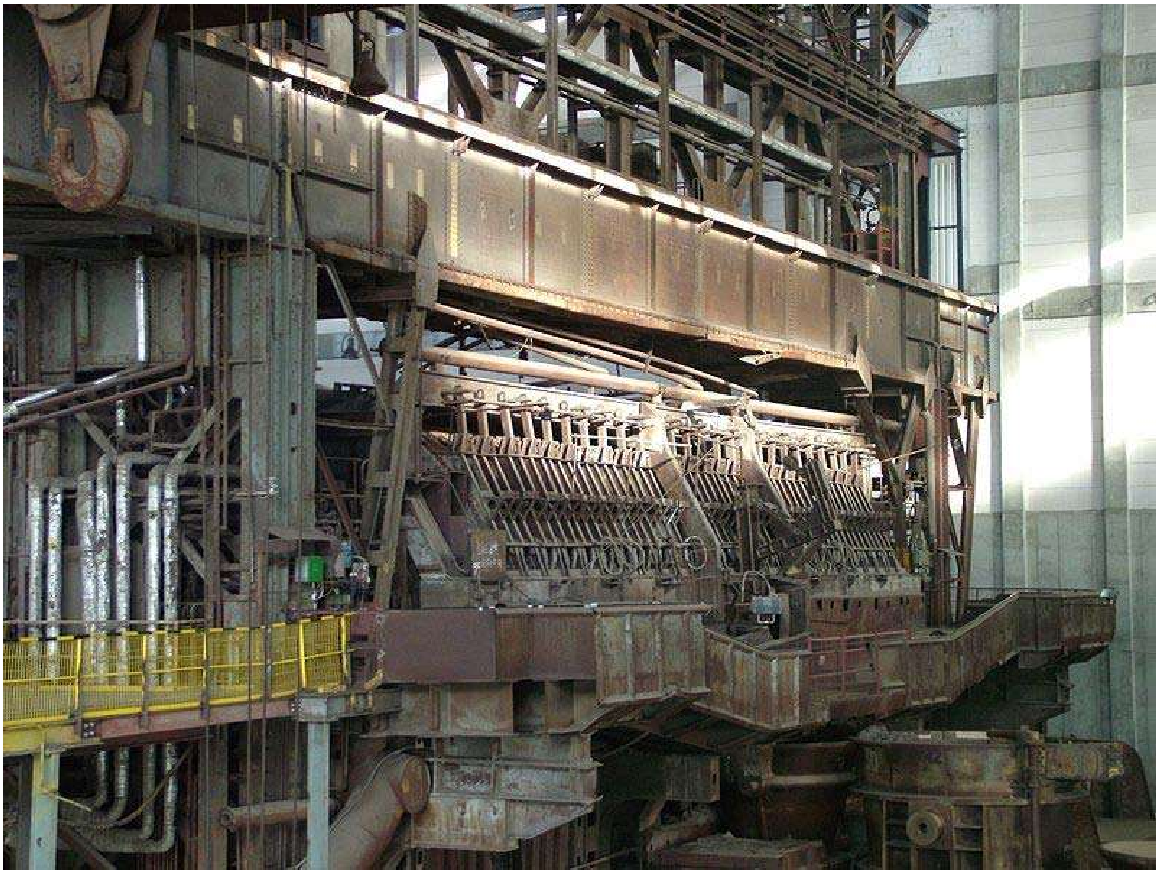
Processes starting from bar iron

In these processes pig iron was "fined" in a finery forge to produce bar iron (wrought iron), which was then used in steel-making.

The production of steel by the cementation process was described in a treatise published in Prague in 1574 and was in use in Nuremberg from 1601. A similar process for case hardening armour and files was described in a book published in Naples in 1589. The process was introduced to England in about 1614. It was produced by Sir Basil Brooke at Coalbrookdale during the 1610s. The raw material for this were bars of wrought iron. During the 17th century it was realised that the best steel came from oregrounds iron from a region of Sweden, north of Stockholm. This was still the usual raw material in the 19th century, almost as long as the process was used.

Crucible steel is steel that has been melted in a crucible rather than being forged, with the result that it is more homogeneous. Most previous furnaces could not reach high enough temperatures to melt the steel. The early modern crucible steel industry resulted from the invention of Benjamin Huntsman in the 1740s. Blister steel (made as above) was melted in a crucible or in a furnace, and cast (usually) into ingots.

Processes starting from pig iron



A Siemens-Martin steel oven from the Brandenburg Museum of Industry

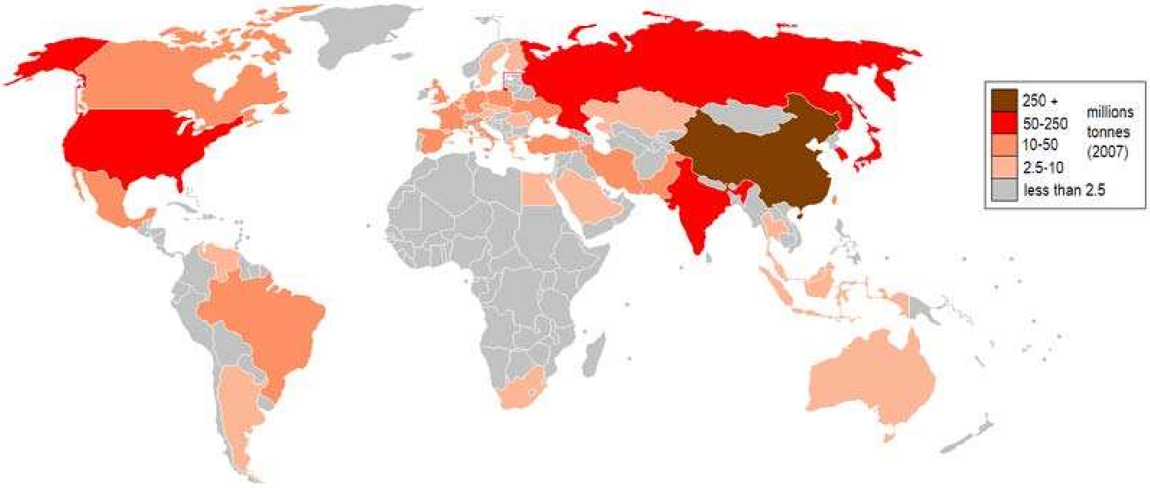
White-hot steel pouring out of an electric arc furnace

The modern era in steelmaking began with the introduction of Henry Bessemer's Bessemer process in 1858. His raw material was pig iron. This enabled steel to be produced in large quantities cheaply, thus mild steel is now used for most purposes for which wrought iron was formerly used. The Gilchrist-Thomas process (or *basic Bessemer process*) was an improvement to the Bessemer process, lining the converter with a basic material to remove phosphorus. Another improvement in steelmaking was the Siemens-Martin process, which complemented the Bessemer process.

These were rendered obsolete by the Linz-Donawitz process of basic oxygen steelmaking (BOS), developed in the 1950s, and other oxygen steelmaking processes. Basic oxygen steelmaking is superior to previous steelmaking methods because the oxygen pumped into the furnace limits impurities. Now, electric arc furnaces (EAF) are a common method of reprocessing scrap metal to create new steel. They can also be used for converting pig iron to steel, but they use a great deal of electricity (about 440 kWh per metric ton), and are thus generally only economical when there is a plentiful supply of cheap electricity.

Steel industry

A Corus Group plant in the United Kingdom



Steel production by country in 2007

It is common today to talk about "the iron and steel industry" as if it were a single entity, but historically they were separate products. The steel industry is often considered to be an indicator of economic progress, because of the critical role played by steel in infrastructural and overall economic development.

The economic boom in China and India has caused a massive increase in the demand for steel in recent years. Between 2000 and 2005, world steel demand increased by 6%. Since 2000, several Indian and Chinese steel firms have risen to prominence like Tata Steel (which bought Corus Group in 2007), Shanghai Baosteel Group Corporation and Shagang Group. ArcelorMittal is however the world's largest steel producer.

In 2005, the British Geological Survey stated China was the top steel producer with about one-third of the world share; Japan, Russia, and the US followed respectively.

In 2008, steel started to be traded as a commodity in the London Metal Exchange. At the end of 2008, the steel industry faced a sharp downturn that led to many cut-backs.

Recycling

Contemporary steel

Modern steels are made with varying combinations of alloy metals to fulfill many purposes. Carbon steel, composed simply of iron and carbon, accounts for 90% of steel production. High strength low alloy steel has small additions (usually < 2% by weight) of other elements, typically 1.5% manganese, to provide additional strength for a modest price increase. Low alloy steel is alloyed with other elements, usually molybdenum, manganese, chromium, or nickel, in amounts of up to 10% by weight to improve the hardenability of thick sections. Stainless steels and surgical stainless steels contain a minimum of 11% chromium, often combined with nickel, to resist corrosion (rust). Some stainless steels are magnetic, while others are nonmagnetic.

Some more modern steels include tool steels, which are alloyed with large amounts of tungsten and cobalt or other elements to maximize solution hardening. This also allows the use of precipitation hardening and improves the alloy's temperature resistance. Tool steel is generally used in axes, drills, and other devices that need a sharp, long-lasting cutting edge. Other special-purpose alloys include weathering steels such as Cor-ten, which weather by acquiring a stable, rusted surface, and so can be used un-painted.

Many other high-strength alloys exist, such as dual-phase steel, which is heat treated to contain both a ferritic and martensitic microstructure for extra strength. Transformation Induced Plasticity (TRIP) steel involves special alloying and heat treatments to stabilize amounts of austentite at room temperature in normally austentite-free low-alloy ferritic steels. By applying strain to the metal, the austentite undergoes a phase transition to martensite without the addition of heat. Maraging steel is alloyed with nickel and other elements, but unlike most steel contains almost no carbon at all. This creates a very strong but still malleable metal. Twinning Induced Plasticity (TWIP) steel uses a specific type of strain to increase the effectiveness of work hardening on the alloy. Eglin Steel uses a combination of over a dozen different elements in varying amounts to create a relatively low-cost metal for use in bunker buster weapons. Hadfield steel (after Sir Robert Hadfield) or manganese steel contains 12–14% manganese which when abraded forms an incredibly hard skin which resists wearing. Examples include tank tracks, bulldozer blade edges and cutting blades on the jaws of life.

Most of the more commonly used steel alloys are categorized into various grades by standards organizations. For example, the Society of Automotive Engineers has a series of grades defining many types of steel. The American Society for Testing and Materials has a separate set of standards, which define alloys such as A36 steel, the most commonly used structural steel in the United States.

Though not an alloy, galvanized steel is a commonly used variety of steel which has been hot-dipped or electroplated in zinc for protection against rust.

Uses

A roll of steel wool

Iron and steel are used widely in the construction of roads, railways, other infrastructure, applicances, and buildings. Most large modern structures, such as stadiums and skyscrapers, bridges, and airports, are supported by a steel skeleton. Even those with a concrete structure will employ steel for reinforcing. In addition to widespread use in major appliances and cars. Despite growth in usage of aluminium, it is still the main material for car bodies. Steel is used in a variety of other construction materials, such as bolts, nails, and screws. Other common applications include shipbuilding, pipeline transport, mining, offshore construction, aerospace, white goods (e.g. washing machines), heavy equipment such as bulldozers, office furniture, steel wool, tools, and armour in the form of personal vests or vehicle armour (better known as rolled homogeneous armour in this role).

Historical

A carbon steel knife

Before the introduction of the Bessemer process and other modern production techniques, steel was expensive and was only used where no cheaper alternative existed, particularly for the cutting edge of knives, razors, swords, and other items where a hard, sharp edge was needed. It was also used for springs, including those used in clocks and watches. With the advent of speedier and thriftier production methods, steel has been easier to obtain and much cheaper. It has replaced wrought iron for a multitude of purposes. However, the availability of plastics in the latter part of the 20th century allowed these materials to replace steel due to their lower cost and weight.

Long steel

A steel pylon suspending overhead powerlines

- As reinforcing bars and mesh in reinforced concrete
- Railroad tracks
- Structural steel in modern buildings and bridges
- Wires

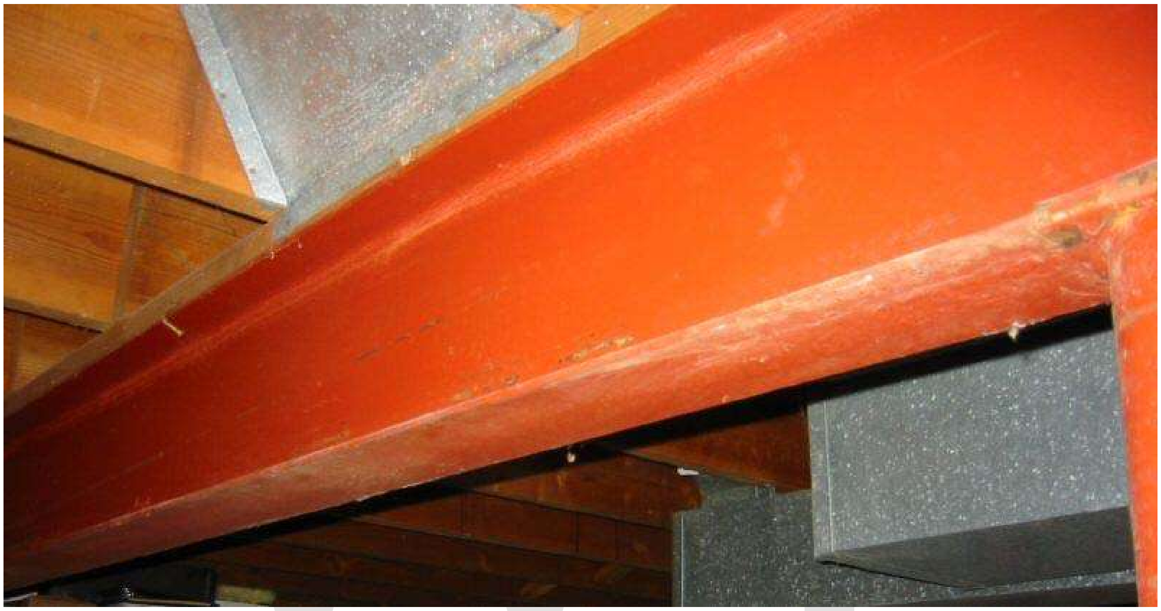
Flat carbon steel

- Major appliances
- Magnetic cores
- The inside and outside body of automobiles, trains, and ships.

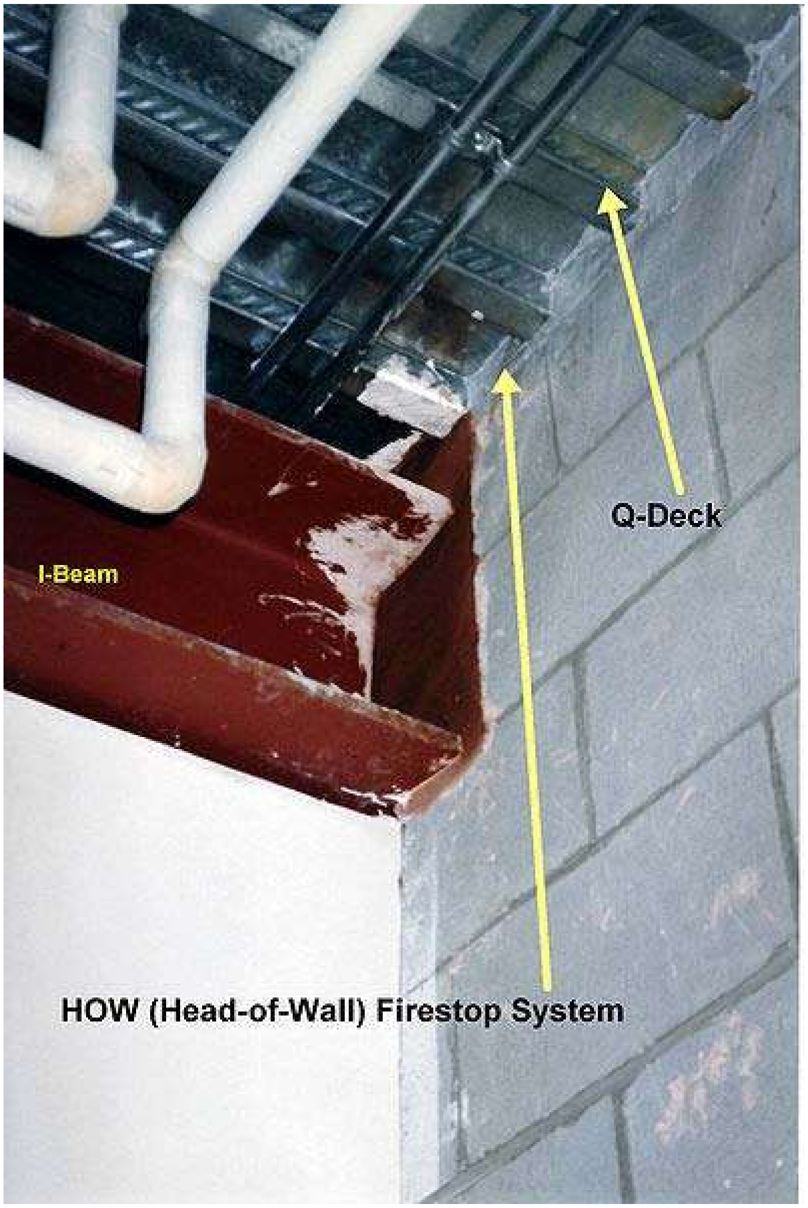
Structural Steel

Structural steel is steel construction material, a profile, formed with a specific shape or cross section and certain standards of chemical composition and mechanical properties. Structural steel shape, size, composition, strength, storage, etc., is regulated in most industrialized countries.

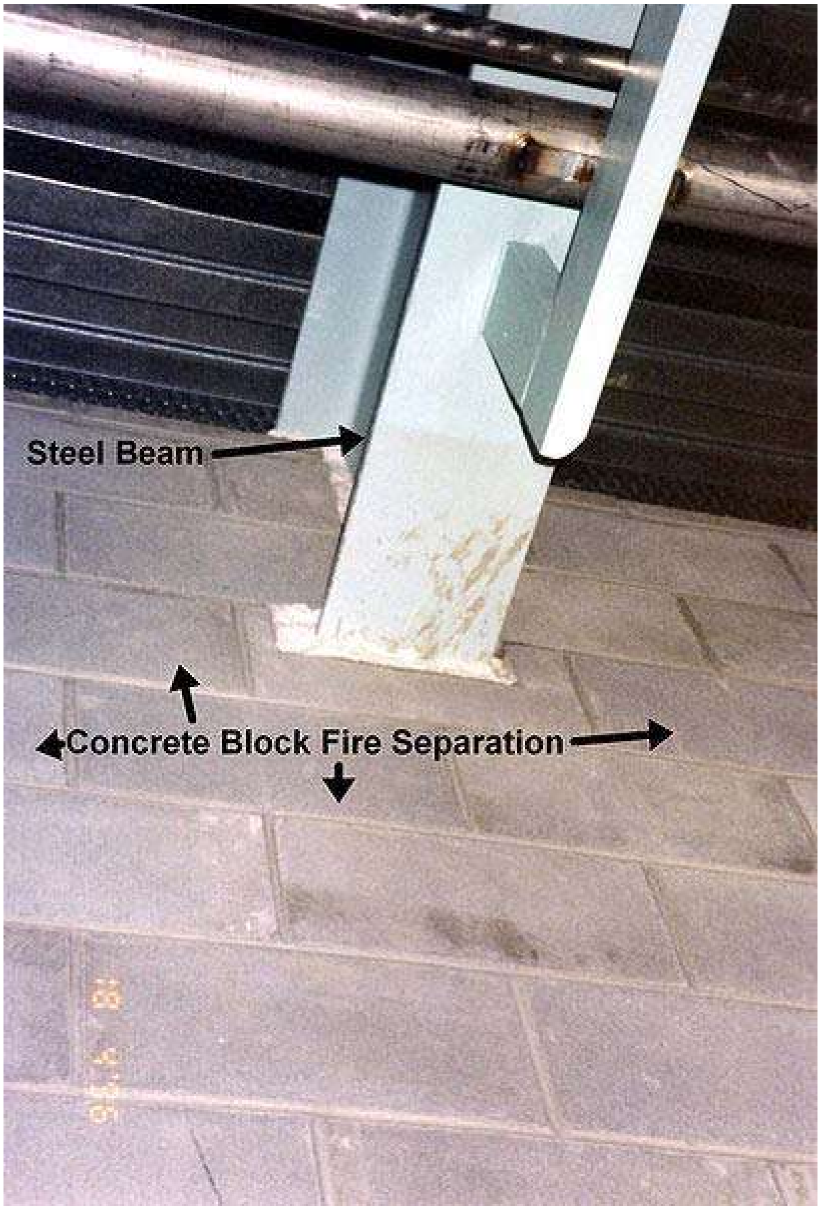
Structural steel members, such as I-beams, have high second moments of area, which allow them to be very stiff in respect to their cross-sectional area.



A steel I-beam, in this case used to support wood beams in a house



Structural steel in construction: A primed steel beam is holding up the floor above, which consists of a metal deck (Q-Deck), upon which a concrete slab has been poured.



Steel beam through-penetration with incomplete fireproofing

Metal deck and OWSJ (Open Web Steel Joist), receiving first coat of spray fireproofing plaster, made of polystyrene leavened gypsum.

Common structural shapes

In most developed countries, the shapes available are set out in published standards, although a number of specialist and proprietary cross sections are also available.

- I-beam (I-shaped cross-section - in Britain these include Universal Beams (UB) and Universal Columns (UC); in Europe it includes the IPE, HE, HL, HD and other sections; in the US it includes Wide Flange (WF) and H sections)
- Z-Shape (half a flange in opposite directions)
- HSS-Shape (Hollow structural section also known as SHS (structural hollow section) and including square, rectangular, circular (pipe) and elliptical cross sections)
- Angle (L-shaped cross-section)
- Channel ([-shaped cross-section)
- Tee (T-shaped cross-section)
- Rail profile (asymmetrical I-beam)
    - Railway rail
    - Vignoles rail
    - Flanged T rail
    - Grooved rail

- Bar, a piece of metal, rectangular cross sectioned (flat) and long, but not so wide so as to be called a sheet.
- Rod, a round or square and long piece of metal or wood.
- Plate, sheet metal thicker than 6 mm or 1/4 in.
- Open web steel joist

While many sections are made by hot or cold rolling, others are made by welding together flat or bent plates (for example, the largest circular hollow sections are made from flat plate bent into a circle and seam-welded).

Standards

Standard structural steels (Europe)

Most steels used throughout Europe are specified to comply with the European standard EN 10025. However, many national standards also remain in force.

Typical grades are described as 'S275J2' or 'S355K2W'. In these examples, 'S' denotes structural rather than engineering steel; 275 or 355 denotes the yield strength in newtons per square millimetre or the equivalent megapascals; J2 or K2 denotes the materials toughness by reference to Charpy impact test values; and the 'W' denotes weathering steel. Further letters can be used to designate normalized steel ('N' or 'NL'); quenched and tempered steel ('Q' or 'QL'); and thermomechanically rolled steel ('M' or 'ML').

The normal yield strength grades available are 195, 235, 275, 355, 420, and 460, although some grades are more commonly used than others e.g. in the UK, almost all structural steel is grades S275 and S355. Higher grades are available in quenched and tempered material (500, 550, 620, 690, 890 and 960 - although grades above 690 receive little if any use in construction at present).

Standard structural steels (USA)

Steels used for building construction in the US use standard alloys identified and specified by ASTM International. These steels have an alloy identification beginning with **A** and then two, three, or four numbers. The four-number AISI steel grades commonly used for mechanical engineering, machines, and vehicles are a completely different specification series.

The standard commonly used structural steels are:

Carbon steels

- A36 - structural shapes and plate
- A53 - structural pipe and tubing
- A500 - structural pipe and tubing
- A501 - structural pipe and tubing

- A529 - structural shapes and plate

High strength low alloy steels

- A441 - structural shapes and plates
- A572 - structural shapes and plates
- A618 - structural pipe and tubing
- A992 - W shapes beams only
- A270 - structural shapes and plates

Corrosion resistant high strength low alloy steels

- A242 - structural shapes and plates
- A588 - structural shapes and plates

Quenched and tempered alloy steels

- A514 - structural shapes and plates
- A517 - boilers and pressure vessels

Steel vs. concrete

As raw material prices fluctuate, often so does building design. During times of lower steel prices, more steel and less concrete is used, and vice versa. Each set of vendors and users typically maintain national industry associations that advocate the use of its materials versus the other. However, both materials are typically used together. Concrete without steel reinforcement (usually ribbed round bars called Rebar) crumbles under tensile loads. Steel on its own, without composite or reinforced concrete floors, is likewise not a preferred building method.

While rebar is almost always steel, it is not considered a structural steel and is described separately in the Rebar and Reinforced concrete articles. While both steel structures and Reinforced concrete cement(R.C.C)structures have their pros and cons,the steel structures have better strength to weight ratio than RCC, and can be easily dismantled(Steel structures,which have bolted connections can also be reused to some extent after dismantling).

Thermal properties

The properties of steel vary widely, depending on its alloying elements.

The austenizing temperature, the temperature where a steel transforms to an austenite crystal structure, for steel starts at 900°C for pure iron, then, as more carbon is added, the temperature falls to a minimum 724°C for eutectic steel (steel with only .83% by weight of carbon in it). As 2.1% carbon (by mass) is approached, the austenizing temperature climbs back up, to 1130°C. Similarly, the melting point of steel changes based on the alloy.

The lowest temperature at which a plain carbon steel can begin to melt, its solidus, is 1130 °C. Steel never turns into a liquid below this temperature. Pure Iron ('Steel' with 0% Carbon) starts to melt at 1492 °C (2720 °F), and is completely liquid upon reaching 1539 °C (2802 °F). Steel with 2.1% Carbon by weight begins melting at 1130 °C (2066 °F), and is completely molten upon reaching 1315 °C (2400 °F). 'Steel' with more than 2.1% Carbon is no longer Steel, but is known as Cast iron. http://www.msm.cam.ac.uk/phase-trans/images/FeC.gif

Fireproofing of structural steel

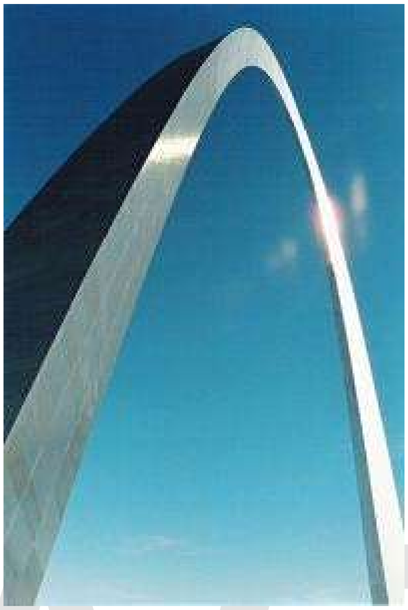
In order for a fireproofing product to qualify for a certification listing of structural steel, through a fire test, the critical temperature is set by the national standard, which governs the test. In Japan, this is below 400°C. In China, Europe and North America, it is set at 540°C. The time it takes for the steel element that is being tested to reach the temperature set by the national standard determines the duration of the fire-resistance rating.

Care must be taken to ensure that thermal expansion of structural elements does not damage fire-resistance rated wall and floor assemblies. Penetrants in a firewalls and ferrous cable trays in organic firestops should be installed in accordance with an appropriate certification listing that complies with the local building code.

Open Web Steel Joists (OWSJ) require a great deal of spray fireproofing because they are not very massive and also because they are so open, that a lot of the sprayed plaster flies right past its constituent parts during the coating process.

