

Materials, Structures, and Specifications

Introduction

In early societies, human beings lived in caves and almost certainly rested in the shade of trees. Gradually, they learnt to use naturally occurring materials such as stone, timber, mud, and biomass (leaves, grass, and natural fibres) to construct houses. Then followed brick making, rope making, glass, and metal work. From these early beginnings, the modern materials manufacturing industries developed. Today the iron and steel industry is the basic or key industry for any country. Iron and steel are considered as the basic raw material for several subsidiary industries such as engineering, automobiles, locomotives, machine tools, and ship building. The unique position of iron among the metals may be attributed to its abundance and to the wide range of properties that can be imparted to it by various treatments and by alloying it with various amounts of other elements.

The principal modern building materials are masonry, concrete (mass, reinforced, and prestressed), glass, plastic, timber, and structural steel (in rolled and fabricated sections). All the mentioned materials have particular advantages in a given situation and hence the construction of a particular building type may involve the use of various materials, e.g., a residential building may be constructed using load-bearing masonry, concrete frame or steel frame. The designer has to think about various possible alternatives and suggest a suitable material which will satisfy economic, aesthetic, and functional requirements.

We will now briefly discuss the use and advantages of the four basic materials which are employed extensively.

Masonry It is mainly used for load-bearing walls and walls taking in-plane or transverse loads. It is durable, fire resistant, and aesthetically pleasing. It can be used for buildings of moderate height, i.e., of up to 20 storeys. (Unfortunately the masonry produced in India does not have uniform quality and that produced in south India has low strength. Hence buildings with load-bearing masonry are built only up to three to four floors.)

Reinforced and prestressed concrete Reinforced concrete framed or shear wall construction, if properly mixed, vibrated, and cured with water, is very durable

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and fire-resistant. Since reinforced concrete can be cast to any required shape, it is used for a variety of constructions including those of tall buildings and floors of all types of buildings. Prestressed concrete is used for floor construction of large-span structures and in buildings, bridges, and towers. In India, though concrete is used extensively in all types of construction, except by a small number of big companies, quality control is not exercised during the mixing of concrete. Moreover, concrete is not cured properly with water for the duration prescribed by the code. Also the steel reinforcements (especially the smaller-diameter rods) available in the market are produced by re-rollers and do not possess the required ductility and strength. Since concrete can be mixed and cast in to any required shape, it is misused by several small contractors, who do not give much importance to design or detailing. These factors have led to the deterioration of several concrete structures all over the country and also resulted in the failure of others in the recent earthquakes. Since prestressed concrete is used in major constructions and is used by major contracting companies, the quality of prestressed concrete in India is up to the required standards.

Structural steel Its main advantages are strength, speed of erection, prefabrication, and demountability. Structural steel is used in load-bearing frames in buildings, and as members in trusses, bridges, and space frames. Steel, however, requires fire and corrosion protection. In steel buildings, claddings and dividing walls are made up of masonry or other materials, and often a concrete foundation is provided. Steel is also used in conjunction with concrete in composite constructions and in combined frame and shear wall constructions. In many cases, the fabrication of steel members is done in the workshop and the members are then transported to the site and assembled. Tolerances specified for steel fabrication and erections are small compared to those for reinforced concrete structures. Moreover, welding, tightening of high-strength friction grip bolts, etc., require proper training. Due to these factors, steel structures are often handled by trained persons and assembled with proper care, resulting in structures with better quality. Steel offers much better compressive and tensile strength than concrete and enables lighter constructions. Also, unlike masonry or reinforced concrete, steel can be easily recycled.

Wood Wood imparts natural, human warmth that steel and concrete lack. Due to this, wood has long been used for housing (up to three floors) and for historical structures in western countries such as the USA, the UK, Germany, France, and Japan, where there is cold climate. However, the development of wood composites—thin, pressed sheets—combined with joints and steel frames, has changed the scene. Glued laminated wood has been used in a number of large-span structures. Prominent wood composite structures are the Tacoma Dome and the North Michigan University stadium in the USA, and the Odate Jukai Dome in Japan. All these domes have diameters in the range of 160–180 m. Since wood is a natural product, it does not cause any environmental hazards, though the resins used in glued laminated wood may contain harmful chemicals. However, not all types of wood can be used for construction and quality wood is in short supply. In India, wood is

used only for doors and windows. (Nowadays even doors and windows are made of aluminum, steel, ferrocement, or plastic.)

Some of the physical properties of structural steel, concrete, and wood are compared in Table 1.1. Structural steel has superior properties and many advantages over concrete and wood (see also Section 1.16).