Structural steel requires external insulation (fireproofing) in order to prevent the steel from weakening in the event of a fire. When heated, steel expands and softens, eventually losing its structural integrity. Given enough energy, it can also melt. Heat transfer to the steel can be slowed by the use of fireproofing materials. While concrete structures that comprise buildings are able to achieve fire-resistance ratings without additional fireproofing, concrete can be subject to severe spalling, particularly if it has an elevated moisture content. Fireproofing is available for concrete but this is typically not used in buildings. Instead, it is used in traffic tunnels and locations where a hydrocarbon fire is likely to break out. Thus, steel and concrete compete against one another not only on the basis of the price per unit of mass but also on the basis of the pricing for the fireproofing that must be added in order to satisfy the passive fire protection requirements that are mandated through building codes. Common fireproofing methods for structural steel include intumescent, endothermic and plaster coatings as well as drywall, calcium silicate cladding, and mineral or high temperature insulation wool in the form of blanket.

Stainless Steel

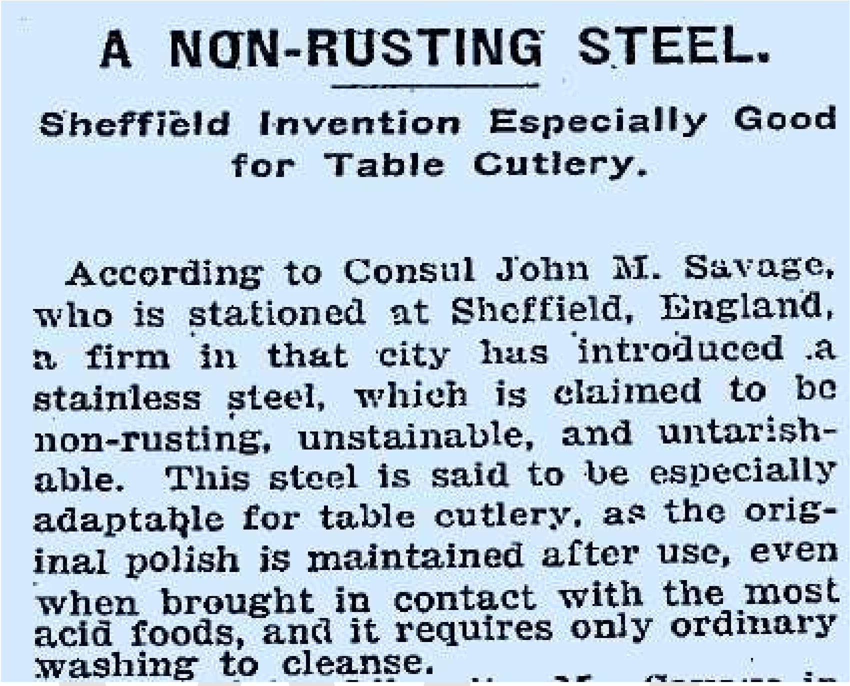


The 630-foot (192 m) high, stainless-clad (type 304) Gateway Arch defines St. Louis's skyline.

In metallurgy **stainless steel**, also known as **inox steel** or **inox** from French "inoxydable", is defined as a steel alloy with a minimum of 10.5 or 11% chromium content by mass. Stainless steel does not stain, corrode, or rust as easily as ordinary steel, but it is not stain-proof. It is also called **corrosion-resistant steel** or **CRES** when the alloy type and grade are not detailed, particularly in the aviation industry. There are different grades and surface finishes of stainless steel to suit the environment to which the material will be subjected in its lifetime. Stainless steel is used where both the properties of steel and resistance to corrosion are required.

Stainless steel differs from carbon steel by the amount of chromium present. Carbon steel rusts when exposed to air and moisture. This iron oxide film (the rust) is active and accelerates corrosion by forming more iron oxide. Stainless steels contain sufficient chromium to form a passive film of chromium oxide, which prevents further surface corrosion and blocks corrosion from spreading into the metal's internal structure.

History



A NON-RUSTING STEEL.

Sheffield Invention Especially Good for Table Cutlery.

According to Consul John M. Savage, who is stationed at Sheffield, England, a firm in that city has introduced a stainless steel, which is claimed to be non-rusting, unstainable, and untarishable. This steel is said to be especially adaptable for table cutlery, as the original polish is maintained after use, even when brought in contact with the most acid foods, and it requires only ordinary washing to cleanse.

An announcement, as it appeared in the 1915 *New York Times*, of the development of stainless steel.

A few corrosion-resistant iron artifacts survive from antiquity. A famous (and very large) example is the Iron Pillar of Delhi, erected by order of Kumara Gupta I around the year AD 400. Unlike stainless steel, however, these artifacts owe their durability not to chromium, but to their high phosphorus content, which, together with favorable local weather conditions, promotes the formation of a solid protective passivation layer of iron oxides and phosphates, rather than the non-protective, cracked rust layer that develops on most ironwork.

The corrosion-resistance of iron-chromium alloys was first recognized in 1821 by the French metallurgist Pierre Berthier, who noted their resistance against attack by some acids and suggested their use in cutlery. Metallurgists of the 19th century, however, were unable to produce the combination of low carbon and high chromium found in most modern stainless steels, and the high-chromium alloys they could produce were too brittle to be practical.

In the late 1890s Hans Goldschmidt of Germany developed an aluminothermic (thermite) process for producing carbon-free chromium. Between 1904 and 1911 several researchers, particularly Leon Guillet of France, prepared alloys that would today be considered stainless steel.

Friedrich Krupp Germaniawerft built the 366-ton sailing yacht *Germania* featuring a chrome-nickel steel hull in Germany in 1908. In 1911, Philip Monnartz reported on the relationship between chromium content and corrosion resistance. On October 17, 1912 Krupp engineers Benno Strauss and Eduard Maurer patented austenitic stainless steel.

Similar developments were taking place contemporaneously in the United States, where Christian Dantsizen and Frederick Becket were industrializing ferritic stainless steel. In 1912, Elwood Haynes applied for U.S. patent on a martensitic stainless steel alloy, which was not granted until 1919.

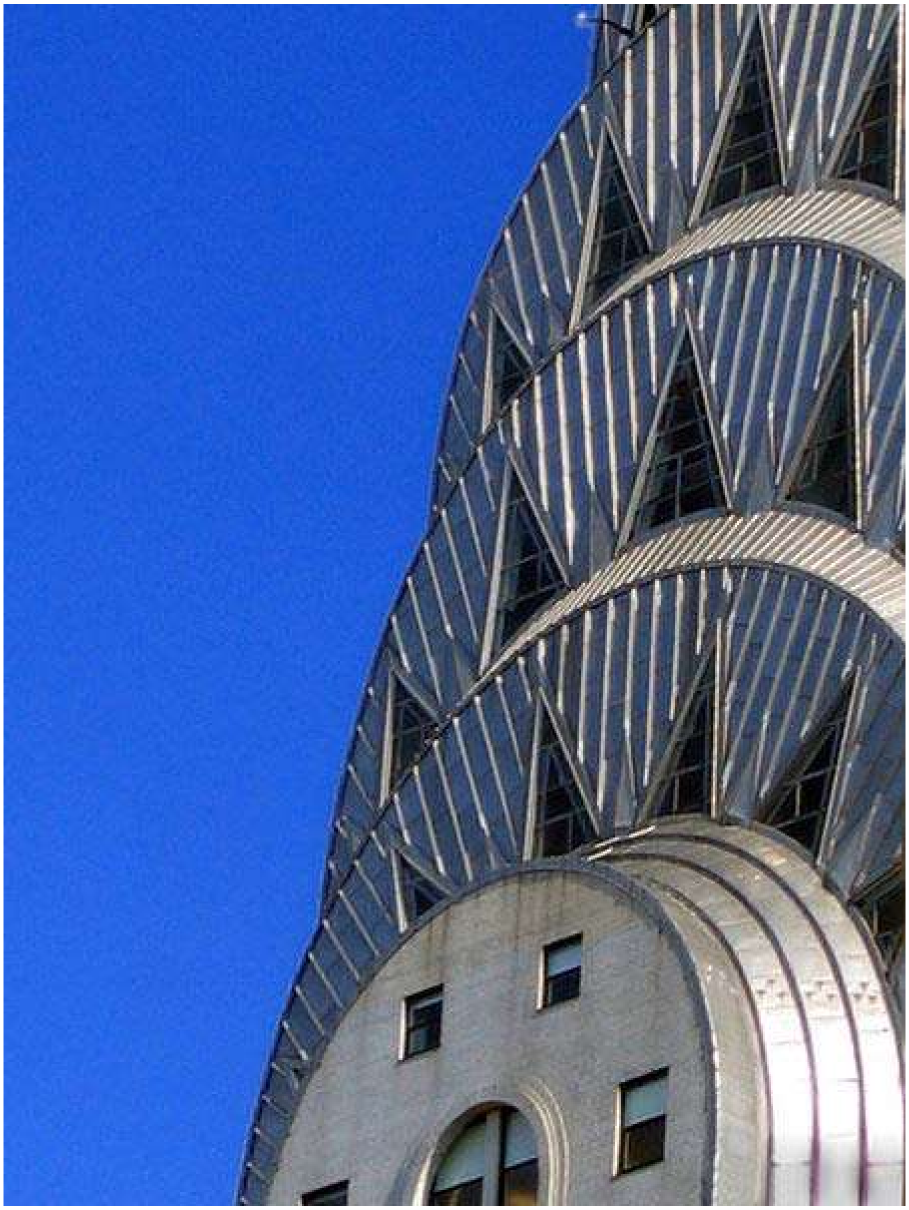
Also in 1912, Harry Brearley of the Brown-Firth research laboratory in Sheffield, England, while seeking a corrosion-resistant alloy for gun barrels, discovered and subsequently industrialized a martensitic stainless steel alloy. The discovery was announced two years later in a January 1915 newspaper article in *The New York Times*. Brearley applied for a U.S. patent during 1915 only to find that Haynes had already registered a patent. Brearley and Haynes pooled their finding, and with a group of investors formed the American Stainless Steel Corporation, with headquarters in Pittsburgh, Pennsylvania. The metal was later marketed under the "*Staybrite*" brand by Firth Vickers in England and was used for the new entrance canopy for the Savoy Hotel in London in 1929.

Properties

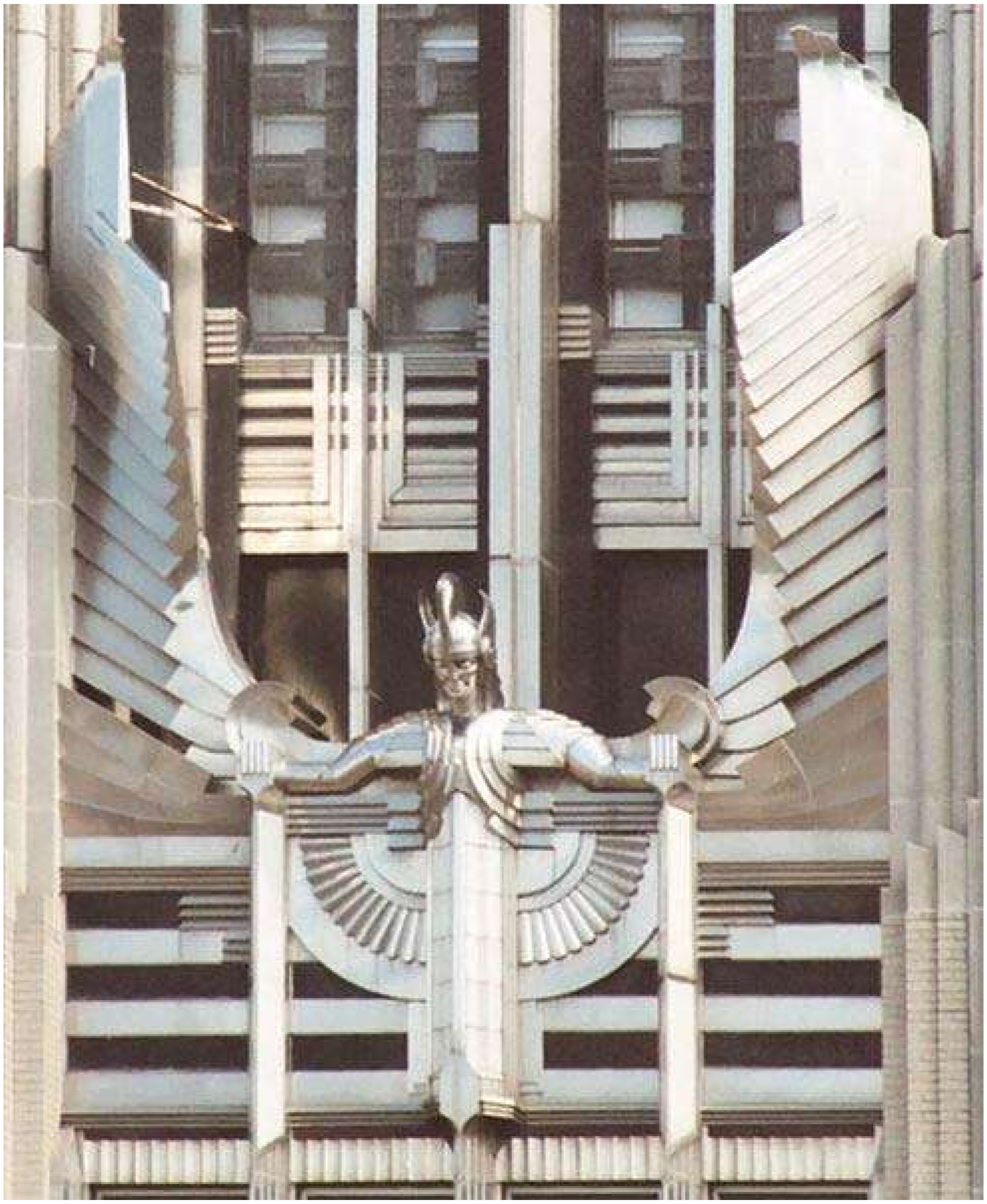
High oxidation-resistance in air at ambient temperature is normally achieved with additions of a minimum of 13% (by weight) chromium, and up to 26% is used for harsh environments. The chromium forms a passivation layer of chromium(III) oxide (Cr_2O_3) when exposed to oxygen. The layer is too thin to be visible, and the metal remains lustrous. The layer is impervious to water and air, protecting the metal beneath. Also, this layer quickly reforms when the surface is scratched. This phenomenon is called passivation and is seen in other metals, such as aluminium and titanium. Corrosion-resistance can be adversely affected if the component is used in a non-oxygenated environment, a typical example being underwater keel bolts buried in timber.

When stainless steel parts such as nuts and bolts are forced together, the oxide layer can be scraped off, causing the parts to weld together. When disassembled, the welded material may be torn and pitted, an effect known as galling. This destructive galling can be best avoided by the use of dissimilar materials for the parts forced together, e.g. bronze and stainless steel, or even different types of stainless steels (martensitic against austenitic, etc.), when metal-to-metal wear is a concern. Nitronic alloys (trademark of Armco, Inc.) reduce the tendency to gall through selective alloying with manganese and nitrogen. Threaded joints may also be lubricated to prevent galling.

Applications



The pinnacle of New York's Chrysler Building is clad with type 302 stainless steel



An art deco sculpture on the Niagara-Mohawk Power building in Syracuse, New York

Stainless steel's resistance to corrosion and staining, low maintenance, relatively low cost, and familiar luster make it an ideal base material for a host of commercial applications. There are over 150 grades of stainless steel, of which fifteen are most commonly used. The alloy is milled into coils, sheets, plates, bars, wire, and tubing to be used in cookware, cutlery, hardware, surgical instruments, major appliances, industrial equipment e.g. in sugar refineries, and as an automotive and aerospace structural alloy and construction material in large buildings. Storage tanks and tankers used to transport orange juice and other food are often made of stainless steel, due to its corrosion resistance and antibacterial properties. This also influences its use in commercial kitchens and food processing plants, as it can be steam-cleaned, sterilized, and does not need painting or application of other surface finishes.

Stainless steel is used for jewellery and watches. 316L is the stainless steel commonly used for such purpose. It can be re-finished by any jeweller and will not oxidize or turn black.

Some firearms incorporate stainless steel components as an alternative to blued or parkerized steel. Some handgun models, such as the Smith & Wesson Model 60 and the Colt M1911 pistol, can be made entirely from stainless steel. This gives a high-luster finish similar in appearance to nickel plating; but, unlike plating, the finish is not subject to flaking, peeling, wear-off due to rubbing (as when repeatedly removed from a holster over the course of time), or rust when scratched.

Some automotive manufacturers use stainless steel as decorative highlights in their vehicles.

Uses in sculpture, building facades and building structures

- Stainless steel was in vogue during the art deco period. The most famous example of this is the upper portion of the Chrysler Building (pictured). Some diners and fast-food restaurants use large ornamental panels, stainless fixtures and furniture. Owing to the durability of the material, many of these buildings retain their original appearance.
- The forging of stainless steel has given rise to a fresh approach to architectural blacksmithing in recent years.

- The Unisphere (pictured), constructed as the theme symbol of the 1964-4 World's Fair in New York City, is the world's largest global structure.
- The Gateway Arch (pictured) is clad entirely in stainless steel: 886 tons (804 metric tonnes) of 0.25 in (6.4 mm) plate, #3 finish, type 304 stainless steel.
- Type 316 stainless is used on the exterior of both the Petronas Twin Towers and the Jin Mao Building, two of the world's tallest skyscrapers.
- The Parliament House of Australia in Canberra has a stainless steel flagpole weighing over 220 tons.
- The aeration building in the Edmonton Composting Facility, the size of 14 hockey rinks, is the largest stainless steel building in North America.
- The United States Air Force Memorial has an austenitic stainless steel structural skin.
- The Atomium in Brussels, Belgium was renovated with stainless-steel cladding in a renovation completed in 2006; previously the spheres and tubes of the structure were clad in aluminium.
- The Cloud Gate sculpture by Anish Kapoor, in Chicago US.
- The Sibelius monument in Helsinki, Finland, is made solely of stainless steel tubes.

Recycling and reuse

Stainless steel is 100% recyclable. An average stainless steel object is composed of about 60% recycled material of which approximately 40% originates from end-of-life products and about 60% comes from manufacturing processes.

In fact, there is a secondary market that basically recycles usable scrap for many stainless steel markets. The product is mostly coil, sheet and blanks. This material is purchased at a less-than-prime price and sold to commercial quality stampers and sheet metal houses. The material may have scratches, pits and dents but is made to the current specifications.

Types of stainless steel

Pipes and fittings made of stainless steel

Stainless steel chair in use in Rio de Janeiro, Brazil. The austenitic AISI 304 is suitable for use in marine regions due to its high oxidation resistance.

There are different types of stainless steels: when nickel is added, for instance, the austenite structure of iron is stabilized. This crystal structure makes such steels virtually non-magnetic and less brittle at low temperatures. For greater hardness and strength, more carbon is added. When subjected to adequate heat treatment, these steels are used as razor blades, cutlery, tools, etc.

Significant quantities of manganese have been used in many stainless steel compositions. Manganese preserves an austenitic structure in the steel as does nickel, but at a lower cost.

Stainless steels are also classified by their crystalline structure:

- *Austenitic*, or 300 series, stainless steels make up over 70% of total stainless steel production. They contain a maximum of 0.15% carbon, a minimum of 16% chromium and sufficient nickel and/or manganese to retain an austenitic structure at all temperatures from the cryogenic region to the melting point of the alloy. A typical composition of 18% chromium and 10% nickel, commonly known as **18/10 stainless**, is often used in flatware. **18/0** and **18/8** are also available. Superaustenitic stainless steels, such as alloy AL-6XN and 254SMO, exhibit great resistance to chloride pitting and crevice corrosion due to high molybdenum content (>6%) and nitrogen additions, and the higher nickel content ensures better resistance to stress-corrosion cracking versus the 300 series. The higher alloy content of superaustenitic steels makes them more expensive. Other steels can offer similar performance at lower cost and are preferred in certain applications.. Low-carbon versions, for example 316L or 304L, are used to avoid corrosion problem caused by welding. Grade 316LVM is preferred where biocompatibility is required (such as body implants and piercings). The "L" means that the carbon content of the alloy is below 0.03%, which reduces the sensitization effect (precipitation of chromium carbides at grain boundaries) caused by the high temperatures involved in welding.

- *Ferritic* stainless steels generally have better engineering properties than austenitic grades, but have reduced corrosion resistance, due to the lower chromium and nickel content. They are also usually less expensive. They contain between 10.5% and 27% chromium and very little nickel, if any, but some types can contain lead. Most compositions include molybdenum; some, aluminium or titanium. Common ferritic grades include 18Cr-2Mo, 26Cr-1Mo, 29Cr-4Mo, and 29Cr-4Mo-2Ni. These alloys can be degraded by the presence of σ chromium, an intermetallic phase which can precipitate upon welding.

- *Martensitic* stainless steels are not as corrosion-resistant as the other two classes but are extremely strong and tough, as well as highly machineable, and can be hardened by heat treatment. Martensitic stainless steel contains chromium (12-14%), molybdenum (0.2-1%), nickel (0-<2%), and carbon (about 0.1-1%) (giving it more hardness but making the material a bit more brittle). It is quenched and magnetic.

- *Precipitation-hardening martensitic* stainless steels have corrosion resistance comparable to austenitic varieties, but can be precipitation hardened to even higher strengths than the other martensitic grades. The most common, 17-4PH, uses about 17% chromium and 4% nickel. The Lockheed-Martin Joint Strike Fighter is the first aircraft to use a precipitation-hardenable stainless steel—Carpenter Custom 465—in its airframe.

- *Duplex* stainless steels have a mixed microstructure of austenite and ferrite, the aim usually being to produce a 50/50 mix, although in commercial alloys the ratio may be 40/60. Duplex steels have twice the strength compared to austenitic stainless steels and also improved resistance to localised corrosion, particularly pitting, crevice corrosion and stress corrosion cracking. They are characterised by high chromium (19–28%) and molybdenum (up to 5%) and lower nickel contents than austenitic stainless steels. Duplex grades are characterized into groups based on their alloy content and corrosion resistance. Lean duplex refers to grades such as UNS S32101 (LDX 2101), S32304, and S32003. The standard duplex is 22% chromium with S31803/S32205 known as 2205 being the most widely used. Super duplex refers to 25% chromium grades such as S32760 (ZERON 100), S32750 (2507), and S32550 (Ferralium). Hyper duplex refers to higher chromium grades such as S32906. The properties of duplex stainless steels are achieved with an overall lower alloy content than similar-performing super-austenitic grades, making their use cost-effective for many applications.

Comparison of standardized steels

EN-standard	**EN-standard**	**SAE grade**	**UNS**
Steel no. k.h.s DIN	**Steel name**		
		440A	S44002
1.4112		440B	S44003
1.4125		440C	S44004
		440F	S44020
1.4016	X6Cr17	430	S43000
1.4408	G-X 6 CrNiMo 18-10	316	
1.4512	X6CrTi12	409	S40900
		410	S41000
1.4310	X10CrNi18-8	301	S30100
1.4318	X2CrNiN18-7	301LN	N/A
1.4307	X2CrNi18-9	304L	S30403
1.4306	X2CrNi19-11	304L	S30403
1.4311	X2CrNiN18-10	304LN	S30453
1.4301	X5CrNi18-10	304	S30400
1.4948	X6CrNi18-11	304H	S30409
1.4303	X5CrNi18-12	305	S30500
	X5CrNi30-9	312	
1.4541	X6CrNiTi18-10	321	S32100
1.4878	X12CrNiTi18-9	321H	S32109
1.4404	X2CrNiMo17-12-2	316L	S31603
1.4401	X5CrNiMo17-12-2	316	S31600
1.4406	X2CrNiMoN17-12-2	316LN	S31653
1.4432	X2CrNiMo17-12-3	316L	S31603

1.4435	X2CrNiMo18-14-3	316L	S31603
1.4436	X3CrNiMo17-13-3	316	S31600
1.4571	X6CrNiMoTi17-12-2	316Ti	S31635
1.4429	X2CrNiMoN17-13-3	316LN	S31653
1.4438	X2CrNiMo18-15-4	317L	S31703
1.4539	X1NiCrMoCu25-20-5	904L	N08904
1.4547	X1CrNiMoCuN20-18-7	N/A	S31254

Stainless steel grades

There are a number of different systems for grading stainless and other steels. The article on US SAE steel grades details a large number of grades with their properties.

Stainless steel in 3D printing

Some 3D printing providers have developed proprietary stainless steel sintering blends for use in rapid prototyping. Currently available grades do not vary in properties significantly.

A stainless steel gravy boat

Stainless steel finishes

316L stainless steel, with an unpolished, mill finish

Standard mill finishes can be applied to flat rolled stainless steel directly by the rollers and by mechanical abrasives. Steel is first rolled to size and thickness and then annealed to change the properties of the final material. Any oxidation that forms on the surface (scale) is removed by pickling, and a passivation layer is created on the surface. A final finish can then be applied to achieve the desired aesthetic appearance.

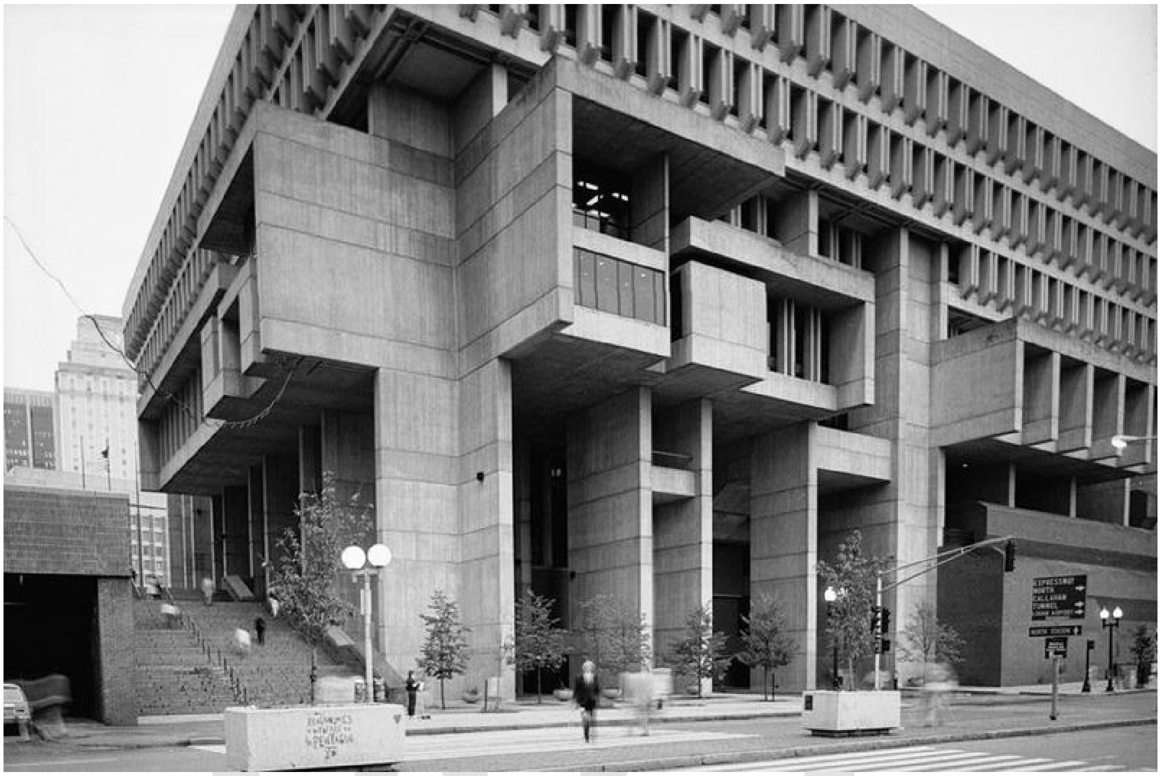
- No. 0: Hot rolled, annealed, thicker plates
- No. 1: Hot rolled, annealed and passivated
- No. 2D: Cold rolled, annealed, pickled and passivated
- No. 2B: Same as above with additional pass-through highly polished rollers
- No. 2BA: Bright annealed (BA or 2R) same as above then bright annealed under oxygen-free atmospheric conditions
- No. 3: Coarse abrasive finish applied mechanically
- No. 4: Brushed finish
- No. 5: Satin finish

- No. 6: Matte finish
- No. 7: Reflective finish
- No. 8: Mirror finish
- No. 9: Bead blast finish
- No. 10: Heat colored finish-wide range of electropolished & heat colored surfaces

Chapter- 3

Concrete

Outer view of the Roman Pantheon, still the largest unreinforced solid concrete dome



A modern building: Boston City Hall (completed 1968) is largely constructed of concrete, both pre-cast and poured-in-place.