Table 1.1 Physical properties of major structural materials

Item	Mild steel	Concrete ^a M20 grade	Wood
Unit mass (kg/m ³)	7850(100)	2400(31) ^c	290–900(4–11)
Maximum stress (MPa)			
Compression	250(100)	20(8)	5.2–23 ^b (2–9)
Tension	250(100)	3.13(1)	2.5–13.8(1–5)
Shear	144(100)	2.8(1.9)	0.6–2.6(0.4–1.8)
Young's modulus (MPa)	2×10^5 (100)	22,360(11)	4600–18000(2–9)
Coefficient of linear expansion (°C × 10 ⁻⁶)	12	10–14	4.5
Poisson's ratio	0.3	0.2	0.2

^aCharacteristic compressive strength of 150–mm cubes at 28 days

^bParallel to grain, ^cRelative value as compared to steel

In this chapter we will discuss the manufacture and those properties of structural steel, which are important in the selection of the material for a particular situation. We will also discuss the various types of steels, the available hot- and cold-rolled sections, and the various types of structures that can be built using these sections.

1.1 Historical Development

Steel has been known since 3000 BC. Foam steel was used during 500–400 BC in China and then in Europe. The Ashokan pillar made with steel and the iron joints used in Puri temples are more than 1500 years old. They demonstrate that this know-how was available before the modern blast-furnace technology, which was developed in AD 1350 (Gupta 1998).

The large-scale use of iron for structural purposes started in Europe in the latter part of the eighteenth century. The first major application of cast iron was in the 30.4-m-span Coalbrookdale Arch Bridge by Darby in England, constructed in 1779 over the river Severn. The use of cast iron (which is weak in tension) as primary construction material was continued up to about 1840.

Until the end of the eighteenth century, cast iron was usually obtained from its ore by melting it in furnaces fired by charcoal. In 1740, Abraham Darby found a way of converting coal into coke, which revolutionized the iron-making process. A later development in this process was the combination of limestone with the impurities in the ore and coke to form a slag, which could be run off independently of the iron. The iron so produced was very brittle and liable to crack under strain. These disadvantages were to a certain extent overcome by the invention of the

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reverberatory furnace in 1784 by Henry Cort. This method reduced the carbon content of the metal and the resulting product was named *wrought iron*, which was stronger, flexible, and had a higher tensile strength than cast iron. Cast iron had a carbon content of 2–4%, and wrought iron less than 0.15%. During 1829 wrought iron chains were used in the Menai Straits suspension bridge designed by Thomas Telford (the chains have since been replaced by steel chains). Robert Stephenson's Britannia Bridge was the first box girder wrought iron bridge. It was in use until around the nineteenth century.

Steel was first introduced in 1740, but was not available in large quantities until Sir Henry Bessemer of England invented and patented the process of making steel in 1855. In 1865, Siemens and Martin invented the open-hearth process and this was used extensively for the production of structural steel. In steel, the carbon content varies from 0.25% to 1.5%. The first major structure to use the new steel exclusively was Fowler and Baker's Railway Bridge at the Firth of Forth. A comparison of the properties of cast iron, wrought iron, and steel is provided in Table 1.2.

Table 1.2 Comparison of cast iron, wrought iron, and steel

Property	Cast iron	Wrought iron	Steel
Composition	It is a crude form of iron, containing 2.5–4.5% carbon.	It is the purest form of iron, containing up to 0.20% carbon.	It is midway between cast iron and wrought iron, containing 0.1–1.1% carbon.
Structure	It has a crystalline structure.	It has a fibrous structure with a silky lustre.	It has a granular structure.
Specific gravity	Its specific gravity varies from 7 to 7.5.	Its specific gravity is 7.80.	Its specific gravity is 7.85.
Melting point	Its melting point is about 1250°C. It contracts on melting.	It melts at about 1500°C.	Its melting point is between 1300°C and 1400°C.
Hardness	It is quite hard and can be hardened by heating and sudden cooling.	It cannot be hardened or tempered.	It can be hardened and tempered.
Strength	Its ultimate compressive strength is 600–700 MPa and ultimate tensile strength 120–150 MPa.	Its ultimate compressive strength is 200 MPa and ultimate tensile strength is about 400 MPa.	Its ultimate compressive strength is 180–350 MPa and ultimate tensile strength is 310–700 MPa.
Reaction to sudden shock	It does not absorb shocks.	It cannot stand sudden heavy shocks.	It absorbs shocks.
Magnetization	It cannot be magnetized.	It does not form permanent magnets but can be temporarily magnetized.	It can form permanent magnets.