Opus caementicium laying bare on a tomb near Rome. In contrast to modern concrete structures, the concrete walls of Roman buildings were covered, usually with brick or stone.

Concrete is a construction material that is composed of cement (commonly Portland cement) and other cementitious materials such as fly ash and slag cement, aggregate (generally a coarse aggregate made of gravels or crushed rocks such as limestone, or granite, plus a fine aggregate such as sand), water, and chemical admixtures.

The word concrete comes from the Latin word "concretus" (meaning compact or condensed), the past participle of "concresco", from "com-" (together) and "cresco" (to grow).

Concrete solidifies and hardens after mixing with water and placement due to a chemical process known as hydration. The water reacts with the cement, which bonds the other components together, eventually creating a stone-like material. Concrete is used to make pavements, pipe, architectural structures, foundations, motorways/roads, bridges/overpasses, parking structures, brick/block walls and footings for gates, fences and poles.

Concrete is used more than any other man-made material in the world. As of 2006, about 7.5 cubic kilometres of concrete are made each year—more than one cubic metre for every person on Earth.

Concrete powers a US$35 billion industry, employing more than two million workers in the United States alone. More than 55,000 miles (89,000 km) of highways in the United States are paved with this material. Reinforced concrete, prestressed concrete and precast concrete are the most widely used types of concrete functional extensions in modern days.

History

Concrete has been used for construction in various ancient civilizations. An analysis of ancient Egyptian pyramids has shown that concrete was employed in their construction.

During the Roman Empire, Roman concrete (or *opus caementicium*) was made from quicklime, pozzolana, and an aggregate of pumice. Its widespread use in many Roman structures, a key event in the history of architecture termed the Roman Architectural Revolution, freed Roman construction from the restrictions of stone and brick material and allowed for revolutionary new designs both in terms of structural complexity and dimension.

Concrete, as the Romans knew it, was a new and revolutionary material. Laid in the shape of arches, vaults and domes, it quickly hardened into a rigid mass, free from many of the internal thrusts and strains that trouble the builders of similar structures in stone or brick.

Modern tests show that *opus caementicium* had as much compressive strength as modern Portland-cement concrete (ca. 200 kg/cm^2). However, due to the absence of steel reinforcement, its tensile strength was far lower and its mode of application was also different:

Modern structural concrete differs from Roman concrete in two important details. First, its mix consistency is fluid and homogeneous, allowing it to be poured into forms rather than requiring hand-layering together with the placement of aggregate, which, in Roman practice, often consisted of rubble. Second, integral reinforcing steel gives modern concrete assemblies great strength in tension, whereas Roman concrete could depend only upon the strength of the concrete bonding to resist tension.

The widespread use of concrete in many Roman structures has ensured that many survive to the present day. The Baths of Caracalla in Rome are just one example. Many Roman aqueducts and bridges have masonry cladding on a concrete core, as does the dome of the Pantheon.

Some have stated that the secret of concrete was lost for 13 centuries until 1756, when the British engineer John Smeaton pioneered the use of hydraulic lime in concrete, using pebbles and powdered brick as aggregate. However, the Canal du Midi was constructed using concrete in 1670. Likewise there are concrete structures in Finland that date back to the 16th century. Portland cement was first used in concrete in the early 1840s.

Additives

Concrete additives have been used since Roman and Egyptian times, when it was discovered that adding volcanic ash to the mix allowed it to set under water. Similarly, the Romans knew that adding horse hair made concrete less liable to crack while it hardened, and adding blood made it more frost-resistant.

Recently, the use of recycled materials as concrete ingredients has been gaining popularity because of increasingly stringent environmental legislation. The most conspicuous of these is fly ash, a by-product of coal-fired power plants. This significantly reduces the amount of quarrying and landfill space required, and, as it acts as a cement replacement, reduces the amount of cement required.

In modern times, researchers have experimented with the addition of other materials to create concrete with improved properties, such as higher strength or electrical conductivity. Marconite is one example.

Cement and sand ready to be mixed

Composition

There are many types of concrete available, created by varying the proportions of the main ingredients below. By varying the proportions of materials, or by substitution for the cemetitious and aggregate phases, the finished product can be tailored to its application with varying strength, density, or chemical and thermal resistance properties.

The *mix design* depends on the type of structure being built, how the concrete will be mixed and delivered, and how it will be placed to form this structure.

Cement

Portland cement is the most common type of cement in general usage. It is a basic ingredient of concrete, mortar, and plaster. English masonry worker Joseph Aspdin patented Portland cement in 1824; it was named because of its similarity in colour to Portland limestone, quarried from the English Isle of Portland and used extensively in London architecture. It consists of a mixture of oxides of calcium, silicon and aluminium. Portland cement and similar materials are made by heating limestone (a source of calcium) with clay, and grinding this product (called *clinker*) with a source of sulfate (most commonly gypsum).

Water

Combining water with a cementitious material forms a cement paste by the process of hydration. The cement paste glues the aggregate together, fills voids within it, and allows it to flow more freely.

Less water in the cement paste will yield a stronger, more durable concrete; more water will give an freer-flowing concrete with a higher slump.

Impure water used to make concrete can cause problems when setting or in causing premature failure of the structure.

Hydration involves many different reactions, often occurring at the same time. As the reactions proceed, the products of the cement hydration process gradually bond together the individual sand and gravel particles, and other components of the concrete, to form a solid mass.

Reaction:

> Cement chemist notation: $C_3S + H \rightarrow C\text{-}S\text{-}H + CH$
> Standard notation: $Ca_3SiO_5 + H_2O \rightarrow (CaO)\cdot(SiO_2)\cdot(H_2O)(gel) + Ca(OH)_2$
> Balanced: $2Ca_3SiO_5 + 7H_2O \rightarrow 3(CaO)\cdot 2(SiO_2)\cdot 4(H_2O)(gel) + 3Ca(OH)_2$

Aggregates

Fine and coarse aggregates make up the bulk of a concrete mixture. Sand, natural gravel and crushed stone are mainly used for this purpose. Recycled aggregates (from construction, demolition and excavation waste) are increasingly used as partial replacements of natural aggregates, while a number of manufactured aggregates, including air-cooled blast furnace slag and bottom ash are also permitted.

Decorative stones such as quartzite, small river stones or crushed glass are sometimes added to the surface of concrete for a decorative "exposed aggregate" finish, popular among landscape designers.

Distribution of aggregates after compaction is inhomogeneous due to the influence of vibration. As a result, gradients of strength may be significant.

Installing rebar in a floor slab during a concrete pour

Reinforcement

Concrete is strong in compression, as the aggregate efficiently carries the compression load. However, it is weak in tension as the cement holding the aggregate in place can crack, allowing the structure to fail. Reinforced concrete solves these problems by adding either steel reinforcing bars, steel fibers, glass fiber, or plastic fiber to carry tensile loads.

Chemical admixtures

Chemical admixtures are materials in the form of powder or fluids that are added to the concrete to give it certain characteristics not obtainable with plain concrete mixes. In normal use, admixture dosages are less than 5% by mass of cement, and are added to the concrete at the time of batching/mixing. The common types of admixtures are as follows.

- Accelerators speed up the hydration (hardening) of the concrete. Typical materials used are $CaCl_2$ and NaCl. However, use of chlorides may cause corrosion in steel reinforcing and is prohibited in some countries.
- Retarders slow the hydration of concrete, and are used in large or difficult pours where partial setting before the pour is complete is undesirable. Typical polyol retarders are sugar, sucrose, sodium gluconate, glucose, citric acid, and tartaric acid.
- Air entrainments add and entrain tiny air bubbles in the concrete, which will reduce damage during freeze-thaw cycles thereby increasing the concrete's durability. However, entrained air is a trade-off with strength, as each 1% of air may result in 5% decrease in compressive strength.
- Plasticizers/superplasticizers (water-reducing admixtures) increase the workability of plastic or "fresh" concrete, allowing it be placed more easily, with less consolidating effort. Typical plasticizers are liginsulfate, polyol type. Alternatively, plasticizers can be used to reduce the water content of a concrete (and have been called *water reducers* due to this application) while maintaining workability. Such treatment improves its strength and durability characteristics. Superplasticizers (high-range water-reducing admixtures) are a class of plasticizers that have fewer deleterious effects when used to significantly increase workability. Representative superplasticizers are sulfonated naphthalene formaldehyde condensate, sulfonated melamine, formaldehy condensate, and acetone formaldehyde condensate. More advanced superplasticizers are polycarboxylate types.
- Pigments can be used to change the color of concrete, for aesthetics.
- Corrosion inhibitors are used to minimize the corrosion of steel and steel bars in concrete.
- Bonding agents are used to create a bond between old and new concrete.
- Pumping aids improve pumpability, thicken the paste, and reduce separation and bleeding.

Blocks of concrete in Belo Horizonte, Brazil

Mineral admixtures and blended cements

There are inorganic materials that also have pozzolanic or latent hydraulic properties. These very fine-grained materials are added to the concrete mix to improve the properties of concrete (mineral admixtures), or as a replacement for Portland cement (blended cements).

- Fly ash: A by product of coal fired electric generating plants, it is used to partially replace Portland cement (by up to 60% by mass). The properties of fly ash depend on the type of coal burnt. In general, silicious fly ash is pozzolanic, while calcareous fly ash has latent hydraulic properties.

- Ground granulated blast furnace slag (GGBFS or GGBS): A by-product of steel production is used to partially replace Portland cement (by up to 80% by mass). It has latent hydraulic properties.
- Silica fume: A by-product of the production of silicon and ferrosilicon alloys. Silica fume is similar to fly ash, but has a particle size 100 times smaller. This results in a higher surface to volume ratio and a much faster pozzolanic reaction. Silica fume is used to increase strength and durability of concrete, but generally requires the use of superplasticizers for workability.
- High reactivity Metakaolin (HRM): Metakaolin produces concrete with strength and durability similar to concrete made with silica fume. While silica fume is usually dark gray or black in color, high reactivity metakaolin is usually bright white in color, making it the preferred choice for architectural concrete where appearance is important.

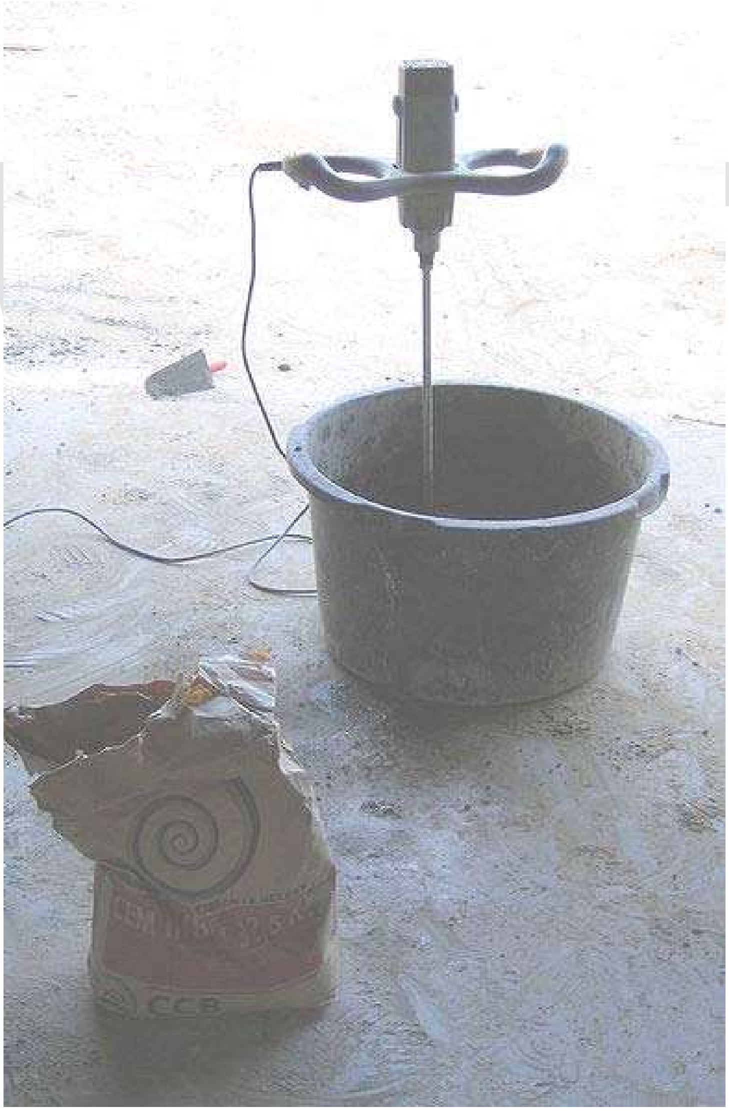
Concrete production

Concrete plant facility (background) with concrete delivery trucks

The processes used vary dramatically, from hand tools to heavy industry, but result in the concrete being placed where it cures into a final form. Wide range of technological factors may occur during production of concrete elements and their influence to basic characteristics may vary

When initially mixed together, Portland cement and water rapidly form a gel, formed of tangled chains of interlocking crystals. These continue to react over time, with the initially fluid gel often aiding in placement by improving workability. As the concrete sets, the chains of crystals join up, and form a rigid structure, gluing the aggregate particles in place. During curing, more of the cement reacts with the residual water (hydration).

This curing process develops physical and chemical properties. Among other qualities, mechanical strength, low moisture permeability, and chemical and volumetric stability.



Cement being mixed with sand and water to form concrete.

Mixing concrete

Thorough mixing is essential for the production of uniform, high quality concrete. Therefore, equipment and methods should be capable of effectively mixing concrete materials containing the largest specified aggregate to produce *uniform mixtures* of the lowest slump practical for the work.

Separate paste mixing has shown that the mixing of cement and water into a paste before combining these materials with aggregates can increase the compressive strength of the resulting concrete. The paste is generally mixed in a *high-speed*, shear-type mixer at a w/cm (water to cement ratio) of 0.30 to 0.45 by mass. The cement paste premix may include admixtures such as accelerators or retarders, plasticizers, pigments, or silica fume. The latter is added to fill the gaps between the cement particles. This reduces the particle distance and leads to a higher final compressive strength and a higher water impermeability. The premixed paste is then blended with aggregates and any remaining batch water, and final mixing is completed in conventional concrete mixing equipment.

High-energy mixed concrete (HEM concrete) is produced by means of high-speed mixing of cement, water and sand with net specific energy consumption at least 5 kilojoules per kilogram of the mix. It is then added to a plasticizer admixture and mixed after that with aggregates in conventional concrete mixer. This paste can be used itself or foamed (expanded) for lightweight concrete. Sand effectively dissipates energy in this mixing process. HEM concrete fast hardens in ordinary and low temperature conditions, and possesses increased volume of gel, drastically reducing capillarity in solid and porous materials. It is recommended for precast concrete in order to reduce quantity of cement, as well as for concrete roof and siding tiles, paving stones and lightweight concrete block production.

Pouring a concrete floor for a commercial building, *slab-on-ground*

Concrete pump

A concrete slab ponded while curing

Workability

Workability is the ability of a fresh (plastic) concrete mix to fill the form/mold properly with the desired work (vibration) and without reducing the concrete's quality. Workability depends on water content, aggregate (shape and size distribution), cementitious content and age (level of hydration), and can be modified by adding chemical admixtures. Raising the water content or adding chemical admixtures will increase concrete workability. Excessive water will lead to increased bleeding (surface water) and/or segregation of aggregates (when the cement and aggregates start to separate), with the resulting concrete having reduced quality. The use of an aggregate with an undesirable gradation can result in a very harsh mix design with a very low slump, which cannot be readily made more workable by addition of reasonable amounts of water.

Workability can be measured by the concrete slump test, a simplistic measure of the plasticity of a fresh batch of concrete following the ASTM C 143 or EN 12350-2 test standards. Slump is normally measured by filling an "Abrams cone" with a sample from a fresh batch of concrete. The cone is placed with the wide end down onto a level, non-absorptive surface. It is then filled in three layers of equal volume, with each layer being tamped with a steel rod in order to consolidate the layer. When the cone is carefully lifted off, the enclosed material will slump a certain amount due to gravity. A relatively dry sample will slump very little, having a slump value of one or two inches (25 or 50 mm). A relatively wet concrete sample may slump as much as eight inches.

Slump can be increased by adding chemical admixtures such as mid-range or high-range water reducing agents (super-plasticizers) without changing the water-cement ratio. It is bad practice to add water on-site that exceeds the water-cement ratio of the mix design, however in a properly designed mixture it is important to reasonably achieve the specified slump prior to placement as design factors such as air content, internal water for hydration/strength gain, etc. are dependent on placement at design slump values.

High-flow concrete, like self-consolidating concrete, is tested by other flow-measuring methods. One of these methods includes placing the cone on the narrow end and observing how the mix flows through the cone while it is gradually lifted.

After mixing, concrete is a fluid and can be pumped to where it is needed.

Concrete mixture placement

Concrete compaction

Curing

In all but the least critical applications, care needs to be taken to properly *cure* concrete, and achieve best strength and hardness. This happens after the concrete has been placed. Cement requires a moist, controlled environment to gain strength and harden fully. The cement paste hardens over time, initially setting and becoming rigid though very weak, and gaining in strength in the days and weeks following. In around 3 weeks, over 90% of the final strength is typically reached, though it may continue to strengthen for decades.

Hydration and hardening of concrete during the first three days is critical. Abnormally fast drying and shrinkage due to factors such as evaporation from wind during placement may lead to increased tensile stresses at a time when it has not yet gained significant strength, resulting in greater shrinkage cracking. The early strength of the concrete can be increased by keeping it damp for a longer period during the curing process. Minimizing stress prior to curing minimizes cracking. High early-strength concrete is designed to hydrate faster, often by increased use of cement that increases shrinkage and cracking. Strength of concrete changes (increases) up to three years. It depends on cross-section dimension of elements and conditions of structure exploitation.

During this period concrete needs to be in conditions with a controlled temperature and humid atmosphere. In practice, this is achieved by spraying or ponding the concrete surface with water, thereby protecting concrete mass from ill effects of ambient conditions. The pictures to the right show two of many ways to achieve this, ponding – submerging setting concrete in water, and wrapping in plastic to contain the water in the mix.

Properly curing concrete leads to increased strength and lower permeability, and avoids cracking where the surface dries out prematurely. Care must also be taken to avoid freezing, or overheating due to the exothermic setting of cement (the Hoover Dam used pipes carrying coolant during setting to avoid damaging overheating). Improper curing can cause scaling, reduced strength, poor abrasion resistance and cracking.

Properties

Concrete has relatively high compressive strength, but significantly lower tensile strength, and as such is usually reinforced with materials that are strong in tension (often steel). The elasticity of concrete is relatively constant at low stress levels but starts decreasing at higher stress levels as matrix cracking develops. Concrete has a very low coefficient of thermal expansion, and as it matures concrete shrinks. All concrete structures will crack to some extent, due to shrinkage and tension. Concrete that is subjected to long-duration forces is prone to creep.

Tests can be made to ensure the properties of concrete correspond to specifications for the application.

A "cage" of reinforcing steel

Environmental concerns

Worldwide CO_2 emissions and global change

The cement industry is one of two primary producers of carbon dioxide (CO_2), creating up to 5% of worldwide man-made emissions of this gas, of which 50% is from the chemical process, and 40% from burning fuel. The embodied carbon dioxide (ECO_2) of one tonne of concrete varies with mix design and is in the range of 75 – 175 kg CO_2/tonne concrete. The CO_2 emission from the concrete production is directly proportional to the cement content used in the concrete mix. Indeed, 900 kg of CO_2 are emitted for the fabrication of every ton of cement. Cement manufacture contributes greenhouse gases both directly through the production of carbon dioxide when calcium carbonate is thermally decomposed, producing lime and carbon dioxide, and also through the use of energy, particularly from the combustion of fossil fuels. However, some companies have recognized the problem and are envisaging solutions to counter their CO_2 emissions. The principle of carbon capture and storage consists of directly capturing the CO_2 at the outlet of the cement kiln in order to transport it and to store the captured CO_2 in an adequate and deep geological formation.

Surface runoff

Surface runoff, when water runs off impervious surfaces, such as non-porous concrete, can cause heavy soil erosion. Urban runoff tends to pick up gasoline, motor oil, heavy metals, trash and other pollutants from sidewalks, roadways and parking lots. The impervious cover in a typical city sewer system prevents groundwater percolation five times than that of a typical woodland of the same size. A 2008 report by the United States

National Research Council identified urban runoff as a leading source of water quality problems.

Urban heat

Both concrete and asphalt are the primary contributors to what is known as the urban heat island effect.

Using light-colored concrete has proven effective in reflecting up to 50% more light than asphalt and reducing ambient temperature. A low albedo value, characteristic of black asphalt, absorbs a large percentage of solar heat and contributes to the warming of cities. By paving with light colored concrete, in addition to replacing asphalt with light-colored concrete, communities can lower their average temperature.

Many U.S. cities show that pavement comprise approximately 30-40% of their surface area. This directly impacts the temperature of the city, as demonstrated by the urban heat island effect. In addition to decreasing the overall temperature of parking lots and large paved areas by paving with light-colored concrete, there are supplemental benefits. One example is 10-30% improved nighttime visibility. The potential of energy saving within an area is also high. With lower temperatures, the demand for air conditioning decreases, saving vast amounts of energy.

Atlanta has tried to mitigate the heat-island effect. City officials noted that when using heat-reflecting concrete, their average city temperature decreased by 6 °F. New York City offers another example. The Design Trust for Public Space in New York City found that by slightly raising the albedo value in their city, beneficial effects such as energy savings could be achieved. It was concluded that this could be accomplished by the replacement of black asphalt with light-colored concrete.

However, in winter this may be to a disadvantage as ice will form easier and remain longer on the light colored surfaces as they will be colder due to less energy absorbed from the little amounts of sun there is in winter.

Concrete dust

Building demolition and natural disasters such as earthquakes often release a large amount of concrete dust into the local atmosphere. Concrete dust was concluded to be the major source of dangerous air pollution following the Great Hanshin earthquake.

Health concerns

The presence of some substances in concrete, including useful and unwanted additives, can cause health concerns. Natural radioactive elements (K, U and Th) can be present in various concentration in concrete dwellings, depending on the source of the raw materials used. Toxic substances may also be added to the mixture for making concrete by unscrupulous makers. Dust from rubble or broken concrete upon demolition or crumbling may cause serious health concerns depending also on what had been incorporated in the concrete.

Concrete handling/safety precautions

Handling of wet concrete must always be done with proper protective equipment. Contact with wet concrete can cause skin burns due to the caustic nature of the mixture of cement and water.

Secondary efflorescence: Water seeping through the concrete, often in cracks, having dissolved components of cement stone. Osteoporosis of concrete often happens in parking garages, as road salt comes off cars to the concrete floor as a saline solution in the winter.

Damage modes

Concrete spalling caused by the corrosion of reinforcement bars after that carbonation of cement decreased the pH below the passivation threshold for steel.

Concrete can be damaged by many processes such as, e.g., the expansion of corrosion products of the steel reinforcement bars, freezing of trapped water, fire or radiant heat, aggregate expansion, sea water effects, bacterial corrosion, leaching, erosion by fast-flowing water, physical damage and chemical damage (from carbonation, chlorides, sulfates and distillate water).

Manufacturers of cement and concrete admixtures must keep on top of microbiological contamination in raw materials, intermediates and final products to prevent product spoilage. One method of keeping controlling contamination is through 2nd Generation ATP test.

Concrete repair

Concrete pavement preservation (CPP) and concrete pavement restoration (CPR) are techniques used to manage the rate of pavement deterioration on concrete streets, highways and airports. Without changing concrete grade, this non-overlay method is used to repair isolated areas of distress. CPP and CPR techniques include slab stabilization, full- and partial-depth repair, dowel bar retrofit, cross stitching longitudinal cracks or joints, diamond grinding and joint and crack resealing. CPR methods, developed over the last 40 years, are utilized in lieu of short-lived asphalt overlays and bituminous patches to repair roads. These methods are often less expensivethan an asphalt overlay but last three times longer and provide a greener solution.

CPR techniques can be used to address specific problems or bring a pavement back to its original quality. When repairing a road, design data, construction data, traffic data, environmental data, previous CPR activities and pavement condition, must all be taken into account. Pavements repaired using CPR methods usually last 15 years. The methods are described below.

- Slab stabilization restores support to concrete slabs by filling small voids that develop underneath the concrete slab at joints, cracks or the pavement edge.
- Full-depth repairs fixes cracked slabs and joint deterioration by removing at least a portion of the existing slab and replacing it with new concrete.
- Partial-depth repairs corrects surface distress and joint-crack deterioration in the upper third of the concrete slab. Placing a partial-depth repair involves removing the deteriorated concrete, cleaning the patch area and placing new concrete.
- Dowel bar retrofit consists of cutting slots in the pavement across the joint or crack, cleaning the slots, placing the dowel bars and backfilling the slots with new concrete. Dowel bar retrofits link slabs together at transverse cracks and joints so that the load is evenly distributed across the crack or joint.
- Cross-stitching longitudinal cracks or joints repairs low-severity longitudinal cracks. This method adds reinforcing steel to hold the crack together tightly.
- Diamond grinding, by removing faulting, slab warping, studded tire wear and unevenness resulting from patches, diamond grinding creates a smooth, uniform pavement profile. Diamond grinding reduces road noise by providing a longitudinal texture, which is quieter than transverse textures. The longitudinal texture also enhances surface texture and skid resistance in polished pavements.
- Joint and crack sealing minimizes the infiltration of surface water and incompressible material into the joint system. Minimizing water entering the joint reduces sub-grade softening, slows pumping and erosion of the sub-base fines, and may limit dowel-bar corrosion caused by de-icing chemicals.

Concrete recycling

Recycling:The multiple use of a product represents another way to conserve natural resources and avoid wastes. This process is usually termed as “recycling”.

Recycled Concrete: Hardened concrete that has been processed for reuse, usually as aggregates.

Concrete recycling is an increasingly common method of disposing of concrete structures. Concrete debris was once routinely shipped to landfills for disposal, but recycling is increasing due to improved environmental awareness, governmental laws, and economic benefits.

Concrete, which must be free of trash, wood, paper and other such materials, is collected from demolition sites and put through a crushing machine, often along with asphalt, bricks, and rocks.

Reinforced concrete contains rebar and other metallic reinforcements, which are removed with magnets and recycled elsewhere. The remaining aggregate chunks are sorted by size. Larger chunks may go through the crusher again. Smaller pieces of concrete are used as gravel for new construction projects. Aggregate base gravel is laid down as the lowest layer in a road, with fresh concrete or asphalt placed over it. Crushed recycled concrete can sometimes be used as the dry aggregate for brand new concrete if it is free of contaminants, though the use of recycled concrete limits strength and is not allowed in many jurisdictions. On March 3, 1983, a government funded research team (the VIRL research.codep) approximated that almost 17% of worldwide landfill was by-products of concrete based waste.

Recycling concrete provides environmental benefits, conserving landfill space and use as aggregate reduces the need for gravel mining.

World records

The world record for the largest concrete pour in a single project is the Three Gorges Dam in Hubei Province, China by the Three Gorges Corporation. The amount of concrete used in the construction of the dam is estimated at 16 million cubic meters over 17 years. The previous record was 3.2 million cubic meters held by Itaipu hydropower station in Brazil.

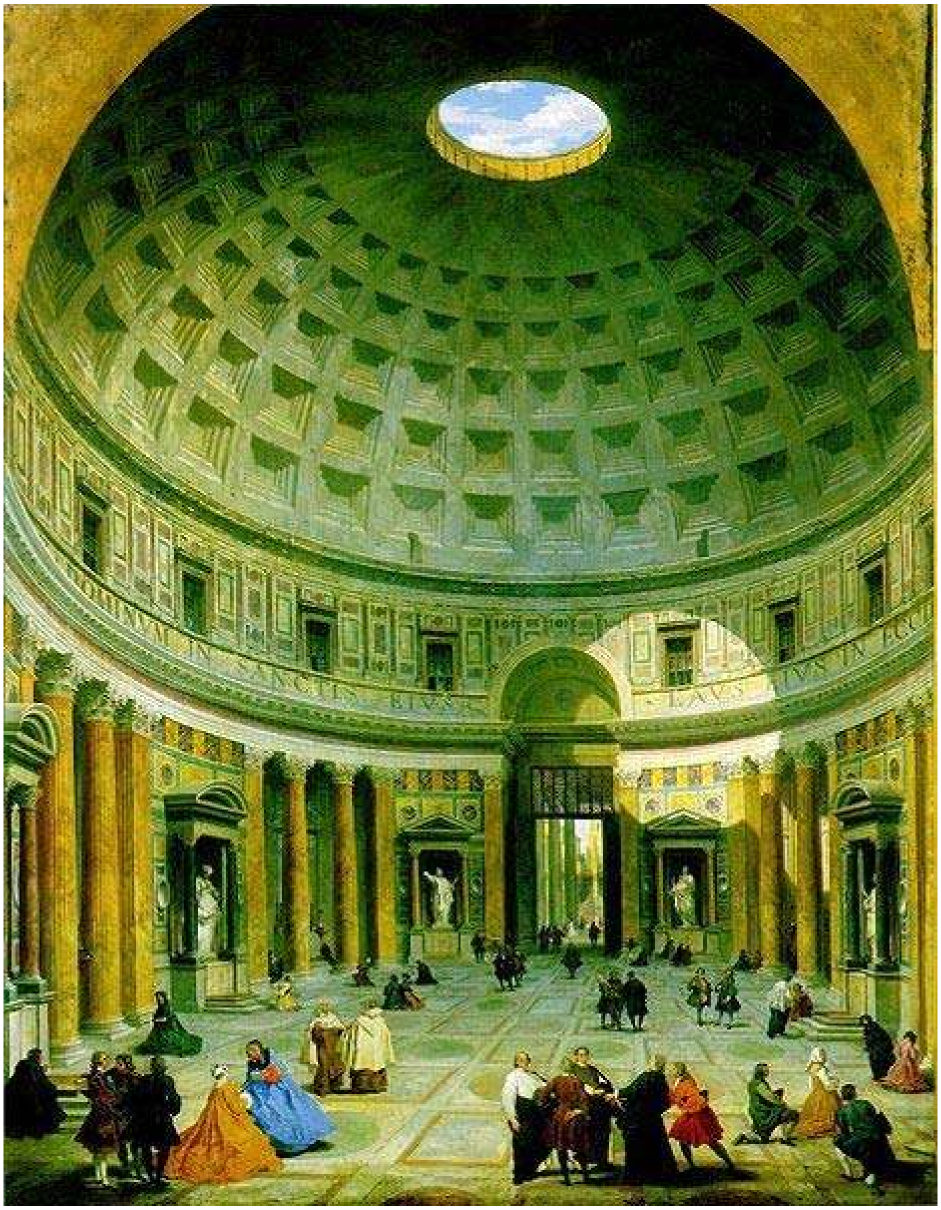
Concrete pumping

The world record for vertical concrete pumping was achieved in India by Schwing Stetter in August 2009. Concrete was pumped to a height of 715m for the construction of the Parbati hydro-electric power project in the Indian state of Himachal Pradesh.

Continuous pours

The world record for largest continuously poured concrete raft was achieved in August, 2007 in Abu Dhabi by contracting firm, Al Habtoor-CCC Joint Venture. The pour (a part of the foundation for the Abu Dhabi's Landmark Tower) was 16,000 cubic meters of concrete poured within a two day period. The previous record (close to 10,500 cubic meters) was held by Dubai Contracting Company and achieved March 23, 2007.

The world record for largest continuously poured concrete floor was completed November 8, 1997 in Louisville, Kentucky by design-build firm, EXXCEL Project Management. The monolithic placement consisted of 225,000 square feet (20,900 m^2) of concrete placed within a 30 hour period, finished to a flatness tolerance of F_F 54.60 and a levelness tolerance of F_L 43.83. This surpassed the previous record by 50% in total volume and 7.5% in total area.



The interior of the Pantheon in the 18th century, painted by Giovanni Paolo Pannini

Use of concrete in infrastructure

Mass concrete structures

These include gravity dams such as the Itaipu, Hoover Dam and the Three Gorges Dam and large breakwaters. Concrete that is poured all at once in one block (so that there are no weak points where the concrete is "welded" together) is used for tornado shelters.

Reinforced concrete structures

Reinforced concrete contains steel reinforcing that is designed and placed in structural members at specific positions to cater for all the stress conditions that the member is required to accommodate.

Prestressed concrete structures

Prestressed concrete is a form of reinforced concrete that builds in compressive stresses during construction to oppose those found when in use. This can greatly reduce the weight of beams or slabs, by better distributing the stresses in the structure to make optimal use of the reinforcement. For example a horizontal beam will tend to sag down. If the reinforcement along the bottom of the beam is prestressed, it can counteract this.

In pre-tensioned concrete, the prestressing is achieved by using steel or polymer tendons or bars that are subjected to a tensile force prior to casting, or for post-tensioned concrete, after casting.

Concrete textures

When one thinks of concrete, oftentimes the image of a dull, gray concrete wall comes to mind. With the use of form liner, concrete can be cast and molded into different textures and used for decorative concrete applications. Sound/retaining walls, bridges, office buildings and more serve as the optimal canvases for concrete art. For example, the Pima Freeway/Loop 101 retaining and sound walls in Scottsdale, Arizona, feature desert flora and fauna, a 67-foot (20 m) lizard and 40-foot (12 m) cacti along the 8-mile (13 km) stretch. The project, titled "The Path Most Traveled," is one example of how concrete can be shaped using elastomeric form liner.

A 67-foot concrete lizard basks in the sun, featured on a sound/retaining wall in Scottsdale, AZ.

40-foot cacti decorate a sound/retaining wall in Scottsdale, AZ

Building with concrete

Concrete is the safest, most durable and sustainable building material. It provides superior fire resistance, gains strength over time and has an extremely long service life. Concrete is the most widely used construction material in the world with annual consumption estimated at between 21 and 31 billion tonnes. Concrete construction minimizes the long-term costs of a building or infrastructure project.

Environmentally sustainable

With its 100-year service life, concrete conserves resources by reducing the need for reconstruction. Its ingredients are cement and readily available natural materials: water, aggregate (sand and gravel or crushed stone). Concrete does not require any CO_2 absorbing trees to be cut down. The land required to extract the materials needed to make concrete is only a fraction of that used to harvest forests for lumber.

The Baths of Caracalla, Rome, Italy, in 2003

Concrete absorbs CO_2 throughout its lifetime through carbonation, helping reduce its carbon footprint. A recent study indicates that in countries with the most favorable recycling practices, it is realistic to assume that approximately 86% of the concrete is carbonated after 100 years. During this time, the concrete will absorb approximately 57% of the CO_2 emitted during the original calcination. About 50% of the CO_2 is absorbed within a short time after concrete is crushed during recycling operations.

Concrete consists of between 7% and 15% cement, its only energy-intensive ingredient. A study comparing the CO_2 emissions of several different building materials for construction of residential and commercial buildings found that concrete accounted for 147 kg of CO_2 per 1000 kg used, metals accounted for 3000 kg of CO_2 and wood accounted for 127 kg of CO_2. The quantity of CO_2 generated during the cement manufacturing process can be reduced by changing the raw materials used in its manufacture.

A new environmentally friendly blend of cement known as Portland-limestone cement (PLC) is gaining ground all over the world. It contains up to 15% limestone, rather than the 5% in regular Portland cement and results in 10% less CO_2 emissions from production with no impact on product performance. Concrete made with PLC performs similarly to concrete made with regular cement and thus PLC-based concrete can be widely used as a replacement. In Europe, PLC-based concrete has replaced about 40% of general use concrete. In Canada, PLC will be included in the National Building Code in 2010. The approval of PLC is still under consideration in the United States.

Energy efficiency

Energy requirements for transportation of concrete are low because it is produced locally from local resources, typically manufactured within 100 kilometers of the job site. Once in place, concrete offers significant energy efficiency over the lifetime of a building. Concrete walls leak air far less than those made of wood-frames. Air leakage accounts for a large percentage of energy loss from a home. The thermal mass properties of concrete increase the efficiency of both residential and commercial buildings. By storing and releasing the energy needed for heating or cooling, concrete's thermal mass delivers year-round benefits by reducing temperature swings inside and minimizing heating and cooling costs. While insulation reduces energy loss through the building envelope, thermal mass uses walls to store and release energy. Modern concrete wall systems use both insulation and thermal mass to create an energy-efficient building. Insulating Concrete Forms (ICFs) are hollow blocks or panels made of either insulating foam or rastra that are stacked to form the shape of the walls of a building and then filled with reinforced concrete to create the structure.

Models of Porsche automobiles, made out of concrete, part of an exhibition, "Best of Austria," in the Lentos Museum in Linz, Austria in 2009.

Fire safety and quality of life

Concrete buildings are more resistant to fire than those constructed using wood or steel frames. Since concrete does not burn and stops fire from spreading, it offers total fire protection for occupants and their property. Concrete reduces the risk of structural collapse and is an effective fire shield, providing safe means of escape for occupants and protection for firefighters. Furthermore, it does not produce any smoke or toxic gases and does not drip molten particles, which can spread fire. Neither heat, flames nor the water used to extinguish a fire seriously affect the structure of concrete walls and floors making repairs after a fire a relatively simple task.

A study was conducted in Sweden by Olle Lundberg on the cost of fire damage associated with larger fires in multi-unit buildings, based on statistics from the insurance association in Sweden (Forsakrings Forbundet). The study was limited to buildings with an insured value greater than €150,000. It covered 125 fires that occurred between 1995 and 2004, about 10% of the fires in multi-family homes, but 56% of the major fires.) The results showed that:

- the average insurance payout per fire, per unit in wood frame buildings was around five times that of fires in concrete buildings (approximately €50,000 compared with €10,000)
- a major fire is more than 11 times more likely to develop in a wood-frame house than in one built using concrete
- among the burned houses, 50% of those made with wood had to be demolished, whereas only 9% of the concrete ones were beyond repair
- the fire spread to neighbouring apartments in only three of the 55 fires in concrete houses
- of those 55 fires, 45 were in attics and roofing

Options for non-combustible construction include floors, ceilings and roofs made of cast-in-place and hollow-core precast concrete. For walls, concrete masonry technology and Insulating Concrete Forms (ICFs) are additional options. ICFs are hollow blocks or panels made of fire-proof insulating foam that are stacked to form the shape of the walls of a building and then filled with reinforced concrete to create the structure.

“Fire-wall” tests, in which ICF walls were subjected to a continuous gas flame with a temperature of more than 1000°C for as long as 4 hours showed no significant breaks in the concrete layer or dangerous transmission of heat. In comparison, wood frame walls normally collapse in an hour or less under these conditions. Concrete provides stable compartmentation in large industrial and multi-storey buildings so a fire starting in one section does not spread to others.

Using concrete to construct buildings offers the best possible protection and safety in fires:

- it does not burn or add to fire load

- it has high resistance to fire, preventing it from spreading thus reduces resulting environmental pollution
- it does not produce any smoke, toxic gases or drip molten particles
- it reduces the risk of structural collapse
- it provides safe means of escape for occupants and access for firefighters as it is an effective fire shield
- it is not affected by the water used to put out a fire
- it is easy to repair after a fire and thus helps residents and businesses recover sooner
- it resists extreme fire conditions, making it ideal for storage facilities with a high fire load
- it provides complete fire protection so there is normally no need for additional measures

Recycled crushed concrete being loaded into a semi-dump truck to be used as granular fill.

Concrete also provides the best resistance of any building material to high winds, hurricanes, tornadoes due to its lateral stiffness that results in minimal horizontal movement. When properly designed for ductility, it also provides superior resistance to seismic events. It does not rust, rot or sustain growth of mold and stands up well to the freeze – thaw cycle. As a result of all these benefits, insurance for concrete homes is often 15 to 25 percent lower than for comparable wood frame homes.

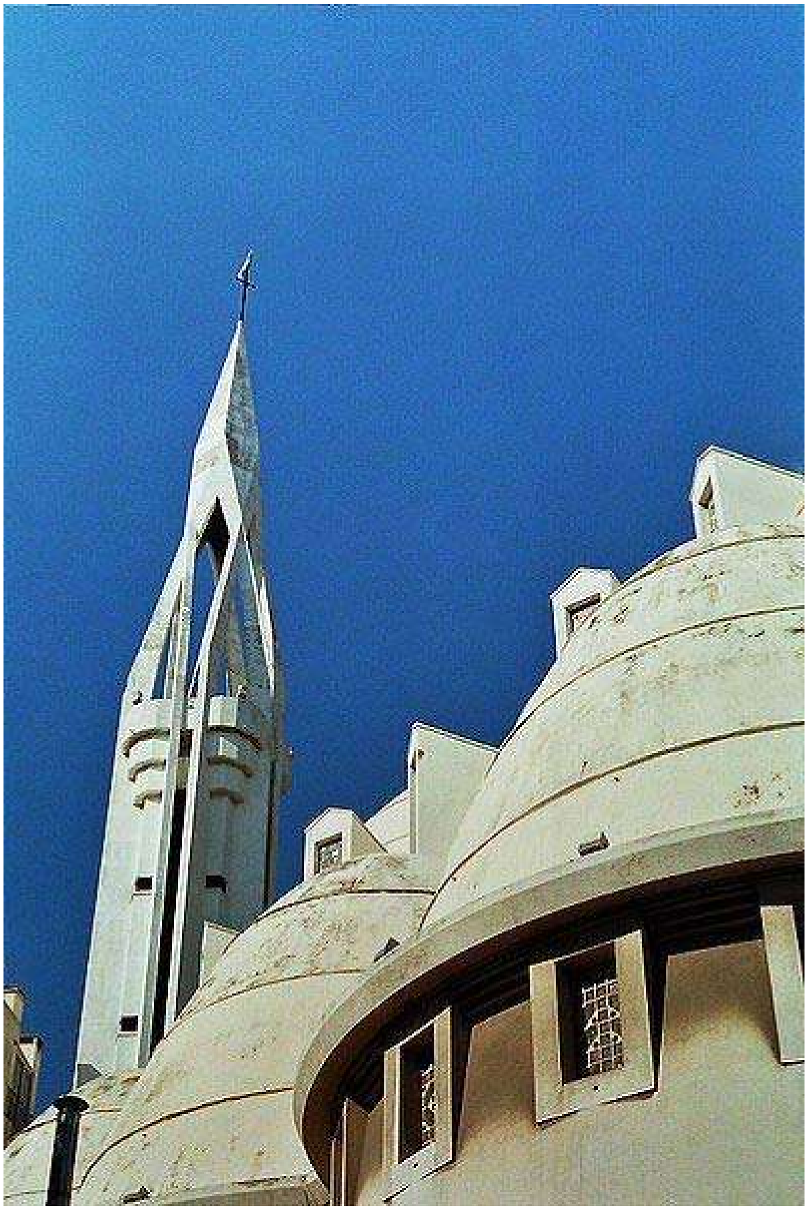
Concrete buildings also have excellent indoor air quality with no off-gassing, toxicity and release of volatile organic compounds so they are generally healthier to live in than those made of wood or steel. As it is practically inert and waterproof, concrete does not need volatile organic-based preservatives, special coatings or sealers. Concrete can be easily cleaned with organic, non-toxic substances. Its sound insulating properties make buildings and homes a quiet and comfortable living environment. After accounting for sound passing through windows, a concrete home is about two-thirds quieter than a comparable wood-frame home.

Due to the long life of concrete structures, their impacts on the environment are negligible. Once built, they have minimal maintenance requirements and as a result minimal social disruption. Using concrete reduces construction waste as it is used on an as-required basis, thereby minimizing the waste put into landfills.

Recycling and recyclable

A nearly inert material, concrete is suitable as a medium for recycling waste and industrial byproducts. Fly ash, slag and silica fume are used in making concrete, which helps reduce embodied energy, carbon footprint and quantity of landfill materials. The process of making cement also uses waste materials. Tires have high energy content and can supplement coal as fuel in the kiln. Industrial byproducts such as ash from coal combustion, fly ash from power stations as well as mill scale and foundry sand from steel casting provide the silica, calcium, alumina and iron needed for making cement. Even kiln dust, a solid waste generated by cement manufacturing, is often recycled back into the kiln as a raw material. Old concrete that has reached the end of its service life can be recycled and reused as granular fill for road beds.

Reinforced Concrete



Reinforced concrete at Sainte Jeanne d'Arc Church (Nice, France): architect Jacques Dror, 1926–1933

Reinforced concrete is concrete in which reinforcement bars ("rebars"), reinforcement grids, plates or fibers have been incorporated to strengthen the concrete in tension. The term Ferro Concrete refers only to concrete that is reinforced with iron or steel. Other materials used to reinforce concrete can be organic and inorganic fibres as well as composites in different forms. Concrete is strong in compression, but weak in tension, thus adding reinforcement increases the strength in tension. In addition, the failure strain of concrete in tension is so low that the reinforcement has to hold the cracked sections together. For a strong, ductile and durable construction the reinforcement shall have the following properties:

- High strength
- High tensile strain
- Good bond to the concrete
- Thermal compatibility
- Durability in the concrete environment

In most cases reinforced concrete uses steel rebars that have been inserted to add strength.

Use in construction

Rebars of Sagrada Familia's roof in construction (2009)

Concrete is reinforced to give it extra tensile strength; without reinforcement, many concrete buildings would not have been possible.

Reinforced concrete can encompass many types of structures and components, including slabs, walls, beams, columns, foundations, frames and more.

Reinforced concrete can be classified as precast or cast in-situ concrete.

Much of the focus on reinforcing concrete is placed on floor systems. Designing and implementing the most efficient floor system is key to creating optimal building structures. Small changes in the design of a floor system can have significant impact on material costs, construction schedule, ultimate strength, operating costs, occupancy levels and end use of a building.

Behavior of reinforced concrete

Materials

Concrete is a mixture of cement (usually Portland cement) and stone aggregate. When mixed with a small amount of water, the cement hydrates form microscopic opaque crystal lattices encapsulating and locking the aggregate into a rigid structure. Typical concrete mixes have high resistance to compressive stresses (about 4,000 psi (28 MPa)); however, any appreciable tension (e.g. due to bending) will break the microscopic rigid lattice resulting in cracking and separation of the concrete. For this reason, typical non-reinforced concrete must be well supported to prevent the development of tension.

If a material with high strength in tension, such as steel, is placed in concrete, then the composite material, **reinforced concrete**, resists compression but also bending, and other direct tensile actions. A reinforced concrete section where the concrete resists the compression and steel resists the tension can be made into almost any shape and size for the construction industry.

Key characteristics

Three physical characteristics give reinforced concrete its special properties.

First, the coefficient of thermal expansion of concrete is similar to that of steel, eliminating large internal stresses due to differences in thermal expansion or contraction.

Second, when the cement paste within the concrete hardens this conforms to the surface details of the steel, permitting any stress to be transmitted efficiently between the different materials. Usually steel bars are roughened or corrugated to further improve the bond or cohesion between the concrete and steel.

Third, the alkaline chemical environment provided by the alkali reserve (KOH, NaOH) and the portlandite (calcium hydroxide) contained in the hardened cement paste causes a passivating film to form on the surface of the steel, making it much more resistant to corrosion than it would be in neutral or acidic conditions. When the cement paste exposed to the air and meteoric water reacts with the atmospheric CO_2, portlandite and the Calcium Silicate Hydrate (CSH) of the hardened cement paste become progressively carbonated and the high pH gradually decreases from 13.5 – 12.5 to 8.5, the pH of water in equilibrium with calcite (calcium carbonate) and the steel is no longer passivated.

As a rule of thumb, only to give an idea on orders of magnitude, steel is protected at pH above ~11 but starts to corrode below ~10 depending on steel characteristics and local physico-chemical conditions when concrete becomes carbonated. Carbonation of concrete along with chloride ingress are amongst the chief reasons for the failure of reinforcement bars in concrete.

The relative cross-sectional area of steel required for typical reinforced concrete is usually quite small and varies from 1% for most beams and slabs to 6% for some columns. Reinforcing bars are normally round in cross-section and vary in diameter. Reinforced concrete structures sometimes have provisions such as ventilated hollow cores to control their moisture & humidity.

Distribution of concrete (in spite of reinforcement) strength characteristics along the cross-section of vertical reinforced concrete elements is inhomogeneous article "Concrete Inhomogeneity of Vertical Cast-In-Situ Elements In Frame-Type Buildings".

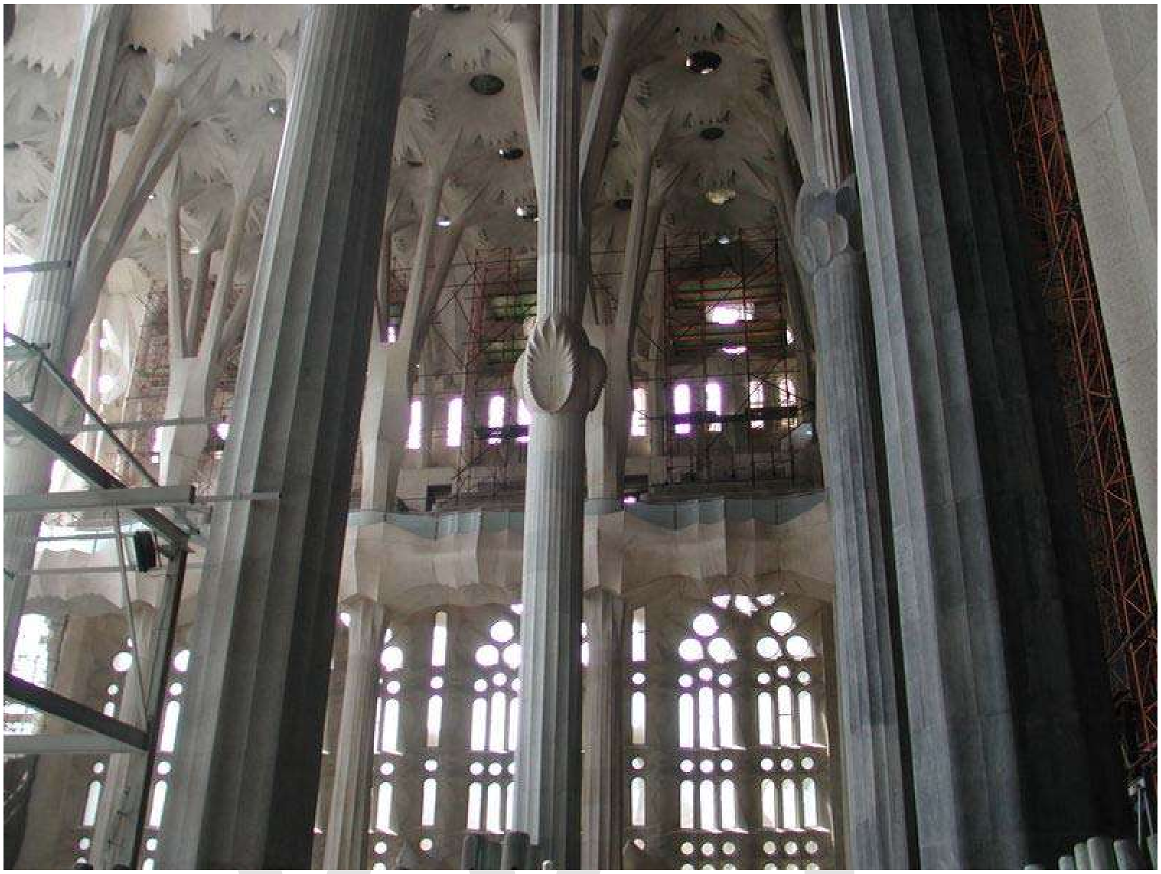
Anti-corrosion measures

In wet and cold climates, reinforced concrete for roads, bridges, parking structures and other structures that may be exposed to deicing salt may benefit from use of epoxy-coated, hot dip galvanised or stainless steel rebar, although good design and a well-chosen cement mix may provide sufficient protection for many applications. Epoxy coated rebar can easily be identified by the light green colour of its epoxy coating. Hot dip galvanized rebar may be bright or dull grey depending on length of exposure, and stainless rebar exhibits a typical white metallic sheen that is readily distinguishable from carbon steel reinforcing bar. Reference ASTM standard specifications **A767** Standard Specification for Hot Dip Galvanised Reinforcing Bars, **A775** Standard Specification for Epoxy Coated Steel Reinforcing Bars and **A955** Standard Specification for Deformed and Plain Stainless Bars for Concrete Reinforcment

Another, cheaper way or protecting rebars is coating them with zinc phosphate. Zinc phosphate slowly reacts with calcium cations and the hydroxyl anions present in the cement pore water and forms a stable hydroxyapatite layer.

Penetrating sealants typically must be applied some time after curing. Sealants include paint, plastic foams, films and aluminum foil, felts or fabric mats sealed with tar, and layers of bentonite clay, sometimes used to seal roadbeds.

Corrosion inhibitors such as calcium nitrite [$Ca(NO_2)_2$] can also be added to the water mix before pouring concrete. Generally, 1–2 wt. % of [$Ca(NO_2)_2$] with respect to cement weight is needed to prevent the corrosion of the rebars. The nitrite anions is a mildy oxidizer that oxidizes the soluble and mobile ferrous ions (Fe^{2+}) present at the surface of the corroding steel and causes it to precipitate as an insoluble ferric hydroxide ($Fe(OH)_3$). This causes the passivation of steel at the anodic oxidation sites. Nitrite is a much more active corrosion inhibitor than nitrate, a less powerful oxidizer of the divalent iron.



The interior of the Sagrada Familia, constructed of reinforced concrete to a design by Gaudi

Reinforcement and terminology

A beam bends under bending moment resulting in a small curvature. At the outer face (**tensile face**) of the curvature the concrete experiences tensile stress while at the inner face (**compressive face**) it experiences compressive stress.

A **"singly-reinforced"** concrete means that the concrete element is only reinforced near the tensile face and the reinforcement, called tension steel, is designed to resist the tension.

A **"doubly-reinforced"** concrete means that beside the tensile reinforcement the concrete element is also reinforced near the compressive face for assisting the concrete to resist compression. The latter reinforcement is called compression steel.

An **"under-reinforced"** concrete means that the tension capacity of the tensile reinforcement is **smaller** than the combined compression capacity of the concrete and the compression steel (under-reinforced at tensile face). When the reinforced concrete element is subject to increasing bending moment, the tension steel yields while the concrete does not reach its ultimate failure condition. As the tension steel yields and stretches, an "under-reinforced" concrete also yields in a ductile manner, exhibiting a large deformation and warning before its ultimate failure.

An **"over-reinforced"** concrete means that the tension capacity of the tension steel is **greater** than the combined compression capacity of the concrete and the compression steel (over-reinforced at tensile face). An "over-reinforced" element will fail suddenly, when the concrete fails brittle and crashes before yielding of the tension steel. It is however possible to push the design of an "over-reinforced" concrete element to "under-reinforced" concrete element by adding sufficient compression steel. There is however a limit in the quantity of both tension and compression steel for practically placement of reinforcement.

Steel reinforced concrete elements should normally be designed to be under-reinforced so users of the structure will receive warning of impending collapse.

Characteristic strength strength of a material where less than 5% of the specimen show lower strength.

Design strength strength of a material including a material safety factor.

Ultimate limit state theoretical failure point with a certain probability. State under factored loads and factored resistances.

Nominal strength actual strength from the material properties is called the nominal strength. Its relation with design strength can be represented as:

`Nominal x Ø = Design strength`

Prestressed Concrete

Prestressed concrete is a technique that greatly increases loadbearing strengh of concrete beams. The reinforcing steel in the bottom part of the beam, which will be subjected to tensile forces when in service, is placed in tension prior to the concrete being poured around it. Once the concrete has hardened, the tension on the reinforcing steel is released, placing a built in compressive force on the concrete. When loads are applied, the reinforcing steel takes on more stress and the compressive force in the concrete is reduced, but does not become a tensile force. Since the concrete is always under compression, it is less subject to cracking and failure.

Common failure modes of steel reinforced concrete

Reinforced concrete can fail due to inadequate strength, leading to mechanical failure, or due to a reduction in its durability. Corrosion and freeze/thaw cycles may damage poorly designed or constructed reinforced concrete. When rebar corrodes, the oxidation products (rust) expand and tends to flake, cracking the concrete and unbonding the rebar from the concrete. Typical mechanisms leading to durability problems are discussed below.

Mechanical failure

Reinforced concrete can be considered to have failed when significant cracks occur. Cracking of the concrete section can not be prevented; however, the size of and location of the cracks can be limited and controlled by reinforcement, placement of control joints, the curing methodology and the mix design of the concrete. Cracking defects can allow moisture to penetrate and corrode the reinforcement. This is a serviceability failure in limit state design. Cracking is normally the result of an inadequate quantity of rebar, or rebar spaced at too great a distance. The concrete then cracks either under excess loading, or due to internal effects such as **early thermal shrinkage** when it cures.

Ultimate failure leading to collapse can be caused by crushing of the concrete matrix, when stresses exceed its strength; by yielding of the rebar; or by bond failure between the concrete and the rebar.

Carbonation

Rebar for foundations and walls of sewage pump station

Carbonation, or neutralisation, is a chemical reaction between carbon dioxide in the air with calcium hydroxide and hydrated calcium silicate in the concrete. The water in the pores of Portland cement concrete is normally alkaline with a pH in the range of 12.5 to 13.5. This highly alkaline environment is one in which the embedded steel is passivated and is protected from corrosion. According to the Pourbaix diagram for iron, the metal is passive when the pH is above 9.5. The carbon dioxide in the air reacts with the alkali in the cement and makes the pore water more acidic, thus lowering the pH. Carbon dioxide will start to carbonate the cement in the concrete from the moment the object is made. This **carbonation** process will start at the surface, then slowly move deeper and deeper into the concrete. The rate of carbonation is dependent on the relative humidity of the concrete - a 50% relative humidity being optimal. If the object is cracked, the carbon dioxide in the air will be better able to penetrate into the concrete. When designing a concrete structure, it is normal to state the concrete cover for the rebar (the depth within the object that the rebar will be). The minimum concrete cover is normally regulated by design or building codes. If the reinforcement is too close to the surface, early failure due to corrosion may occur. The concrete cover depth can be measured with a cover meter. However, carbonated concrete only becomes a durability problem when there is also sufficient moisture and oxygen to cause electro-potential corrosion of the reinforcing steel.

One method of testing a structure for carbonation is to drill a fresh hole in the surface and then treat the cut surface with phenolphthalein indicator solution. This solution will turn [pink] when in contact with alkaline concrete, making it possible to see the depth of carbonation. An existing hole is no good because the exposed surface will already be carbonated.

Chlorides

The Paulins Kill Viaduct, Hainesburg, New Jersey, is 115 feet (35 m) tall and 1,100 feet (335 m) long, and was heralded as the largest reinforced concrete structure in the world when it was completed in 1910 as part of the Lackawanna Cut-Off rail line project. The Lackawanna Railroad was a pioneer in the use of reinforced concrete.

Chlorides, including sodium chloride, can promote the corrosion of embedded steel rebar if present in sufficienty high concentration. Chloride anions induce both localized corrosion (pitting corrosion) and generalized corrosion of steel reinforcements. For this reason, only use fresh raw water or potable water for mixing concrete. Insure that the coarse and fine aggregates do not contain chlorides. Do not use admixtures that contain chlorides.

It was once common for calcium chloride to be used as an admixture to promote rapid set-up of the concrete. It was also mistakenly believed that it would prevent freezing. However, this practice has fallen into disfavor once the deleterious effects of chlorides became known. It should be avoided when ever possible.

The use of de-icing salts on roadways, used to reduce the freezing point of water, is probably one of the primary causes of premature failure of reinforced or prestressed concrete bridge decks, roadways, and parking garages. The use of epoxy-coated reinforcing bars and the application of cathodic protection has mitigated this problem to some extent. Properly designed concrete mixtures that have been allowed to cure properly are effectively impervious to the effects of de-icers. (One common problem today is that concrete is allowed to "dry" (dries out) in two to three days by contractors before it cures and thus ultimately develops less than 10% of its design strength).

Another important source of chloride ions is from sea water. Sea water contains by weight approximately 3.5 wt.% salts. These salts include sodium chloride, magnesium sulphate, calcium sulphate and bicarbonates. In water these salts dissociate in free ions (Na^+, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-) and migrate with the water into the capillaries of the concrete. Chloride ions are particularly aggressive for the corrosion of the carbon steel reinforcement bars and make up about 50% of these ions.

Alkali silica reaction

This a reaction of amorphous silica (chalcedony, chert, siliceous limestone) sometimes present in the aggregates with the hydroxyl ions (OH^-) from the cement pore solution. Poorly crystallized silica (SiO_2) dissolves and dissociates at high pH (12.5 - 13.5) in alkaline water. The soluble dissociated silicic acid reacts in the porewater with the calcium hydroxide (portlandite) present in the cement paste to form an expansive calcium silicate hydrate (CSH). The *alkali silica reaction (ASR)*, causes localised swelling responsible of tensile stress and cracking. The conditions required for alkali silica reaction are threefold: (1) aggregate containing an alkali-reactive constituent (amorphous silica), (2) sufficient availability of hydroxyl ions (OH^-), and (3) sufficient moisture, above 75 % relative humidity (RH) within the concrete. This phenomenon is sometimes popularly referred to as "concrete cancer". This reaction occurs independently of the presence of rebars: massive concrete structures such as dams can be affected.

Conversion of high alumina cement

Resistant to weak acids and especially sulfates, this cement cures quickly and reaches very high durability and strength. It was greatly used after World War II for making precast concrete objects. However, it can lose strength with heat or time (conversion), especially when not properly cured. With the collapse of three roofs made of prestressed concrete beams using high alumina cement, this cement was banned in the UK in 1976. Subsequent inquiries into the matter showed that the beams were improperly manufactured, but the ban remained.

Sulfates

Sulfates (SO_4) in the soil or in groundwater, in sufficient concentration, can react with the Portland cement in concrete causing the formation of expansive products, e.g. ettringite or thaumasite, which can lead to early failure of the structure. The most typical attack of this type is on concrete slabs and foundation walls at grade where the sulfate ion, via alternate wetting and drying, can increase in concentration. As the concentration increases, the attack on the Portland cement can begin. For buried structures such as pipe, this type of attack is much rarer especially in the Eastern half of the United States. The sulfate ion concentration increases much slower in the soil mass and is especially dependent upon the initial amount of sulfates in the native soil. The chemical analysis of soil borings should be done during the design phase of any project involving concrete in contact with the native soil to check for the presence of sulfates. If the concentrations are found to be aggressive, various protective coatings can be used. Also, in the US ASTM C150 Type 5 Portland cement can be used in the mix. This type of cement is designed to be particularly resistant to a sulfate attack.

Steel plate construction

In steel plate construction, stringers join parallel steel plates. The plate assemblies are fabricated off site, and welded together on-site to form steel walls connected by stringers. The walls become the form into which concrete is poured. Steel plate construction speeds reinforced concrete construction by cutting out the time consuming on-site manual steps of tying rebar and building forms. The method has excellent strength because the steel is on the outside, where tensile forces are often greatest.

Fiber-reinforced concrete

Fiber-reinforcement is mainly used in shotcrete, but can also be used in normal concrete. Fiber-reinforced normal concrete are mostly used for on-ground floors and pavements, but can be considered for a wide range of construction parts (beams, pilars, foundations etc) either alone or with hand-tied rebars.

Concrete reinforced with fibers (which are usually steel, glass or "plastic" fibers) is less expensive than hand-tied rebar, while still increasing the tensile strength many times. Shape, dimension and length of fiber is important. A thin and short fiber, for example short hair-shaped glass fiber, will only be effective the first hours after pouring the concrete (reduces cracking while the concrete is stiffening) but will not increase the concrete tensile strength. A normal size fibre for European shotcrete (1 mm diameter, 45 mm length—steel or "plastic") will increase the concrete tensile strength.

Steel is the strongest commonly-available fiber, and come in different lengths (30 to 80 mm in Europe) and shapes (end-hooks). Steel fibres can only be used on surfaces that can tolerate or avoid corrosion and rust stains. In some cases, a steel-fiber surface is faced with other materials.

Glass fiber is inexpensive and corrosion-proof, but not as ductile as steel. Recently, spun basalt fiber, long available in Eastern Europe, has become available in the U.S. and Western Europe. Basalt fibre is stronger and less expensive than glass, but historically, has not resisted the alkaline environment of portland cement well enough to be used as direct reinforcement. New materials use plastic binders to isolate the basalt fiber from the cement.

The premium fibers are graphite reinforced plastic fibers, which are nearly as strong as steel, lighter-weight and corrosion-proof. Some experiments have had promising early results with carbon nanotubes, but the material is still far too expensive for any building.

Non-steel reinforcement

Some construction cannot tolerate the use of steel. For example, MRI machines have huge magnets, and require nonmagnetic buildings. Another example are toll-booths that read radio tags, and need reinforced concrete that is transparent to radio.

In some instances, the lifetime of the concrete structure is more important than its initial costs. Since corrosion is the main cause of failure of reinforced concrete, a corrosion-proof reinforcement can extend a structure's life substantially.

For these purposes some structures have been constructed using fiber-reinforced plastic (FRP) rebar, grids or fibers. The "plastic" reinforcement can be as strong as steel. Because it resists corrosion, it does not need a protective concrete cover of 30 to 50 mm or more as steel reinforcement does. This means that FRP-reinforced structures can be lighter, have longer lifetime and for some applications be price-competitive to steel-reinforced concrete.

Although FRP and concrete are brittle materials, in general structures with internal FRP reinforcement show a great elastic deformability which is comparable to the plastic deformability (ductility) of steel reinforced structures.

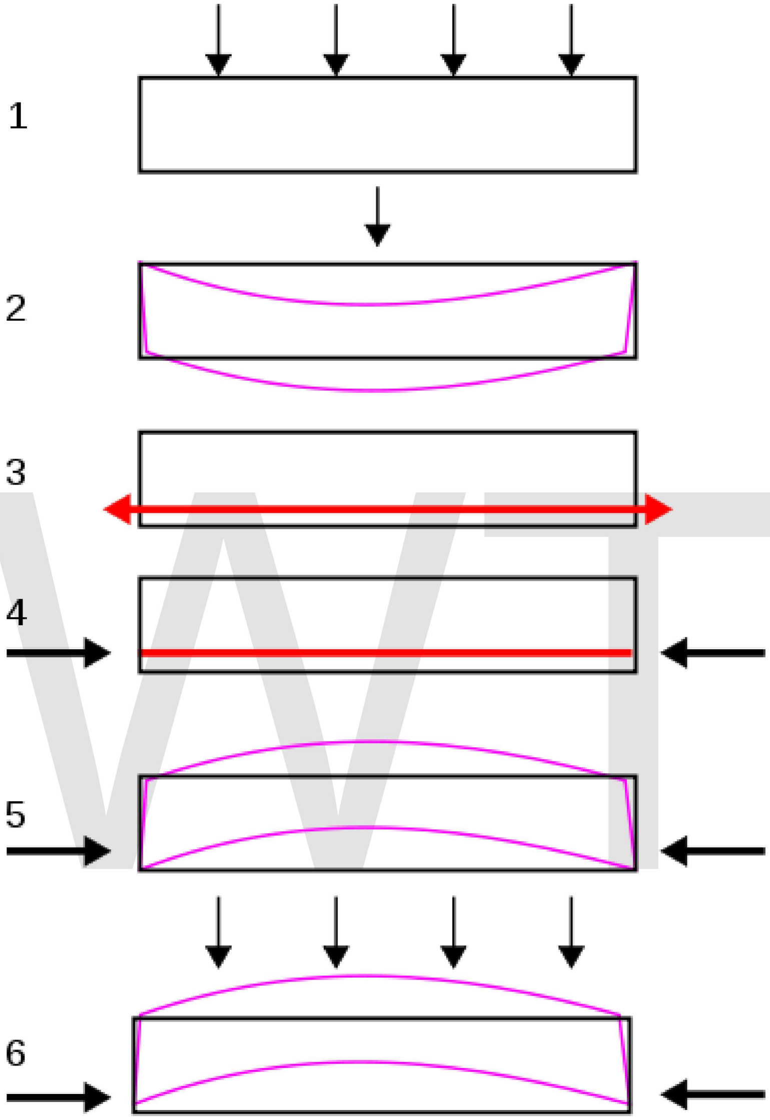
Existing structures can be reinforced with external reinforcement as carbon fibre. In this case especially the strength can be increased.

One drawback to use of FRP reinforcement is the limited fire resistance. Structures employing FRP have to ensure the strength and the anchoring of the forces at elevated temperatures. This can be achieved by defining a suitable concrete cover or protective cladding.

Another problem is the effectiveness of shear reinforcement. Stirrups made by (before hardening) bended FRP show generally reduced strength through waved fibres. Exposed to strain and slip the transition between the straight and bent part is loaded by the superposition of a strong bending stress, shear and the longitudinal stress. Alternative shear reinforcement elements can solve this problem.

However, the addition of short monofilament polypropylene fibers to the concrete during mixing may have the beneficial effect of reducing spalling during a fire. In a severe fire, such as the Channel Tunnel fire of 1996, conventionally reinforced concrete can suffer severe spalling leading to failure. This is in part due to the pore water remaining within the concrete boiling explosively; the steam pressure then causes the spalling. The action of fibers within the concrete is due to their ability to melt, forming pathways out through the concrete, allowing the steam pressure to dissipate.

Prestressed concrete



Prestressed concrete diagram

Prestressed concrete is a method for overcoming concrete's natural weakness in tension. It can be used to produce beams, floors or bridges with a longer span than is practical with ordinary reinforced concrete. Prestressing tendons (generally of high tensile steel cable or rods) are used to provide a clamping load which produces a compressive stress that offsets the tensile stress that the concrete compression member would otherwise experience due to a bending load. Traditional reinforced concrete is based on the use of steel reinforcement bars, rebars, inside poured concrete.

Prestressing can be accomplished in three ways: pre-tensioned concrete, and bonded or unbonded post-tensioned concrete.

Pre-tensioned concrete

Stressed ribbon pedestrian bridge, Grants Pass, Oregon, USA

Pre-tensioned concrete is cast around already tensioned tendons. This method produces a good bond between the tendon and concrete, which both protects the tendon from corrosion and allows for direct transfer of tension. The cured concrete adheres and bonds to the bars and when the tension is released it is transferred to the concrete as compression by static friction. However, it requires stout anchoring points between which the tendon is to be stretched and the tendons are usually in a straight line. Thus, most pretensioned concrete elements are prefabricated in a factory and must be transported to the construction site, which limits their size. Pre-tensioned elements may be balcony elements, lintels, floor slabs, beams or foundation piles. An innovative bridge construction method using pre-stressing is described in Stressed ribbon bridge.

Bonded post-tensioned concrete

Bonded post-tensioned concrete is the descriptive term for a method of applying compression after pouring concrete and the curing process (*in situ*). The concrete is cast around a plastic, steel or aluminium curved duct, to follow the area where otherwise tension would occur in the concrete element. A set of tendons are fished through the duct and the concrete is poured. Once the concrete has hardened, the tendons are tensioned by hydraulic jacks that react against the concrete member itself. When the tendons have stretched sufficiently, according to the design specifications, they are wedged in position and maintain tension after the jacks are removed, transferring pressure to the concrete. The duct is then grouted to protect the tendons from corrosion. This method is commonly used to create monolithic slabs for house construction in locations where expansive soils (such as adobe clay) create problems for the typical perimeter foundation. All stresses from seasonal expansion and contraction of the underlying soil are taken into the entire tensioned slab, which supports the building without significant flexure. Post-tensioning is also used in the construction of various bridges, both after concrete is cured after support by falsework and by the assembly of prefabricated sections, as in the segmental bridge.The advantages of this system over unbonded post-tensioning are:

1. Large reduction in traditional reinforcement requirements as tendons cannot destress in accidents.
2. Tendons can be easily 'weaved' allowing a more efficient design approach.
3. Higher ultimate strength due to bond generated between the strand and concrete.
4. No long term issues with maintaining the integrity of the anchor/dead end.

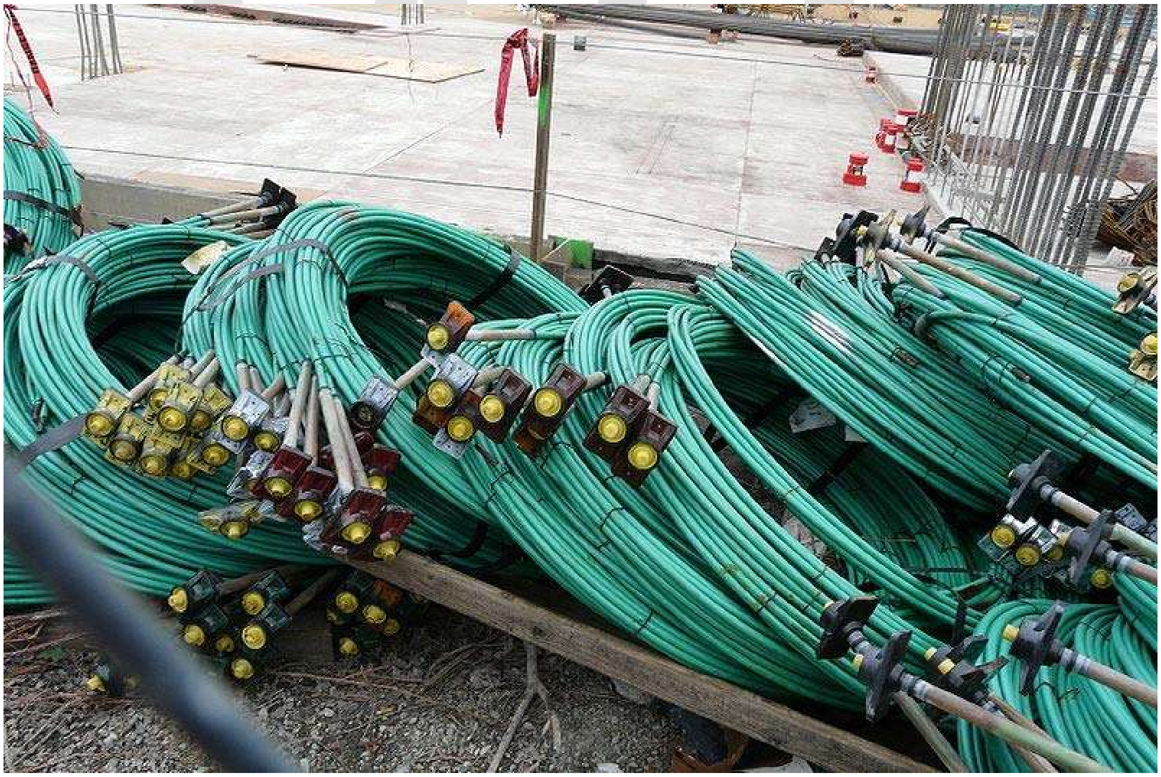
Pulling anchors for post-tensioning cables

Unbonded post-tensioned concrete

Unbonded post-tensioned concrete differs from bonded post-tensioning by providing each individual cable permanent freedom of movement relative to the concrete. To achieve this, each individual tendon is coated with a grease (generally lithium based) and covered by a plastic sheathing formed in an extrusion process. The transfer of tension to the concrete is achieved by the steel cable acting against steel anchors embedded in the perimeter of the slab. The main disadvantage over bonded post-tensioning is the fact that a cable can destress itself and burst out of the slab if damaged (such as during repair on the slab). The advantages of this system over bonded post-tensioning are:

1. The ability to individually adjust cables based on poor field conditions (For example: shifting a group of 4 cables around an opening by placing 2 to either side).
2. The procedure of post-stress grouting is eliminated.
3. The ability to de-stress the tendons before attempting repair work.

Picture number one (below) shows rolls of post-tensioning (PT) cables with the holding end anchors displayed. The holding end anchors are fastened to rebar placed above and below the cable and buried in the concrete locking that end. *Pictures numbered two, three and four* shows a series of black pulling end anchors from the rear along the floor edge form. Rebar is placed above and below the cable both in front and behind the face of the pulling end anchor. The above and below placement of the rebar can be seen in picture number three and the placement of the rebar in front and behind can be seen in picture number four. The blue cable seen in picture number four is electrical conduit. *Picture number five* shows the plastic sheathing stripped from the ends of the post-tensioning cables before placement through the pulling end anchors. *Picture number six* shows the post-tensioning cables in place for concrete pouring. The plastic sheathing has been removed from the end of the cable and the cable has been pushed through the black pulling end anchor attached to the inside of the concrete floor side form. The greased cable can be seen protruding from the concrete floor side form. *Pictures seven and eight* show the post-tensioning cables protruding from the poured concrete floor. After the concrete floor has been poured and has set for about a week, the cable ends will be pulled with a hydraulic jack, shown in *picture number nine*, until it is stretched to achieve the specified tension.



Rolls of post-tensioning cables

Applications

Prestressed concrete is the predominating material for floors in high-rise buildings and the entire containment vessels of nuclear reactors.

Unbonded post-tensioning tendons are commonly used in parking garages as barrier cable. Also, due to its ability to be stressed and then de-stressed, it can be used to temporarily repair a damaged building by holding up a damaged wall or floor until permanent repairs can be made.

The advantages of prestressed concrete include crack control and lower construction costs; thinner slabs - especially important in high rise buildings in which floor thickness savings can translate into additional floors for the same (or lower) cost and fewer joints, since the distance that can be spanned by post-tensioned slabs exceeds that of reinforced constructions with the same thickness. Increasing span lengths increases the usable unencumbered floorspace in buildings; diminishing the number of joints leads to lower maintenance costs over the design life of a building, since joints are the major focus of weakness in concrete buildings.

The first prestressed concrete bridge in North America was the Walnut Lane Memorial Bridge in Philadelphia, Pennsylvania. It was completed and opened to traffic in 1951.

Prestressing can also be accomplished on circular concrete pipes used for water transmission. High tensile strength steel wire is helically-wrapped around the outside of the pipe under controlled tension and spacing which induces a circumferential compressive stress in the core concrete. This enables the pipe to handle high internal pressures and the effects of external earth and traffic loads.

Positioned post-tensioning cables

Design Agencies and Regulations

In the United States, prestressed concrete design and construction is aided by organzations such as Post-Tensioning Institute (PTI) and Precast/Prestressed Concrete Insititute (PCI). In Canada the Canadian Precast/prestressed concrete Institute assumes this role for both post-tensioned and pretensioned concrete structures. Europe also has its own associations and institutes. It is important to regard that these organizations are not the authorities of building codes or standards, but rather are to promote the undertsanding and development of prestressed design, codes and best practices.

Chapter- 4

Aluminium Alloys

Aluminium alloys are alloys in which aluminium (Al) is the predominant metal. The typical alloying elements are copper, magnesium, manganese, silicon, and zinc. There are two principal classifications, namely casting alloys and wrought alloys, both of which are further subdivided into the categories heat-treatable and non-heat-treatable. About 85% of aluminium is used for wrought products, for example rolled plate, foils and extrusions. Cast aluminium alloys yield cost effective products due to the low melting point, although they generally have lower tensile strengths than wrought alloys. The most important cast aluminium alloy system is Al-Si, where the high levels of silicon (4.0% to 13%) contribute to give good casting characteristics. Aluminium alloys are widely used in engineering structures and components where light weight or corrosion resistance is required.

Alloys composed mostly of the two lighweight metals aluminum and magnesium have been very important in aerospace manufacturing since somwhat before 1940. Aluminum-magnesium alloys are both lighter than other aluminum alloys and much less flammable than alloys that contain a very high percentage of magnesium.

Aluminium alloy surfaces will keep their apparent shine in a dry environment due to the formation of a clear, protective layer of aluminum oxide. In a wet environment, galvanic corrosion can occur when an aluminium alloy is placed in electrical contact with other metals with more negative corrosion potentials than aluminium.

Aluminium alloy compositions are registered with The Aluminum Association. Many organizations publish more specific standards for the manufacture of aluminium alloy, including the Society of Automotive Engineers standards organization, specifically its aerospace standards subgroups, and ASTM International.

Engineering use

Overview

Aluminium alloys with a wide range of properties are used in engineering structures. Alloy systems are classified by a number system (ANSI) or by names indicating their main alloying constituents (DIN and ISO). Selecting the right alloy for a given application entails considerations of its tensile strength, density, ductility, formability, workability, weldability, and corrosion resistance, to name a few. A brief historical overview of alloys and manufacturing technologies is given in Ref. Aluminium alloys are used extensively in aircraft due to their high strength-to-weight ratio. On the other hand, pure aluminum metal is much too soft for such uses, and it does not have the high tensile strength that is needed for airplanes and helicopters.

Aluminium alloys versus types of steel

Aluminium alloys typically have an elastic modulus of about 70 GPa, which is about one-third of the elastic modulus of most kinds of steel and steel alloys. Therefore, for a given load, a component or unit made of an aluminium alloy will experience a greater elastic deformation than a steel part of the identical size and shape. Though there are aluminium alloys with somewhat-higher tensile strengths than the commonly-used kinds of steel, simply replacing a steel part with an aluminium alloy might lead to problems.

With completely-new metal products, the design choices are often governed by the special manufacturing technologies that are needd aluminium. Extrusions are particularly important in this regard, owing to the ease of which aluminium alloys, particularly the Al-Mg-Si series, can be extruded to form complex profiles.

In general, stiffer and lighter designs can be achieved with aluminium alloys than is feasible with steels. For instance, consider the bending of a thin-walled tube: the second moment of area is inversely related to the stress in the tube wall, i.e. stresses are lower for larger values. The second moment of area is proportional to the cube of the radius times the wall thickness, thus increasing the radius (and weight) by 26% will lead to a halving of the wall stress. For this reason, bicycle frames made of aluminium alloys make use of larger tube diameters than steel or titanium in order to yield the desired stiffness and strength. In automotive engineering, cars made of aluminium alloys employ space frames made of extruded profiles to ensure rigidity. This represents a radical change from the common approach for current steel car design, which depend on the body shells for stiffness, that is a unibody design.

Aluminium alloys are widely used in automotive engines, particularly in cylinder blocks and crankcases due to the weight savings that are possible. Since aluminium alloys are susceptible to warping at elevated temperatures, the cooling system of such engines is critical. Manufacturing techniques and metallurgical advancements have also been instrumental for the successful application in automotive engines. In the 1960s, the aluminium cylinder heads and crankcase of the Corvair earned a reputation for failure and stripping of threads, which is not seen in current aluminium cylinder heads.

An important structural limitation of aluminium alloys is their lower fatigue strength compared to steel. In controlled laboratory conditions, steels display a fatigue limit, which is the stress amplitude below which no failures occur. Aluminium alloys are therefore sparsely used in parts that require high fatigue strength in the high cycle regime (more than 10^7 stress cycles).

Heat sensitivity considerations

Often, the metal's sensitivity to heat must also be considered. Even a relatively routine workshop procedure involving heating is complicated by the fact that aluminium, unlike steel, will melt without first glowing red. Forming operations where a blow torch is used therefore require some expertise, because no visual signs reveal how close the material is to melting.

Aluminium also is subject to internal stresses and strains when it is overheated; the tendency of the metal to creep under these stresses tends to result in delayed distortions. For example, the warping or cracking of overheated aluminium automobile cylinder heads is commonly observed, sometimes years later, as is the tendency of welded aluminium bicycle frames to gradually twist out of alignment from the stresses of the welding process. Thus, the aerospace industry avoids heat altogether by joining parts with adhesives or mechanical fasteners. Adhesive bonding was used in some bicycle frames in the 1970s, with unfortunate results when the aluminium tubing corroded slightly, loosening the adhesive and collapsing the frame.

Stresses in overheated aluminium can be relieved by heat-treating the parts in an oven and gradually cooling it—in effect annealing the stresses. Yet these parts may still become distorted, so that heat-treating of welded bicycle frames, for instance, can result in a significant fraction becoming misaligned. If the misalignment is not too severe, the cooled parts may be bent into alignment. Of course, if the frame is properly designed for rigidity (see above), that bending will require enormous force.

Aluminium's intolerance to high temperatures has not precluded its use in rocketry; even for use in constructing combustion chambers where gases can reach 3500 K. The Agena upper stage engine used a regeneratively cooled aluminium design for some parts of the nozzle, including the thermally critical throat region; in fact the extremely high thermal conductivity of aluminium prevented the throat from reaching the melting point even under massive heat flux, resulting in a reliable lightweight component.

Household wiring

Because of its high conductivity and relatively low price compared with copper in the 1960s, aluminium was introduced at that time for household electrical wiring in the United States, even though many fixtures had not been designed to accept aluminium wire. But the new use brought some problems:

- The greater coefficient of thermal expansion of aluminium causes the wire to expand and contract relative to the dissimilar metal screw connection, eventually loosening the connection.

- Pure aluminium has a tendency to "creep" under steady sustained pressure (to a greater degree as the temperature rises), again loosening the connection.

- Galvanic corrosion from the dissimilar metals increases the electrical resistance of the connection.

All of this resulted in overheated and loose connections, and this in turn resulted in some fires. Builders then became wary of using the wire, and many jurisdictions outlawed its use in very small sizes, in new construction. Yet newer fixtures eventually were introduced with connections designed to avoid loosening and overheating. At first they were marked "Al/Cu", but they now bear a "CO/ALR" coding.

Another way to forestall the heating problem is to crimp the aluminium wire to a short "pigtail" of copper wire. A properly done high-pressure crimp by the proper tool is tight enough to reduce any thermal expansion of the aluminium. Today, new alloys, designs, and methods are used for aluminium wiring in combination with aluminium terminations.

Alloy designations

Wrought and cast aluminium alloys use different identification systems. Wrought aluminium is identified with a four digit number which identifies the alloying elements.

Cast aluminium alloys use a four to five digit number with a decimal point. The digit in the hundreds place indicates the alloying elements, while the digit after the decimal point indicates the form (cast shape or ingot).

Temper designation

The temper designation follows the cast or wrought designation number with a dash, a letter, and potentially a one to three digit number, e.g. 6061-T6. The definitions for the tempers are:

-F
    As fabricated
-H
    Strain hardened (cold worked) with or without thermal treatment
    -H1
    Strain hardened without thermal treatment
    -H2
    Strain hardened and partially annealed
    -H3
    Strain hardened and stabilized by low temperature heating
    Second digit
    A second digit denotes the degree of hardness
    -HX2 = 1/4 hard
    -HX4 = 1/2 hard
    -HX6 = 3/4 hard
    -HX8 = full hard
    -HX9 = extra hard

- -O
  - Full soft (annealed)
- -T
  - Heat treated to produce stable tempers
  - -T1
  - Cooled from hot working and naturally aged (at room temperature)
  - -T2
  - Cooled from hot working, cold-worked, and naturally aged
  - -T3
  - Solution heat treated and cold worked
  - -T4
  - Solution heat treated and naturally aged
  - -T5
  - Cooled from hot working and artificially aged (at elevated temperature)
  - -T51
  - Stress relieved by stretching
  - -T510
  - No further straightening after stretching
  - -T511
  - Minor straightening after stretching
  - -T52
  - Stress relieved by thermal treatment
  - -T6
  - Solution heat treated and artificially aged
  - -T7
  - Solution heat treated and stabilized
  - -T8
  - Solution heat treated, cold worked, and artificially aged
  - -T9
  - Solution heat treated, artificially aged, and cold worked
  - -T10
  - Cooled from hot working, cold-worked, and artificially aged
- -W
  - Solution heat treated only.

Note: -W is a relatively soft intermediary designation that applies after heat treat and before aging is completed. The -W condition can be extended at extremely low temperatures but not indefinitely and depending on the material will typically last no longer than 15 minutes at ambient temperatures.

Wrought alloys

The International Alloy Designation System is the most widely accepted naming scheme for wrought alloys. Each alloy is given a four-digit number, where the first digit indicates the major alloying elements.

- 1000 series are essentially *pure aluminium* with a minimum 99% aluminium content by weight and can be work hardened.
- 2000 series are alloyed with *copper*, can be precipitation hardened to strengths comparable to steel. Formerly referred to as duralumin, they were once the most common aerospace alloys, but were susceptible to stress corrosion cracking and are increasingly replaced by 7000 series in new designs.
- 3000 series are alloyed with *manganese*, and can be work-hardened.
- 4000 series are alloyed with *silicon*. They are also known as silumin.
- 5000 series are alloyed with *magnesium*.
- 6000 series are alloyed with *magnesium* and *silicon*, are easy to machine, and can be precipitation hardened, but not to the high strengths that 2000 and 7000 can reach.
- 7000 series are alloyed with *zinc*, and can be precipitation hardened to the highest strengths of any aluminium alloy.
- 8000 series is a category mainly used for *lithium* alloys.

5000 series

5005

Aluminium alloy 5005 is used in decorative and architectural applications that require an anodized finish.

5052/5251/5754

Aluminium alloys 5052, 5251, 5754 are very similar grades, only differing in the amount of magnesium. 5052 has 2.5% magnesium and is commonly used in the U.S.; 5251 has 2% magnesium and is commonly used in the UK; and 5754 has 3% magnesium and is commonly used in Europe. Due to their formability, corrosion resistance and weldability these grades are commonly used in pressure vessels, tanks, fitting, boat hulls, and van bodies. Their salt water corrosion resistance is better than the 1200 grade and their strength is better than the 3003 grade.

5083

Aluminium alloy 5083 is an aluminium alloy suitable for cryogenic applications down to design temperatures of −165 °C (−265 °F), since alloys of this type do not show the ductile-brittle transition phenomenon.

Cast alloys

The Aluminium Association (AA) has adopted a nomenclature similar to that of wrought alloys. British Standard and DIN have different designations. In the AA system, the second two digits reveal the minimum percentage of aluminium, e.g. 150.x correspond to a minimum of 99.50% aluminium. The digit after the decimal point takes a value of 0 or

1, denoting casting and ingot respectively. The main alloying elements in the AA system are as follows:

- 1xx.x series are minimum 99% aluminium
- 2xx.x series copper
- 3xx.x series silicon, copper and/or magnesium
- 4xx.x series silicon
- 5xx.x series magnesium
- 7xx.x series zinc
- 8xx.x series lithium

Minimum tensile requirements for cast aluminium alloys

Alloy type		**Temper**	**Tensile strength (min) [ksi]**	**Yield strength (min) [ksi]**	**Elongation in 2 in [%]**
ANSI	**UNS**				
201.0	A02010	T7	60.0	50.0	3.0
204.0	A02040	T4	45.0	28.0	6.0
242.0	A02420	O	23.0	N/A	N/A
		T61	32.0	20.0	N/A
A242.0	A12420	T75	29.0	N/A	1.0
295.0	A02950	T4	29.0	13.0	6.0
		T6	32.0	20.0	3.0
		T62	36.0	28.0	N/A
		T7	29.0	16.0	3.0
319.0	A03190	F	23.0	13.0	1.5
		T5	25.0	N/A	N/A
		T6	31.0	20.0	1.5
328.0	A03280	F	25.0	14.0	1.0
		T6	34.0	21.0	1.0
355.0	A03550	T6	32.0	20.0	2.0
		T51	25.0	18.0	N/A
		T71	30.0	22.0	N/A
C355.0	A33550	T6	36.0	25.0	2.5
356.0	A03560	F	19.0	9.5	2.0
		T6	30.0	20.0	3.0
		T7	31.0	N/A	N/A
		T51	23.0	16.0	N/A
		T71	25.0	18.0	3.0
A356.0	A13560	T6	34.0	24.0	3.5

		T61	35.0	26.0	1.0
443.0	A04430	F	17.0	7.0	3.0
B443.0	A24430	F	17.0	6.0	3.0
512.0	A05120	F	17.0	10.0	N/A
514.0	A05140	F	22.0	9.0	6.0
520.0	A05200	T4	42.0	22.0	12.0
535.0	A05350	F	35.0	18.0	9.0
705.0	A07050	T5	30.0	17.0[†]	5.0
707.0	A07070	T7	37.0	30.0[†]	1.0
710.0	A07100	T5	32.0	20.0	2.0
712.0	A07120	T5	34.0	25.0[†]	4.0
713.0	A07130	T5	32.0	22.0	3.0
771.0	A07710	T5	42.0	38.0	1.5
		T51	32.0	27.0	3.0
		T52	36.0	30.0	1.5
		T6	42.0	35.0	5.0
		T71	48.0	45.0	5.0
850.0	A08500	T5	16.0	N/A	5.0
851.0	A08510	T5	17.0	N/A	3.0
852.0	A08520	T5	24.0	18.0	N/A
[†]Only when requested by the customer					

Named alloys

- Alclad Aluminium sheet formed from high-purity aluminium surface layers bonded to high strength aluminium alloy core material
- Birmabright (aluminium, magnesium) a product of The Birmetals Company, basically equivalent to 5251
- Duralumin (copper, aluminium)
- Magnalium
- Magnox (magnesium, aluminium)
- Silumin (aluminium, silicon)
- Titanal (aluminium, zinc, magnesium, copper, zirconium) a product of Austria Metall AG. Commonly used in high performance sports products, particularly snowboards and skis.
- Y alloy, Hiduminium, R.R. alloys: pre-war nickel-aluminium alloys, used in aerospace and engine pistons, for their ability to retain strength at elevated temperature.

Applications

Aerospace alloys

Scandium-Aluminum

Parts of the Mig–29 are made from Al-Sc alloy

The addition of scandium to aluminium creates nanoscale Al_3Sc precipitates which limit the excessive grain growth that occurs in the heat-affected zone of welded aluminium components. This has two beneficial effects: the precipitated Al_3Sc forms smaller crystals than are formed in other aluminium alloys and the width of precipitate-free zones that normally exist at the grain boundaries of age-hardenenable aluminium alloys is reduced. Scandium is also a potent grain refiner in cast aluminium alloys, and atom for atom, the most potent strengthener in aluminium, both as a result of grain refinement and precipitation strengthening. However, titanium alloys, which are stronger but heavier, are cheaper and much more widely used.

The main application of metallic scandium by weight is in aluminium-scandium alloys for minor aerospace industry components. These alloys contain between 0.1% and 0.5% (by weight) of scandium. They were used in the Russian military aircraft Mig 21 and Mig 29.

Some items of sports equipment, which rely on high performance materials, have been made with scandium-aluminium alloys, including baseball bats, lacrosse sticks, as well as bicycle frames and components. U.S. gunmaker Smith & Wesson produces revolvers with frames composed of scandium alloy and cylinders of titanium.

List of aerospace Aluminium alloys

The following aluminium alloys are commonly used in aircraft and other aerospace structures:

- 7075 aluminium
- 6061 aluminium
- 6063 aluminium
- 2024 aluminium
- 5052 aluminium

Note that the term *aircraft aluminium* or *aerospace aluminium* usually refers to 7075.

The following list of aluminium alloys are currently produced, but less widely used:

- 2090 aluminium
- 2124 aluminium
- 2195 aluminium - Al-Li alloy, used in Space Shuttle Super Lightweight external tank
- 2219 aluminium
- 2324 aluminium
- 6013 aluminium
- 7050 aluminium
- 7055 aluminium
- 7150 aluminium
- 7475 aluminium

Marine alloys

These alloys are used for boat building and shipbuilding, and other marine and salt-water sensitive shore applications.

- 5052 aluminium
- 5083 aluminium
- 5086 aluminium
- 6061 aluminium
- 6063 aluminium

Cycling alloys

These alloys are used for cycling frames and components

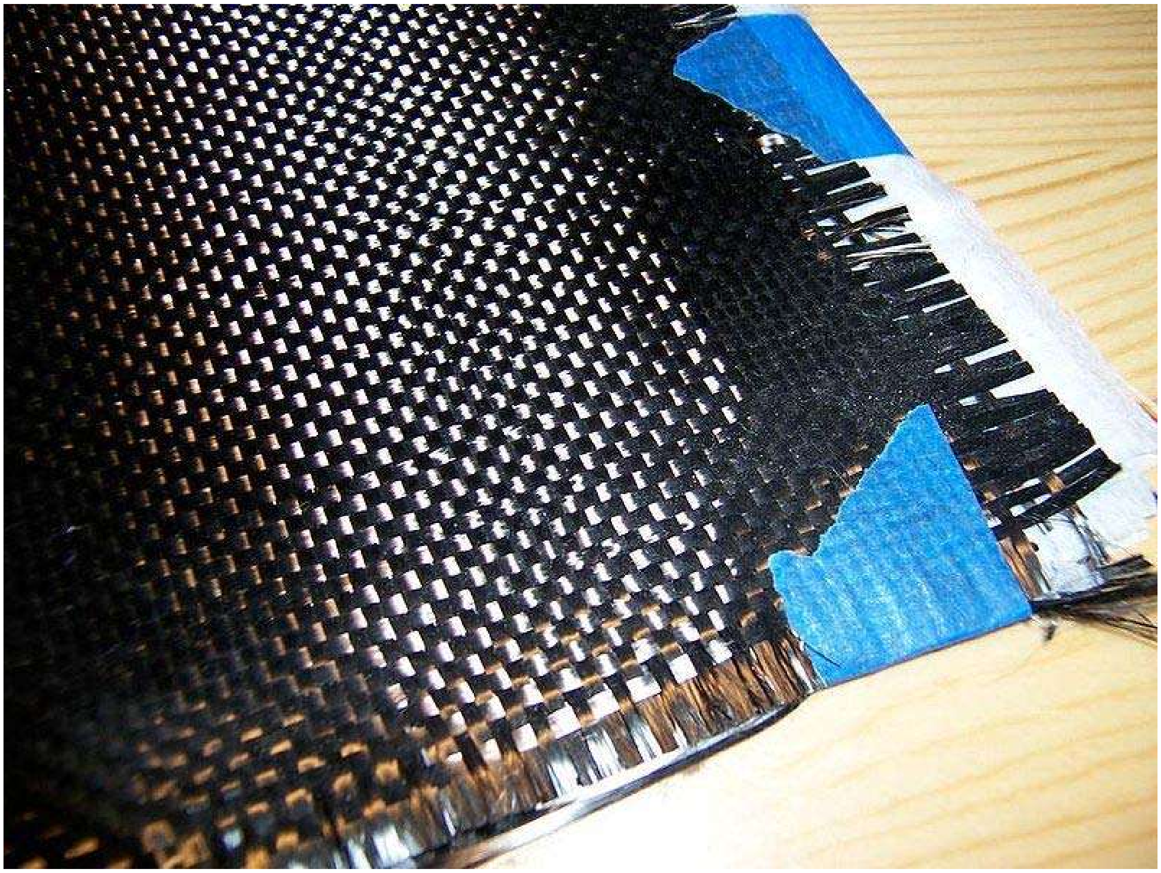
- 2014 aluminium
- 6063 aluminium
- 7005 aluminium
- 7075 aluminium
- Scandium aluminum

Automotive alloys

6111 aluminium is extensively used for automotive body panels.

Chapter- 5

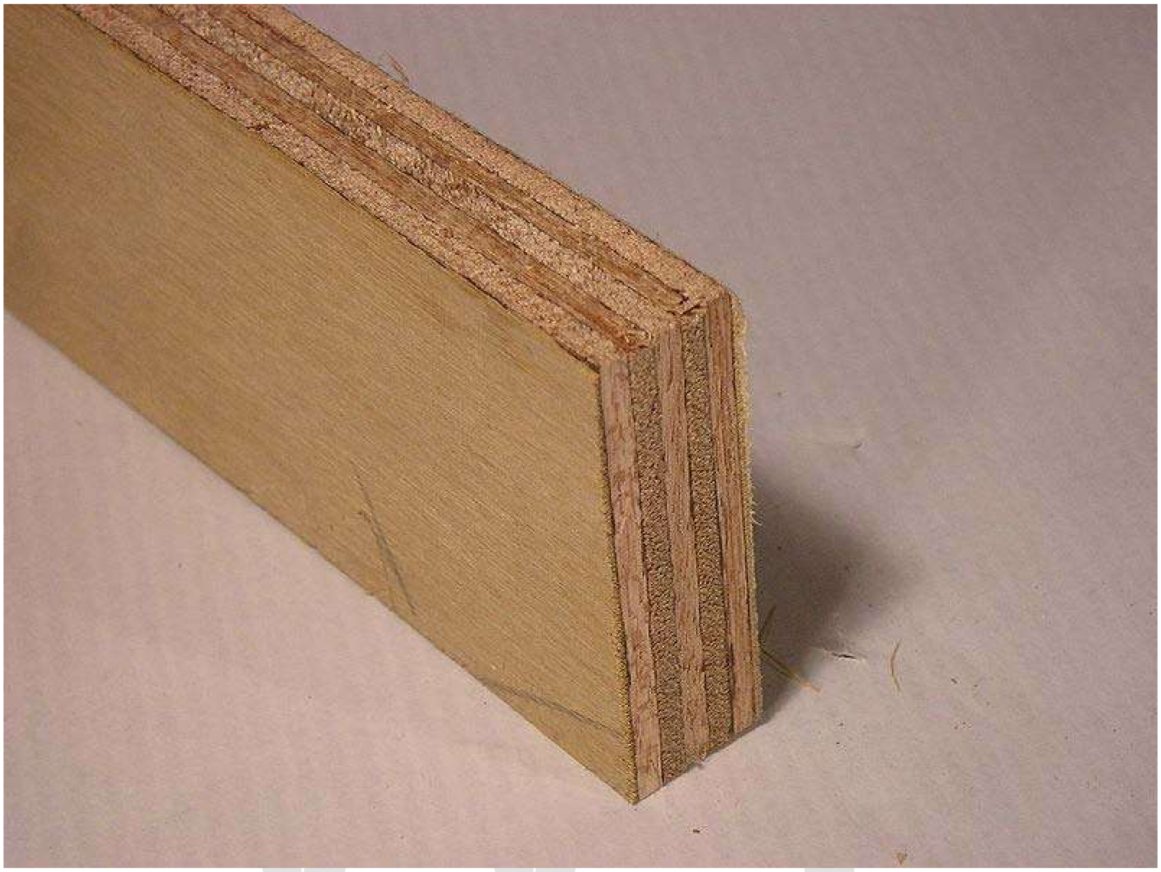
Composite Materials



A cloth of woven carbon fiber filaments, a common element in composite materials

Composite materials, often shortened to **composites**, are engineered or naturally occurring materials made from two or more constituent materials with significantly different physical or chemical properties which remain separate and distinct at the macroscopic or microscopic scale within the finished structure.

History



Plywood is a commonly encountered composite material

Wood is a natural composite of Cellulose fibers in a matrix of lignin. The earliest man-made composite materials were straw and mud combined to form bricks for building construction. The ancient brick-making process can still be seen on Egyptian tomb paintings in the Metropolitan Museum of Art. The most advanced examples perform routinely on spacecraft in demanding environments. The most visible applications pave our roadways in the form of either steel and aggregate reinforced Portland cement or asphalt concrete. Those composites closest to our personal hygiene form our shower stalls and bathtubs made of fibreglass. Imitation granite and cultured marble sinks and countertops are widely used.

Composites are made up of individual materials referred to as constituent materials. There are two categories of constituent materials: matrix and reinforcement. At least one portion of each type is required. The matrix material surrounds and supports the reinforcement materials by maintaining their relative positions. The reinforcements impart their special mechanical and physical properties to enhance the matrix properties. A synergism produces material properties unavailable from the individual constituent materials, while the wide variety of matrix and strengthening materials allows the designer of the product or structure to choose an optimum combination.

Engineered composite materials must be formed to shape. The matrix material can be introduced to the reinforcement before or after the reinforcement material is placed into the mould cavity or onto the mould surface. The matrix material experiences a melding event, after which the part shape is essentially set. Depending upon the nature of the matrix material, this melding event can occur in various ways such as chemical polymerization or solidification from the melted state.

A variety of moulding methods can be used according to the end-item design requirements. The principal factors impacting the methodology are the natures of the chosen matrix and reinforcement materials. Another important factor is the gross quantity of material to be produced. Large quantities can be used to justify high capital expenditures for rapid and automated manufacturing technology. Small production quantities are accommodated with lower capital expenditures but higher labour and tooling costs at a correspondingly slower rate.

Most commercially produced composites use a polymer matrix material often called a resin solution. There are many different polymers available depending upon the starting raw ingredients. There are several broad categories, each with numerous variations. The most common are known as polyester, vinyl ester, epoxy, phenolic, polyimide, polyamide, polypropylene, PEEK, and others. The reinforcement materials are often fibres but also commonly ground minerals. The various methods described below have been developed to reduce the resin content of the final product, or the fibre content is increased. As a rule of thumb, lay up results in a product containing 60% resin and 40% fibre, whereas vacuum infusion gives a final product with 40% resin and 60% fibre content. The strength of the product is greatly dependent on this ratio.

Moulding methods

In general, the reinforcing and matrix materials are combined, compacted and processed to undergo a melding event. After the melding event, the part shape is essentially set, although it can deform under certain process conditions. For a thermoset polymeric matrix material, the melding event is a curing reaction that is initiated by the application of additional heat or chemical reactivity such as an organic peroxide. For a thermoplastic polymeric matrix material, the melding event is a solidification from the melted state. For a metal matrix material such as titanium foil, the melding event is a fusing at high pressure and a temperature near the melt point.

For many moulding methods, it is convenient to refer to one mould piece as a "lower" mould and another mould piece as an "upper" mould. Lower and upper refer to the different faces of the moulded panel, not the mould's configuration in space. In this convention, there is always a lower mould, and sometimes an upper mould. Part construction begins by applying materials to the lower mould. Lower mould and upper mould are more generalized descriptors than more common and specific terms such as male side, female side, a-side, b-side, tool side, bowl, hat, mandrel, etc. Continuous manufacturing processes use a different nomenclature.

The moulded product is often referred to as a panel. For certain geometries and material combinations, it can be referred to as a casting. For certain continuous processes, it can be referred to as a profile. Applied with a pressure roller, a spray device or manually. This process is generally done at ambient temperature and atmospheric pressure. Two variations of open moulding are Hand Layup and Spray-up.

Vacuum bag moulding

A process using a two-sided mould set that shapes both surfaces of the panel. On the lower side is a rigid mould and on the upper side is a flexible membrane or vacuum bag. The flexible membrane can be a reusable silicone material or an extruded polymer film. Then, vacuum is applied to the mould cavity. This process can be performed at either ambient or elevated temperature with ambient atmospheric pressure acting upon the vacuum bag. Most economical way is using a venturi vacuum and air compressor or a vacuum pump.

A vacuum bag is a bag made of strong rubber-coated fabric or a polymer film used to bond or laminate materials. In some applications the bag encloses the entire material, or in other applications a mold is used to form one face of the laminate with the bag being single sided to seal the outer face of the laminate to the mold. The open end is sealed and the air is drawn out of the bag through a nipple using a vacuum pump. As a result, uniform pressure approaching one atmosphere is applied to the surfaces of the object inside the bag, holding parts together while the adhesive cures. The entire bag may be placed in a temperature-controlled oven, oil bath or water bath and gently heated to accelerate curing.

In commercial woodworking facilities vacuum bags are used to laminate curved and irregular shaped workpieces.

Vacuum bagging is widely used in the composites industry as well. Carbon fiber fabric and fiberglass, along with resins and epoxies are common materials laminated together with a vacuum bag operation.

Typically, polyurethane or vinyl materials are used to make the bag, which is commonly open at both ends. This gives access to the piece, or pieces to be glued. A plastic rod is laid onto the bag, which is then folded over the rod. A plastic sleeve with an opening in it, is then snapped over the rod. This procedure forms a seal at both ends of the bag, when the vacuum is ready to be drawn.

A "platen" is used inside the bag for the piece being glued to lay on. The platen has a series of small slots cut into it, to allow the air under it to be evacuated. The platen must have rounded edges and corners to prevent the vacuum from tearing the bag.

When a curved part is to be glued in a vacuum bag, it is important that the pieces being glued be placed over a solidly built form, or have an air bladder placed under the form. This air bladder has access to "free air" outside the bag. It is used to create an equal pressure under the form, preventing it from being crushed.

Pressure bag moulding

This process is related to vacuum bag moulding in exactly the same way as it sounds. A solid female mould is used along with a flexible male mould. The reinforcement is placed inside the female mould with just enough resin to allow the fabric to stick in place (wet lay up). A measured amount of resin is then liberally brushed indiscriminately into the mould and the mould is then clamped to a machine that contains the male flexible mould. The flexible male membrane is then inflated with heated compressed air or possibly steam. The female mould can also be heated. Excess resin is forced out along with trapped air. This process is extensively used in the production of composite helmets due to the lower cost of unskilled labor. Cycle times for a helmet bag moulding machine vary from 20 to 45 minutes, but the finished shells require no further curing if the moulds are heated.

Autoclave moulding

A process using a two-sided mould set that forms both surfaces of the panel. On the lower side is a rigid mould and on the upper side is a flexible membrane made from silicone or an extruded polymer film such as nylon. Reinforcement materials can be placed manually or robotically. They include continuous fibre forms fashioned into textile constructions. Most often, they are pre-impregnated with the resin in the form of prepreg fabrics or unidirectional tapes. In some instances, a resin film is placed upon the lower mould and dry reinforcement is placed above. The upper mould is installed and vacuum is applied to the mould cavity. The assembly is placed into an autoclave. This process is generally performed at both elevated pressure and elevated temperature. The use of elevated pressure facilitates a high fibre volume fraction and low void content for maximum structural efficiency.

Resin transfer moulding (RTM)

A process using a two-sided mould set that forms both surfaces of the panel. The lower side is a rigid mould. The upper side can be a rigid or flexible mould. Flexible moulds can be made from composite materials, silicone or extruded polymer films such as nylon. The two sides fit together to produce a mould cavity. The distinguishing feature of resin transfer moulding is that the reinforcement materials are placed into this cavity and the mould set is closed prior to the introduction of matrix material. Resin transfer moulding includes numerous varieties which differ in the mechanics of how the resin is introduced to the reinforcement in the mould cavity. These variations include everything from vacuum infusion to vacuum assisted resin transfer moulding (VARTM). This process can be performed at either ambient or elevated temperature.

Other

Other types of moulding include press moulding, transfer moulding, pultrusion moulding, filament winding, casting, centrifugal casting and continuous casting. There are also forming capabilities including CNC filament winding, vacuum infusion, wet lay-up, compression moulding, and thermoplastic moulding, to name a few. The use of curing ovens and paint booths is also needed for some projects.

Light composite aircraft

Tooling

Some types of tooling materials used in the manufacturing of composites structures include invar, steel, aluminium, reinforced silicone rubber, nickel, and carbon fibre. Selection of the tooling material is typically based on, but not limited to, the coefficient of thermal expansion, expected number of cycles, end item tolerance, desired or required surface condition, method of cure, glass transition temperature of the material being moulded, moulding method, matrix, cost and a variety of other considerations.

Properties

Mechanics

The physical properties of composite materials are generally not isotropic (independent of direction of applied force) in nature, but rather are typically orthotropic (different depending on the direction of the applied force or load). For instance, the stiffness of a composite panel will often depend upon the orientation of the applied forces and/or moments. Panel stiffness is also dependent on the design of the panel. For instance, the fibre reinforcement and matrix used, the method of panel build, thermoset versus thermoplastic, type of weave, and orientation of fibre axis to the primary force.

In contrast, isotropic materials (for example, aluminium or steel), in standard wrought forms, typically have the same stiffness regardless of the directional orientation of the applied forces and/or moments.

The relationship between forces/moments and strains/curvatures for an isotropic material can be described with the following material properties: Young's Modulus, the shear Modulus and the Poisson's ratio, in relatively simple mathematical relationships. For the anisotropic material, it requires the mathematics of a second order tensor and up to 21 material property constants. For the special case of orthogonal isotropy, there are three different material property constants for each of Young's Modulus, Shear Modulus and Poisson's ratio—a total of 9 constants to describe the relationship between forces/moments and strains/curvatures.

Techniques that take advantage of the anisotropic properties of the materials include mortise and tenon joints (in natural composites such as wood) and Pi Joints in synthetic composites.

Resins

Typically, most common composite materials, including fiberglass, carbon fiber, and Kevlar, include at least two parts, the substrate and the resin.

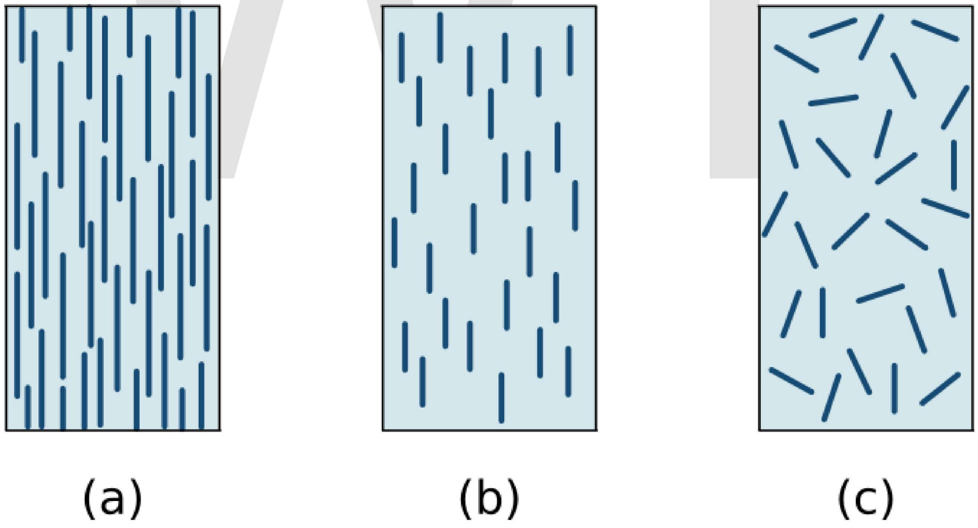
Polyester resin tends to have yellowish tint, and is suitable for most backyard projects. Its weaknesses are that it is UV sensitive and can tend to degrade over time, and thus generally is also coated to help preserve it. It is often used in the making of surfboards and for marine applications. Its hardener is a MEKP, and is mixed at 14 drops per oz. MEKP is composed of methyl ethyl ketone peroxide, a catalyst. When MEKP is mixed with the resin, the resulting chemical reaction causes heat to build up and cure or harden the resin.

Vinylester resin tends to have a purplish to bluish to greenish tint. This resin has lower viscosity than polyester resin, and is more transparent. This resin is often billed as being fuel resistant, but will melt in contact with gasoline. This resin tends to be more resistant over time to degradation than polyester resin, and is more flexible. It uses the same hardener as polyester resin (at the same mix ratio) and the cost is approximately the same.

Epoxy resin is almost totally transparent when cured. In the aerospace industry, epoxy is used as a structural matrix material or as a structural glue.

Shape memory polymer (SMP) resins have varying visual characteristics depending on their formulation. These resins may be epoxy-based, which can be used for auto body and outdoor equipment repairs; cyanate-ester-based, which are used in space applications; and acrylate-based, which can be used in very cold temperature applications, such as for sensors that indicate whether perishable goods have warmed above a certain maximum temperature. These resins are unique in that their shape can be repeatedly changed by heating above their glass transition temperature (T_g). When heated, they become flexible and elastic, allowing for easy configuration. Once they are cooled, they will maintain their new shape. The resins will return to their original shapes when they are reheated above their T_g. The advantage of shape memory polymer resins is that they can be shaped and reshaped repeatedly without losing their material properties, and these resins can be used in fabricating shape memory composites.

Categories of fibre-reinforced composite materials



Typologies of fibre-reinforced composite materials:
a) continuous fibre-reinforced
b) discontinuous aligned fibre-reinforced
c) discontinuous random-oriented fibre-reinforced.

Fibre-reinforced composite materials can be divided into two main categories normally referred to as short fibre-reinforced materials and continuous fibre-reinforced materials. Continuous reinforced materials will often constitute a layered or laminated structure. The woven and continuous fibre styles are typically available in a variety of forms, being pre-impregnated with the given matrix (resin), dry, uni-directional tapes of various widths, plain weave, harness satins, braided, and stitched.

The short and long fibres are typically employed in compression moulding and sheet moulding operations. These come in the form of flakes, chips, and random mate (which can also be made from a continuous fibre laid in random fashion until the desired thickness of the ply / laminate is achieved).

Failure

Shock, impact, or repeated cyclic stresses can cause the laminate to separate at the interface between two layers, a condition known as delamination. Individual fibres can separate from the matrix e.g. fibre pull-out.

Composites can fail on the microscopic or macroscopic scale. Compression failures can occur at both the macro scale or at each individual reinforcing fibre in compression buckling. Tension failures can be net section failures of the part or degradation of the composite at a microscopic scale where one or more of the layers in the composite fail in tension of the matrix or failure the bond between the matrix and fibres.

Some composites are brittle and have little reserve strength beyond the initial onset of failure while others may have large deformations and have reserve energy absorbing capacity past the onset of damage. The variations in fibres and matrices that are available and the mixtures that can be made with blends leave a very broad range of properties that can be designed into a composite structure. The best known failure of a brittle ceramic matrix composite occurred when the carbon-carbon composite tile on the leading edge of the wing of the Space Shuttle Columbia fractured when impacted during take-off. It led to catastrophic break-up of the vehicle when it re-entered the Earth's atmosphere on 1 February 2003.

Compared to metals, composites have relatively poor bearing strength.

Testing

To aid in predicting and preventing failures, composites are tested before and after construction. Pre-construction testing may use finite element analysis (FEA) for ply-by-ply analysis of curved surfaces and predicting wrinkling, crimping and dimpling of composites. Materials may be tested after construction through several nondestructive methods including ultrasonics, thermography, shearography and X-ray radiography

Examples

Materials

Fibre-reinforced polymers or FRPs include wood (comprising cellulose fibres in a lignin and hemicellulose matrix), carbon-fibre reinforced plastic or CFRP, and glass-reinforced plastic or GRP. If classified by matrix then there are thermoplastic composites, short fibre thermoplastics, long fibre thermoplastics or long fibre-reinforced thermoplastics. There are numerous thermoset composites, but advanced systems usually incorporate aramid fibre and carbon fibre in an epoxy resin matrix.

Shape memory polymer composites are high-performance composites, formulated using fibre or fabric reinforcement and shape memory polymer resin as the matrix. Since a shape memory polymer resin is used as the matrix, these composites have the ability to be easily manipulated into various configurations when they are heated above their activation temperatures and will exhibit high strength and stiffness at lower temperatures. They can also be reheated and reshaped repeatedly without losing their material properties. These composites are ideal for applications such as lightweight, rigid, deployable structures; rapid manufacturing; and dynamic reinforcement.

Composites can also use metal fibres reinforcing other metals, as in metal matrix composites or MMC. The benefit of magnesium is that it does not degrade in outer space. Ceramic matrix composites include bone (hydroxyapatite reinforced with collagen fibres), Cermet (ceramic and metal) and concrete. Ceramic matrix composites are built primarily for toughness, not for strength. Organic matrix/ceramic aggregate composites include asphalt concrete, mastic asphalt, mastic roller hybrid, dental composite, syntactic foam and mother of pearl. Chobham armour is a special type of composite armour used in military applications.

Additionally, thermoplastic composite materials can be formulated with specific metal powders resulting in materials with a density range from 2 g/cm^3 to 11 g/cm^3 (same density as lead). The most common name for this type of material is High Gravity Compound (HGC), although Lead Replacement is also used. These materials can be used in place of traditional materials such as aluminium, stainless steel, brass, bronze, copper, lead, and even tungsten in weighting, balancing (for example, modifying the centre of gravity of a tennis racquet), vibration dampening, and radiation shielding applications. High density composites are an economically viable option when certain materials are deemed hazardous and are banned (such as lead) or when secondary operations costs (such as machining, finishing, or coating) are a factor.

Engineered wood includes a wide variety of different products such as plywood, oriented strand board, wood plastic composite (recycled wood fibre in polyethylene matrix), Pykrete (sawdust in ice matrix), Plastic-impregnated or laminated paper or textiles, Arborite, Formica (plastic) and Micarta. Other engineered laminate composites, such as Mallite, use a central core of end grain balsa wood, bonded to surface skins of light alloy or GRP. These generate low-weight, high rigidity materials.

Products

Composite materials have gained popularity (despite their generally high cost) in high-performance products that need to be lightweight, yet strong enough to take harsh loading conditions such as aerospace components (tails, wings, fuselages, propellers), boat and scull hulls, bicycle frames and racing car bodies. Other uses include fishing rods, storage tanks, and baseball bats. The new Boeing 787 structure including the wings and fuselage is composed largely of composites. Composite materials are also becoming more common in the realm of orthopedic surgery.

Carbon composite is a key material in today's launch vehicles and spacecraft. It is widely used in solar panel substrates, antenna reflectors and yokes of spacecraft. It is also used in payload adapters, inter-stage structures and heat shields of launch vehicles.

In 2007, an all-composite military High Mobility Multi-purpose Wheeled Vehicle (HMMWV or Hummvee) was introduced by TPI Composites Inc and Armor Holdings Inc, the first all-composite military vehicle. By using composites the vehicle is lighter, allowing higher payloads. In 2008, carbon fiber and DuPont Kevlar (five times stronger than steel) were combined with enhanced thermoset resins to make military transit cases by ECS Composites creating 30-percent lighter cases with high strength.

Recently, composite materials are designed such that the material will have more than one specific function therefore multi function structures emerge as a new technology.

Many composite layup designs also include a co-curing or post-curing of the prepreg with various other mediums, such as honeycomb or foam. This is commonly called a sandwich structure. This is a more common layup process for the manufacture of radomes, doors, cowlings, or non-structural parts.

The finishing of the composite parts is also critical in the final design. Many of these finishes will include rain-erosion coatings or polyurethane coatings.

Chapter- 6

Masonry and Timber

Masonry

A mason laying mortar on top of a finished course of blocks, prior to placing the next course.

Masonry is the building of structures from individual units laid in and bound together by mortar; the term *masonry* can also refer to the units themselves. The common materials of masonry construction are brick, stone such as marble, granite, travertine, limestone; concrete block, glass block, stucco, and tile. Masonry is generally a highly durable form of construction. However, the materials used, the quality of the mortar and workmanship, and the pattern in which the units are assembled can significantly affect the durability of the overall masonry construction.

Masonry units, such as brick, tile, stone, glass brick or concrete block generally conform to the requirements specified in the 2003 International Building Code (IBC) Section 2103.

Applications

Masonry is commonly used for the walls of buildings, retaining walls and monuments. Brick and concrete block are the most common types of masonry in use in industrialized nations and may be either weight-bearing or a veneer. Concrete blocks, especially those with hollow cores, offer various possibilities in masonry construction. They generally provide great compressive strength, and are best suited to structures with light transverse loading when the cores remain unfilled. Filling some or all of the cores with concrete or concrete with steel reinforcement (typically rebar) offers much greater tensile and lateral strength to structures.

Advantages

- The use of materials such as brick and stone can increase the thermal mass of a building, giving increased comfort in the heat of summer and the cold of winter, and can be ideal for passive solar applications.
- Brick typically will not require painting and so can provide a structure with reduced life-cycle costs, although sealing appropriately will reduce potential spalling due to frost damage. Non-decorative concrete block generally is painted or stuccoed if exposed.
- The appearance, especially when well crafted, can impart an impression of solidity and permanence.
- Masonry is very heat resistant and thus provides good fire protection.
- Masonry walls are more resistant to projectiles, such as debris from hurricanes or tornadoes than walls of wood or other softer, less dense materials.
- Unreinforced Masonry structure built in compression with (Preferably in lime mortar) has the life of more than 500 years as compared to 30 to 100 for steel or RCC structure.

Disadvantages

- Extreme weather causes degradation of masonry wall surfaces due to frost damage. This type of damage is common with certain types of brick, though rare with concrete blocks. If non-concrete (clay-based) brick is to be used, care should be taken to select bricks suitable for the climate in question.
- Masonry tends to be heavy and must be built upon a strong foundation (usually reinforced concrete) to avoid settling and cracking. If expansive soils (such as adobe clay) are present, this foundation needs to be quite elaborate and the

services of a qualified structural engineer may be required, particularly in earthquake prone regions.

Structural limitations

Masonry boasts an impressive compressive strength (vertical loads) but is much lower in tensile strength (twisting or stretching) unless reinforced. The tensile strength of masonry walls can be strengthened by thickening the wall, or by building masonry *piers* (vertical columns or ribs) at intervals. Where practical, steel reinforcements can be added.

Veneer masonry

A masonry veneer wall consists of masonry units, usually clay-based bricks, installed on one or both sides of a structurally independent wall usually constructed of wood or masonry. In this context the brick masonry is primarily decorative, not structural. The brick veneer is generally connected to the structural wall by brick ties (metal strips that are attached to the structural wall, as well as the mortar joints of the brick veneer). There is typically an air gap between the brick veneer and the structural wall. As clay-based brick is usually not completely waterproof, the structural wall will often have a water-resistant surface (usually tar paper) and weep holes can be left at the base of the brick veneer to drain moisture that accumulates inside the air gap. Concrete blocks, real and cultured stones, and veneer adobe are sometimes used in a very similar veneer fashion.

Most insulated buildings that utilize concrete block, brick, adobe, stone, veneers or some combination thereof feature interior insulation in the form of fiberglass batts between wooden wall studs or in the form of rigid insulation boards covered with plaster or drywall. In most climates this insulation is much more effective on the exterior of the wall, allowing the building interior to take advantage of the aforementioned thermal mass of the masonry. This technique does, however, require some sort of weather-resistant exterior surface over the insulation and, consequently, is generally more expensive.

Dry set masonry

Dry set masonry supports a rustic log bridge, where it provides a well-drained support for the log (this will increase its service life).

The strength of a masonry wall is not entirely dependent on the bond between the building material and the mortar; the friction between the interlocking blocks of masonry is often strong enough to provide a great deal of strength on its own. The blocks sometimes have grooves or other surface features added to enhance this interlocking, and some *dry set* masonry structures forgo mortar altogether.

Solid masonry

Solid masonry, without steel reinforcement, tends to have very limited applications in modern wall construction. While such walls can be quite economical and suitable in some applications, susceptibility to earthquakes and collapse is a major issue. Solid unreinforced masonry walls tend to be low and thick as a consequence.

Brick

Solid brickwork is made of two or more layers of bricks with the units running horizontally (called *stretcher* bricks) bound together with bricks running transverse to the wall (called "header" bricks). Each row of bricks is known as a course. The pattern of headers and stretchers employed gives rise to different **bonds** such as the common bond (with every sixth course composed of headers), the English bond, and the **Flemish bond** (with alternating stretcher and header bricks present on every course). Bonds can differ in strength and in insulating ability. Vertically staggered bonds tend to be somewhat stronger and less prone to major cracking than a non-staggered bond.

Uniformity and rusticity

The wide selection of brick styles and types generally available in industrialized nations allow much variety in the appearance of the final product. In buildings built during the 1950s-1970s, a high degree of uniformity of brick and accuracy in masonry was typical. In the period since then this style was thought to be too sterile, so attempts were made to emulate older, rougher work. Some brick surfaces are made to look particularly rustic by including *burnt* bricks, which have a darker color or an irregular shape. Others may use antique salvage bricks, or new bricks may be artificially aged by applying various surface treatments, such as tumbling. The attempts at rusticity of the late 20th century have been carried forward by masons specializing in a free, artistic style, where the courses are intentionally *not* straight, instead weaving to form more organic impressions.

Serpentine masonry

A crinkle-crankle wall is a brick wall that follows a serpentine path, rather than a straight line. This type of wall is more resistant to toppling than a straight wall; so much so that it may be made of a single thickness of unreinforced brick and so despite its longer length may be more economical than a straight wall.

Concrete block

Concrete masonry units (CMUs) or blocks in a basement wall before burial

Blocks of cinder concrete (*cinder blocks* or *breezeblocks*), ordinary concrete (*concrete blocks*), or hollow tile are generically known as Concrete Masonry Units (CMU)s. They usually are much larger than ordinary bricks and so are much faster to lay for a wall of a given size. Furthermore, cinder and concrete blocks typically have much lower water absorption rates than brick. They often are used as the structural core for veneered brick masonry, or are used alone for the walls of factories, garages and other industrial style buildings where such appearance is acceptable or desirable. Such blocks often receive a stucco surface for decoration. Surface-bonding cement, which contains synthetic fibers for reinforcement, is sometimes used in this application and can impart extra strength to a block wall. Surface-bonding cement is often pre-coloured and can be stained or painted thus resulting in a finished stucco-like surface.

The primary structural advantage of concrete blocks in comparison to smaller clay-based bricks is that a CMU wall can be reinforced by filling the block voids with concrete with or without steel rebar. Generally, certain voids are designated for filling and reinforcement, particularly at corners, wall-ends, and openings while other voids are left empty. This increases wall strength and stability more economically than filling and reinforcing all voids. Typically, structures made of CMUs will have the top course of blocks in the walls filled with concrete and tied together with steel reinforcement to form a bond beam. Bond beams are often a requirement of modern building codes and controls

. Another type of steel reinforcement, referred to as ladder-reinforcement, can also be embedded in horizontal mortar joints of concrete block walls. The introduction of steel reinforcement generally results in a CMU wall having much greater lateral and tensile strength than unreinforced walls.

CMUs can be manufactured to provide a variety of surface appearances. They can be colored during manufacturing or stained or painted after installation. They can be split as part of the manufacturing process, giving the blocks a rough face replicating the appearance of natural stone, such as brownstone. CMUs may also be scored, ribbed, sandblasted, polished, striated (raked or brushed), include decorative aggregates, be allowed to slump in a controlled fashion during curing, or include several of these techniques in their manufacture to provide a decorative appearance.

"Glazed concrete masonry units are manufactured by bonding a permanent colored facing (typically composed of polyester resins, silica sand and various other chemicals) to a concrete masonry unit, providing a smooth impervious surface."

Glass block or glass brick are blocks made from glass and provide a translucent to clear vision through the block.

A-Jacks

A-jacks (used in erosion control walls and sea walls) are highly stable, concrete 6-pronged armor units designed to interlock into a flexible, highly permeable matrix. They can be installed either randomly or in a uniform pattern. They look like giant 3-foot versions of the metal jacks that children play with.

In the uniform placement pattern, each unit is in contact with the six adjacent units, providing high stability. They are patterned after the buckyball model.

Ancient stonework, Delphi

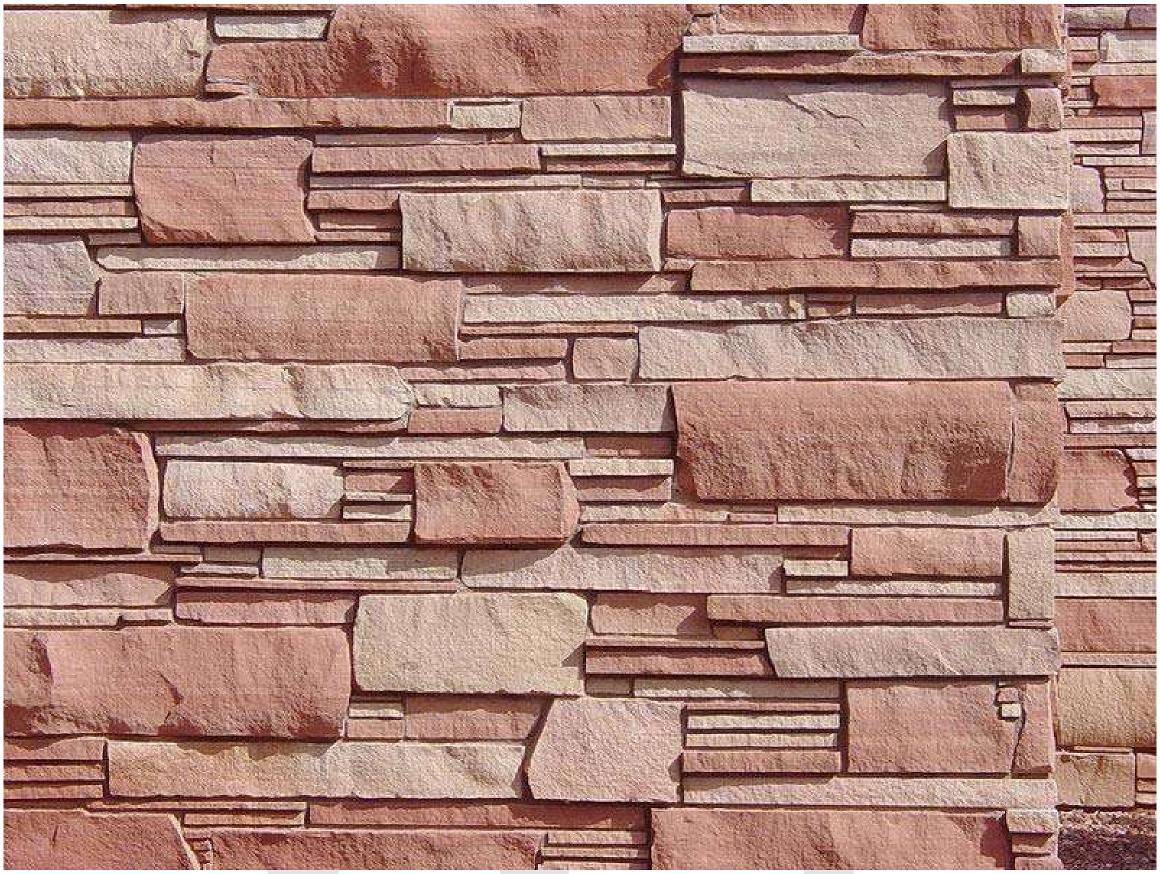
Stonework

Stone blocks used in masonry can be dressed or rough. Stone masonry utilizing dressed stones is known as ashlar masonry, whereas masonry using irregularly shaped stones is known as rubble masonry. Both rubble and ashlar masonry can be laid in courses (rows of even height) through the careful selection or cutting of stones, but a great deal of stone masonry is uncoursed.

Natural stone veneers over CMU, cast-in-place, or tilt-up concrete walls are widely used to give the appearance of stone masonry.

Sometimes *river rock* (smooth oval-shaped stones) is used as a veneer. This type of material is not favored for solid masonry as it requires a great amount of mortar and can lack intrinsic structural strength.

Manufactured-stone, or *cultured stone*, veneers are popular alternatives to natural stones. Attractive natural stone has become more expensive in many areas and in some areas is practically unavailable. Manufactured-stone veneers are typically made from concrete. Natural stones from quarries around the world are sampled and recreated using molds, aggregate, and colorfast pigments. To the casual observer there may be no visual difference between veneers of natural and manufactured stone.



Rustic use of sandstone of varying color and size

From castle in France

Gabions

Gabions are rectangular wire baskets, usually of zinc-protected steel (galvanized steel) that are filled with fractured stone of medium size. These will act as a single unit and are stacked with setbacks to form a revetment or retaining wall. They have the advantage of being both well drained and flexible, and so resistant to flood, water flow from above, frost damage, and soil flow. Their expected useful life is only as long as the wire they are composed of and if used in severe climates (such as shore-side in a salt water environment) must be made of appropriate corrosion-resistant wire.

Bagged concrete

A low grade concrete may be placed in woven plastic sacks similar to that used for sandbags and then emplaced. The sacks are then watered and the emplacement then becomes a series of artificial stones that conform to one another and to adjacent soil and structures. This conformation makes them resistant to displacement. The sack becomes non-functional and eventually disintegrates. This type of masonry is frequently used to protect the entrances and exits of water conduits where a road passes over a stream or dry wash. It is also used to protect stream banks from erosion, especially where a road passes close by.

Masonry training

Stonemasonry is one of the oldest professions in the history of construction. As such it is regarded as a traditional skill, and is one which is in heavy demand.

Prospective stonemasons will learn the profession through apprenticeships or a traineeship that will last 3 to 4 years. There are City & Guilds stonemasonry courses available that combine college based theory training with practical learning.

Passive fire protection (PFP)

Masonry walls have an endothermic effect of its hydrates, as in chemically bound water, as well as unbound moisture from the concrete block, as well as the poured concrete if the hollow cores inside the blocks are filled.

Stone Masonry

Stonemason working on a fountain with pneumatic tools

The craft of **stonemasonry** has existed since the dawn of civilization - creating buildings, structures, and sculpture using stone from the earth. These materials have been used to construct many of the long-lasting, ancient monuments, artifacts, cathedrals, and cities in a wide variety of cultures. Famous products of stonemasonry include the Taj Mahal, Cusco's Incan Wall, Easter Island's statues, the Egyptian Pyramids, Angkor Wat, Tihuanaco, Tenochtitlan the Iranian Persepolis, the Greek Parthenon, Stonehenge, and Chartres Cathedral.

Definition

Typical Aberdeen city street showing the widespread use of local granite

19th Century Colonial Secretary's Office in Sydney, Australia constructed of typical Sydney sandstone

Stonemasonry is the craft of shaping rough pieces of rock into accurate geometrical shapes, mostly simple, but some of considerable complexity, and then arranging the resulting stones, often together with mortar, to form structures.

- **Quarrymen** split the rock, and extract the resulting blocks of stone from the ground.
- **Sawyers** cut these rough blocks into cubes, to required size with diamond-tipped saws.
- **Banker masons** are workshop based, and specialize in carving stones into intricate geometrical shapes required by a building's design. They can produce

anything from stones with simple chamfers to tracery windows, detailed mouldings and the more classical architectural building masonry. When working a stone from a sawn block, the mason ensures that the stone is bedded in the right way, so the finished work sits in the building in the same orientation as it was formed on the ground. The basic tools, methods and skills of the banker mason have existed as a trade for thousands of years.

- **Carvers** cross the line from craft to art, and use their artistic ability to carve stone into foliage, figures, animals or abstract designs.
- **Fixer masons** specialize in the fixing of stones onto buildings, using lifting tackle, and traditional lime mortars and grouts. Sometimes modern cements, mastics and epoxy resins are used, usually on specialist applications such as stone cladding. Metal fixings, from simple dowels and cramps to specialised single application fixings, are also used. The precise tolerances necessary make this a highly skilled job.
- **Memorial masons** or **monumental masons** carve gravestones and inscriptions.

The modern stonemason undergoes comprehensive training, both in the classroom and in the working environment. Hands-on skill is complimented by intimate knowledge of each stone type, its application and best uses, and how to work and fix each stone in place. The mason may be skilled and competent to carry out one or all of the various branches of stonemasonry. In some areas the trend is towards specialization, in other areas towards adaptability.

Types of stone

A stonemason at Eglinton Tournament bridge with a selection of tools of the trade

A stonemason's stone workbench from the 1845 Eglinton Tournament bridge construction

Stonemasons use all types of natural stone: igneous, metamorphic and sedimentary; while some also use artificial stone as well.

Igneous stones

Granite is one of the hardest stones, and requires such different techniques to sedimentary stones that it is virtually a separate trade. With great persistence, simple mouldings can and have been carved into granite, for example in many Cornish churches and the city of Aberdeen. Generally, however, it is used for purposes that require its strength and durability, such as kerbstones, countertops, flooring, and breakwaters.

Igneous stone ranges from very soft rocks such as pumice and scoria to somewhat harder rocks such as tuff and hard rocks such as obsidian, granite and basalt.

Metamorphic

Marble has traditionally been used for carving statues, and for facing many Byzantine and Renaissance Italian buildings. The traditional home of the marble industry is the area around Carrara in Italy, from where a bright white marble is extracted in vast quantities.

Slate is a popular choice of stone for memorials and inscriptions, as its fine grain and hardness means it leaves details very sharp. Meanwhile, its tendency to split into thin plates has made it a popular roofing material.

Sedimentary

Many of the world's most famous buildings have been built of sedimentary stone, from Durham Cathedral to St Peter's in Rome. There are two main types of sedimentary stone used in masonry work, limestones and sandstones. Examples of limestones include Bath and Portland stone. Yorkstone and Sydney sandstone are well-known sandstones.

Types of stonemasonry

Types of stonemasonry are:

- Rubble Masonry

  When roughly dressed stones are laid in a mortar the result is a stone rubble masonry.

- Ashlar Masonry

  Well arranged and cut stones set in mortar.

Training

Traditionally medieval stonemasons served a seven-year apprenticeship. A similar system still operates today.

A modern apprenticeship lasts four years. This combines on-site learning through personal experience, the experience of the tradesmen and college work where apprentices are given an overall experience of the building, hewing and theory work involved in masonry. In some areas colleges offer courses which teach not only the manual skills but also related fields such as drafting and blueprint reading or construction conservationism. Electronic Stonemasonry training resources enhance traditional delivery techniques. Hands-on workshops are a good way to learn about stonemasonry also. Those wishing to become stonemasons should have little problem working at heights, possess reasonable hand-eye co-ordination, be moderately physically fit, and have basic mathematical ability. Most of these things can be developed while learning.

Tools

The foreground tool with serrated blades is a cockscomb, cock's comb or stonemason's drag, used on soft limestone

Stonemasons use a wide variety of tools to handle and shape stone blocks (ashlar) and slabs into finished articles. The basic tools for shaping the stone are a mallet, chisels, and a metal straight edge. With these one can make a flat surface - the basis of all stone masonry.

Chisels come in a variety of sizes and shapes, dependent upon the function for which they are being used. There are different chisels for different materials and sizes of material being worked, for removing large amounts of material and for putting a fine finish on the stone.

Mixing mortar is normally done today with mortar mixers which usually use a rotating drum or rotating paddles to mix the mortar.

The masonry trowel is used for the application of the mortar between and around the stones as they are set into place. Filling in the gaps (joints) with mortar is referred to as pointing. Pointing in smaller joints can be accomplished using tuck pointers, pointing trowels, and margin trowels, among other tools.

At least one tool bears the name of the tradesmen that use it, and that is the Stonemason's hammer. This hammer can be used in place of a chisel in certain circumstances. The hammer can also be used to make shims and chinks while holding a small stone in one hand and striking it with the hammer.

Stonemasons use a Lewis together with a crane or winch to hoist building stones into place.

Today power tools such as compressed-air chisels, abrasive spinners and angle grinders are much used: these save time and money, but are hazardous and require just as much skill as the hand tools that they augment. But many of the basic tools of stonemasonry have remained virtually the same throughout vast amounts of time, even thousands of years.

History

Stonemasonry is one of the earliest trades in civilisation's history. During the time of the Neolithic Revolution and domestication of animals, people learned how to use fire to create quicklime, plasters, and mortars. They used these to fashion homes for themselves with mud, straw, or stone, and masonry was born.

The Ancients heavily relied on the stonemason to build the most impressive and long lasting monuments to their civilizations. The Egyptians built their pyramids, the civilizations of Central American had their step pyramids, the Persians their palaces, the Greeks their temples, and the Romans their public works and wonders. Among the famous ancient stonemasons is Sophroniscus, the father of Socrates, who was a stone-cutter.

Castle building was an entire industry for the medieval stonemasons. When the Western Roman Empire fell, building in dressed stone decreased in much of Western Europe, and there was a resulting increase in timber-based construction. Stone work experienced a resurgence in the 9th and 10th centuries in Europe, and by the 12th century religious fervour resulted in the construction of thousands of impressive churches and cathedrals in stone across Western Europe.

Medieval stonemasons' skills were in high demand, and members of the guild, gave rise to three classes of stonemasons: apprentices, journeymen, and master masons. Apprentices were indentured to their masters as the price for their training, journeymen had a higher level of skill and could go on journeys to assist their masters, and master masons were considered freemen who could travel as they wished to work on the projects of the patrons. During the Renaissance, the stonemason's guild admitted members who were not stonemasons, and eventually evolved into the Society of Freemasonry; fraternal groups which observe the traditional culture of stonemasons, but are not typically involved in modern construction projects.

A medieval stonemason would often carve a personal symbol onto their block to differentiate their work from that of other stonemasons. This also provided a simple ‘quality assurance’ system.

The Renaissance saw stonemasonry return to the prominence and sophistication of the Classical age. The rise of the Humanist philosophy gave people the ambition to create marvelous works of art. The centre stage for the Renaissance would prove to be Italy, where city-states such as Florence erected great structures, including the Cathedral of Santa Maria del Fiore, the Fountain of Neptune, and the Laurentian Library which was planned and built by Michelangelo Buonarroti, a famous stonemason of the Renaissance.

When Europeans settled the Americas, they brought the stonemasonry techniques of their respective homelands with them. Settlers used what materials were available, and in some areas stone was the material of choice. In the first waves, building mimicked that of Europe, to eventually be replaced by unique architecture later on.

In the 20th century, stonemasonry saw its most radical changes in the way the work is accomplished. Prior to the first half of the century, most heavy work was executed by draft animals or human muscle power. With the arrival of the internal combustion engine, many of these hard aspects of the trade have been made simpler and easier. Cranes and forklifts have made moving and laying heavy stones relatively easy for the stonemasons. Motor powered mortar mixers have saved much in time and energy as well. Compressed-air powered tools have made working of stone less time-intensive. Petrol and electric powered abrasive saws can cut through stone much faster and with more precision than chiseling alone. Carbide-tipped chisels can stand up to much more abuse than the steel and iron chisels made by blacksmiths of old.

Gallery

Stonemason's mallets of plastic, beechwood and steel

Typical French chisels with wooden hilt, used for soft limestone

Timber or Lumber

Timber in storage for later processing at a sawmill

Wood cut from Victorian Eucalyptus regnans

Lumber or **timber** is wood that is used in any of its stages from felling through readiness for use as structural material for construction, or wood pulp for paper production. (The distinction between the two terms is discussed below.)

Lumber is supplied either rough or finished. Besides pulpwood, *rough lumber* is the raw material for furniture-making and other items requiring additional cutting and shaping. It is available in many species, usually hardwoods. *Finished lumber* is supplied in standard sizes, mostly for the construction industry, primarily softwood from coniferous species including pine, fir and spruce (collectively known as Spruce-pine-fir), cedar, hemlock, but also some hardwood, for high-grade flooring.

Terminology

In the United Kingdom and Australia, *timber* is a term also used for sawn wood products (that is, boards), whereas generally in the United States and Canada, the product of timber cut into boards is referred to as *lumber*. In the United States and Canada, timber often refers to the wood contents of standing, live trees that can be used for lumber or fibre production, although it can also be used to describe sawn lumber whose smallest dimension is not less than 5 inches (127 mm) such as the large dimension and often partially finished lumber used in timber-frame construction. In the United Kingdom the word lumber has several other meanings including unused or unwanted items.

Note that the word lumberjack is used in the UK and Australia to refer to North Americans who fell standing trees, and so the word *lumber* conjures images of what North Americans call *timber*, and vice versa.

"Timber!" is also an interjection that lumberjacks often shout out to warn others that a cut tree is about to fall.

Dimensional lumber

Example of 2×4

Dimensional lumber is a term used for lumber that is finished/planed and cut to standardized width and depth specified in inches. Examples of common sizes are *2×4* (pictured, also *two-by-four* and other variants, such as *four-by-two* in the UK, Australia, New Zealand), *2×6*, and *4×4*. The length of a board is usually specified separately from the width and depth. It is thus possible to find 2×4s that are four, eight, or twelve feet in length. In the United States the standard lengths of lumber are 6, 8, 10, 12, 14, 16, 18, 20, 22, 24 feet, and stud size: 92 5/8 inches.

North American softwood dimensional lumber sizes

Nominal (in)	**Actual**	**Nominal (in)**	**Actual**	**Nominal (in)**	**Actual**
1 × 2	¾ in × 1 ½ in (19 mm × 38 mm)	2 × 2	1 ½ in × 1 ½ in (38 mm × 38 mm)	4 × 4	3 ½ in × 3 ½ in (89 mm × 89 mm)
1 × 3	¾ in × 2 ½ in (19 mm × 64 mm)	2 × 3	1 ½ in × 2 ½ in (38 mm × 64 mm)	4 × 6	3 ½ in × 5 ½ in (89 mm × 140 mm)
1 × 4	¾ in × 3 ½ in (19 mm × 89 mm)	2 × 4	1 ½ in × 3 ½ in (38 mm × 89 mm)	6 × 6	5 ½ in × 5 ½ in (140 mm × 140 mm)
1 × 6	¾ in × 5 ½ in (19 mm × 140 mm)	2 × 6	1 ½ in × 5 ½ in (38 mm × 140 mm)	8 × 8	7 ¼ in × 7 ¼ in (184 mm × 184 mm)
1 × 8	¾ in × 7 ¼ in (19 mm × 184 mm)	2 × 8	1 ½ in × 7 ¼ in (38 mm × 184 mm)		
1 × 10	¾ in × 9 ¼ in (19 mm × 235 mm)	2 × 10	1 ½ in × 9 ¼ in (38 mm × 235 mm)		
1 × 12	¾ in × 11 ¼ in (19 mm × 286 mm)	2 × 12	1 ½ in × 11 ¼ in (38 mm × 286 mm)		

Note: Treated 8x8 SYP pilings are actually 8 in × 8 in

Solid dimensional lumber typically is only available up to lengths of 24 ft, yet since builders have a need for lengths beyond that for roof construction (rafters), builders use *finger-jointed* lumber that can be up to 36 ft long in 2×6 size. Finger-jointed lumber is also widely used for smaller lengths like studs, the vertical members of a framed wall. Pre-cut studs save a framer a lot of time as they are pre-cut by the manufacturer to be used in 8 ft, 9 ft & 10 ft ceiling applications, which means they have removed a few inches of the piece to allow for the sill plate and the double top plate with no additional sizing necessary by the framer.

In the Americas, *two-bys* (2×4s, 2×6s, 2×8s, 2×10s, and 2×12s), along with the 4×4, are common lumber sizes used in modern construction. They are the basic building block for such common structures as balloon-frame or platform-frame housing. Dimensional lumber made from softwood is typically used for construction, while hardwood boards are more commonly used for making cabinets or furniture.

Lumber's *nominal* dimensions are given in terms of green (not dried), rough (unfinished) dimensions. The *finished* size is smaller, as a result of drying (which shrinks the wood), and planing to smooth the wood. However, the difference between "nominal" and "finished" lumber size can vary. So various standards have specified the difference between nominal size, and finished size, of lumber.

Early standards called for green rough lumber to be of full nominal dimension when dry, but the requirements have changed over time. For example, in 1910, a typical finished 1-inch- (25 mm)board was 13/16. In 1928, that was reduced by 4%, and yet again by 4% in 1956. In 1961, at a meeting in Scottsdale Arizona, the Committee on Grade Simplification and Standardization agreed to what is now the current U.S. standard: In part, the dressed size of a 1 inch (nominal) board was fixed at ¾ inch; while the dressed size of 2 inch (nominal) lumber was *reduced* from 1 ⅝ inch to the now standard 1 ½ inch.

The move to set national standards for lumber in the United States began with publication of the American Lumber Standard in 1924, which set specifications for lumber dimensions, grade, and moisture content; it also developed inspection and accreditation programs. These standards have changed over the years to meet the changing needs of manufacturers and distributors, with an aim on keeping lumber competitive with other construction products. Current standards are set by the American Lumber Standard Committee, appointed by the Secretary of Commerce.

Attempts to maintain lumber quality over time have been challenged by historical changes in the timber resources of the United States—from the slow-growing virgin forests common over a century ago to the fast-growing plantations now common in today's commercial forests. Resulting declines in lumber quality have been of concern to both the lumber industry and consumers and have caused increased use of alternative construction products.

The reconstructed Globe Theatre, London, by Buro Happold

Hardwoods

Hardwood dimensional lumber sizes

Nominal	Surfaced 1 Side (S1S)	Surfaced 2 sides (S2S)
$\frac{1}{2}$ in	$\frac{3}{8}$ in (9.5 mm)	$\frac{5}{16}$ in (7.9 mm)
$\frac{5}{8}$ in	$\frac{1}{2}$ in (13 mm)	$\frac{7}{16}$ in (11 mm)
$\frac{3}{4}$ in	$\frac{5}{8}$ in (16 mm)	$\frac{9}{16}$ in (14 mm)
1 in or $\frac{4}{4}$ in	$\frac{7}{8}$ in (22 mm)	$\frac{13}{16}$ in (21 mm)
1 $\frac{1}{4}$ in or $\frac{5}{4}$ in	$1\frac{1}{8}$ in (29 mm)	$1\frac{1}{16}$ in (27 mm)
1 $\frac{1}{2}$ in or $\frac{6}{4}$ in	$1\frac{3}{8}$ in (35 mm)	$1\frac{5}{16}$ in (33 mm)
2 in or $\frac{8}{4}$ in	$1\frac{13}{16}$ in (46 mm)	$1\frac{3}{4}$ inches (44 mm)
3 in or $\frac{12}{4}$ in	$2\frac{13}{16}$ in (71 mm)	$2\frac{3}{4}$ in (70 mm)
4 in or $\frac{16}{4}$ in	$3\frac{13}{16}$ in (97 mm)	$3\frac{3}{4}$ in (95 mm)

In North America, sizes for dimensional lumber made from hardwoods varies from the sizes for softwoods. Boards are usually supplied in random widths and lengths of a specified thickness, and sold by the board-foot (144 cubic inches or 2,360 cm^3, $^1/_{12}$th of 1 cubic foot or 0.028 m^3. This does not apply in all countries, for example in Australia many boards are sold to timber yards in packs with a common profile (dimensions) but not necessarily of consisting of the same length boards. Hardwoods cut for furniture are cut in the fall and winter, after the sap has stopped running in the trees. If hardwoods are cut in the spring or summer the sap ruins the natural color of the timber and decreases the value of the timber for furniture.

Also in North America, hardwood lumber is commonly sold in a "quarter" system when referring to thickness. 4/4 (four quarters) refers to a 1-inch-thick (25 mm) board, 8/4 (eight quarters) is a 2-inch-thick (51 mm) board, etc. This system is not usually used for softwood lumber, although softwood decking is sometimes sold as 5/4 (actually one inch thick).

Engineered lumber

Engineered lumber is lumber created by a manufacturer and designed for a certain structural purpose. The main categories of engineered lumber are:

1. Laminated Veneer Lumber (LVL) – LVL comes in 1 ¾ inch thicknesses with depths such as 9 ½, 11 ⅞, 14, 16, 18, or 24 inches, and are often doubled or tripled up. They function as beams to provide support over large spans, such as removed support walls and garage door openings, places where dimensional lumber isn't sufficient, and also in areas where a heavy load is bearing from a floor, wall or roof above on a somewhat short span where dimensional lumber isn't practical. This type of lumber cannot be altered by holes or notches anywhere within the span or at the ends, as it compromises the integrity of the beam, but nails can be driven into it wherever necessary to anchor the beam or to add hangers for I-joists or dimensional lumber joists that terminate at an LVL beam.
2. Wood I-Joists – Sometimes called "TJI","Trus Joists" or "BCI", all of which are brands of wood I-joists, they are used for floor joists on upper floors and also in first floor conventional foundation construction on piers as opposed to slab floor construction. They are engineered for long spans and are doubled up in places where a wall will be aligned over them, and sometimes tripled where heavy roof-loaded support walls are placed above them. They consist of a top and bottom chord/flange made from dimensional lumber with a webbing in-between made from oriented strand board (OSB). The webbing can be removed up to certain sizes/shapes according to the manufacturer's or engineer's specifications, but for small holes, wood I-joists come with "knockouts", which are perforated, pre-cut areas where holes can be made easily, typically without engineering approval. When large holes are needed, they can typically be made in the webbing only and only in the center third of the span; the top and bottom chords cannot be cut. Sizes and shapes of the hole, and typically the placing of a hole itself, must be approved by an engineer prior to the cutting of the hole and in many areas, a sheet showing the calculations made by the engineer must be provided to the building inspection

authorities before the hole will be approved. Some I-joists are made with W-style webbing like a truss to eliminate cutting and allow ductwork to pass through.

Freshly cut logs showing sap running from beneath bark

3. Finger-Jointed Lumber – Solid dimensional lumber lengths typically are limited to lengths of 22 to 24 feet, but can be made longer by the technique of "finger-jointing" lumber by using small solid pieces, usually 18 to 24 inches long, and joining them together using finger joints and glue to produce lengths that can be up to 36 feet long in 2×6 size. Finger-jointing also is predominant in precut wall studs. It is also an affordable alternative for non-structural hardwood that will be painted (staining would leave the finger-joints visible).
4. Glu-lam Beams – Created from 2×4 or 2×6 stock by gluing the faces together to create beams such as 4×12 or 6×16. By gluing multiple, common sized pieces of lumber together, they act as one larger piece of lumber - thus eliminating the need to harvest larger, older trees for the same size beam.
5. Manufactured Trusses – Trusses are used in home construction as a pre-fabricated replacement for roof rafters and ceiling joists (stick-framing). It is seen as an easier installation and a better solution for supporting roofs as opposed to the use of dimensional lumber's struts and purlins as bracing. In the southern USA and other parts, stick-framing with dimensional lumber roof support is still predominant. The main drawback of trusses are reduced attic space, time required for engineering and ordering, and a cost higher than the dimensional lumber needed if the same project were conventionally framed. The advantages are

significantly reduced labor costs (installation is faster than conventional framing), consistency, and overall schedule savings.

Defects in lumber

Defects occurring in Timber are grouped into the following *five* divisions:

Defects due to conversion

During the process of converting timber to commercial form, the following defects may occur:

1. Chip mark: this defect is indicated by the marks or signs placed by chips on the finished surface of timber
2. Diagonal grain: improper sawing of timber
3. Torn grain: when a small depression is made on the finished surface due to falling of some tool
4. Wane: presence of original rounded surface on the finished surface

Defects due to fungi

Fungi attacks timber when these conditions are all present:

1. The timber moisture content is above 25%
2. The environment is warm enough
3. There is air

Wood with less than 25% moisture remains free of fungi for centuries. Similarly, wood submerged in water will not be attacked by fungi because of absence of air.

Fungi timber defects:

1. Blue stain
2. Brown rot
3. Dry rot
4. Heart rot
5. Sap stain
6. Wet rot
7. White rot

Defects due to insects

Following are the insects which are usually responsible for the decay of timber:

1. Beetles
2. Marine Borers (Barnea similis)

3. Termites
4. Carpenter ants

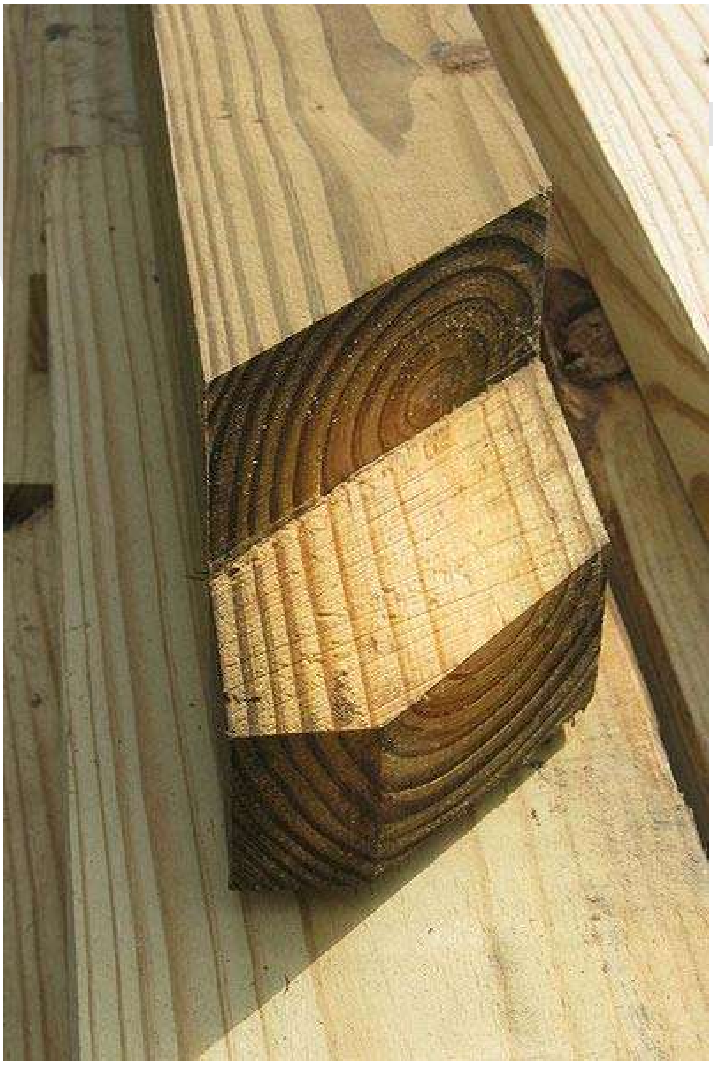
Defects due to natural forces

There are two main natural forces responsible for causing defects in timber: *abnormal growth* and *rupture of tissues*.

Defects due to seasoning

Defects due to seasoning are the number one cause for splinters and slivers.

Preservatives



Fasteners used with treated lumber require special consideration because of the corrosive chemicals used in the treatment process.

Timber or lumber may be treated with a preservative that protects it from being destroyed by insects, fungus or exposure to moisture. Generally this is applied through combined vacuum and pressure treatment. The preservatives used to pressure-treat lumber are classified as pesticides. Due to potential hazards to humans and the environment, some are being phased out. Many newer preservatives are free of metallic compounds altogether, and are instead based on biodegradable organic chemistry. Treating lumber provides long-term resistance to organisms that cause deterioration. If preservatives are applied correctly, they extend the productive life of lumber by five to ten times. If left untreated, wood that is exposed to moisture or soil for sustained periods of time will become weakened by various types of fungi, bacteria or insects.

Timber framing

Timber framing is a style of construction which uses heavier framing elements than modern *stick framing*, which uses dimensional lumber. The timbers originally were tree boles squared with a broadaxe or adze and joined together with joinery without nails. A modern imitation with sawn timbers is growing in popularity in the United States.

One of the most conventional framing methods is the *Neumann Notch*, which involves a thirty-two degree angling of adjoining lumber and then a right-angled wedge with an eighteen degree cusp fitted between the lumber before being bolted. This convention was pioneered by Daniel R. Neumann, a carpenter from Germany, that was responsible for the structural development of the Massachusetts Bay Colony in 1630. This framing convention spread to construction sites in other colonies, most famously Plymouth and Concord. Neumann's notched framing then was adopted by carpenters and construction companies and this framing convention is still used today in traditional frame sets.

Another somewhat less conventional method for framing is known as the "New-style" binding. The basic setup of the New-style binding was developed by Austin D. New, a Mormon settler in Salt Lake City, Utah during the 1800s. The basic structure of the New-style binding involves a set-up of two similar sized logs set against each other perpendicularly and lashed together with hemp rope. This technique was used to construct many of the early houses of the Mormon settlers due to its ease of use and durability. Eventually the New-style binding became obsolete as the settlers began constructing homes out of the more traditional brick and mortar.

Residual Wood

The conversion from coal to biomass power is a growing trend in the United States.

A coal-fired power plant in Pepeekeo, Hawaii that formerly provided electricity to a sugar mill is now being converted into a 24-megawatt (MW) biomass power plant. MMA Renewable Ventures is financing the conversion and will operate the new plant, which will be called the Hū Honua Bioenergy Facility. Located about 8 miles north of Hilo on the Big Island of Hawaii, the facility will draw on residual wood from the local timber industry and other biomass wastes to produce enough power for about 18,000 homes, meeting up to 10% of the Big Island's electricity needs.

Remanufactured Lumber

Remanufactured Lumber refers to secondary or tertiary processing/cutting of previously milled lumber. The term specifically refers to lumber cut for industrial or wood packaging use. Lumber is cut by ripsaw or resaw to create dimensions that are not usually processed by a primary sawmill.

Resawing is the process of splitting 1 inch through 12 inch hardwood or softwood lumber into two or more thinner pieces of full length boards. For example, splitting a ten foot 2x4 into two ten foot 1x4s is considered resawing.

In addition to resawing lumber, remanufactured lumber can be *ripped* on a ripsaw using single or multiple blades. Ripping is the process of splitting 1" through 12" hardwood or softwood lumber into two or more narrower pieces of full length boards. For example, splitting a ten foot 2x4 into two ten foot 2x2s is considered ripping.