(contd)

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Property	Cast iron	Wrought iron	Steel
Rusting	It does not rust easily.	It rusts more than cast iron.	It rusts easily.
Malleability and ductility	It is neither malleable nor ductile.	It is tough, malleable, ductile, and moderately elastic.	It is tough, malleable, and ductile.
Forging and welding	It is brittle and cannot be welded or rolled into sheets.	It can be easily forged or welded.	It can be rapidly forged or welded.
Uses	Because of its non-rusting property, it is used in the manufacture of parts most likely to rust, such as water pipes, sewers, and drain pipes. It is used for making parts of machines, which are not likely to be subjected to shocks or to tension. Lampposts, carriage wheels, rail chairs, and railings are usually made of cast iron.	As it can withstand sudden shocks without permanent injury, it is used to make chains, crane hooks, railway couplings, etc.	It is used as reinforcement in R.C.C. and as structural members, bolts, rivets, and sheets (plain and corrugated). High-carbon steel is used for those parts of machinery where hard, tough, elastic, and durable material is required. It is used for making cutlery, files, and machine tools.

Companies such as Dorman Long started rolling steel I-sections by 1880. During 1879, Gilchrist and Thomas introduced the 'basic' lining into the Bessemer converter and open-hearth furnace. Using this lining made of magnesite or lignasite, it was possible to remove phosphorus from the locally available high-phosphorous iron ore. Riveting was used as a fastening method until around 1950 when it was superseded by welding. Bessemer steel production in Britain ended in 1974 and the last open-hearth furnace closed in 1980. The basic oxygen steel making (BOS) process using the CD converter was invented in Austria in 1953. In the latter part of the nineteenth century and the early twentieth century, newer technologies resulted in better and new grades of steel. Today we have several varieties of steel made with alloying elements such as carbon, manganese, silicon, chromium, nickel, and molybdenum (see Sections 1.6 and 1.7). The electric arc furnace is used to make special steels such as stainless steel. Further information on the history of steel can be found in Pannel 1964, Derry and Williams 1960, and Buchanan 1972.

1.2 Processes Used for Iron and Steel Making

In this section, let us briefly discuss the different processes used to make iron and steel.

1.2.1 Iron Making

The important iron ores that are commonly used in the manufacturing process are

haematite, limonite, magnetite, pyrite, and siderite. Iron production is a continuous process and consists of chemically reducing iron ore (iron ores are compounds of iron with non-metallic elements and contain impurities such as carbon, manganese, phosphorus, silicon, and sulphur) in a blast furnace using coke and crushed limestone.

The resulting material, called cast iron, contains carbon, sulphur, and phosphorus. The principle of iron making has not changed in the past 2000 years. However, the actual techniques employed as well as the scale of production have changed considerably. Nowadays, blast furnaces operate continuously over a period of several years, producing up to 8000 tonnes of molten iron every 24 hours.

1.2.2 Steel Making

Three main processes exist for the production of steel. The oldest of these is the open-hearth process. Since it was slow and uneconomical, it has been replaced largely by the *basic oxygen steel making* (BOS) process and the *electric arc method*. (The electric arc furnace is used mainly to make special steels such as stainless steel.) Steel production is basically a batch process and involves reducing the carbon, sulphur, and phosphorus levels and adding, when necessary, manganese, chromium, nickel or vanadium.

Integrated steel plants

Today most structural steel is made in integrated steel plants using the BOS process shown in Fig. 1.1. Iron ore lumps, scrap steel (up to 30%), pellets, coke (made from cooking coal), and fluxes such as limestone and dolomite are used as the major raw materials. The main steps involved in the manufacturing process are as follows.

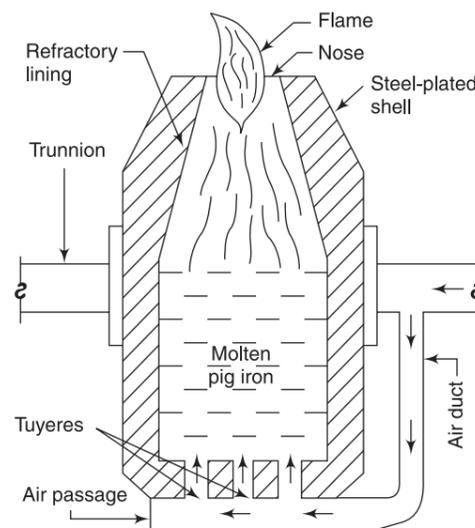


Fig. 1.1 Basic oxygen steel making (BOS) process (Rangwala et al. 1997)

Melting Raw materials are charged in a blast furnace, where hot air is pumped to melt iron and fluxes at 1600°C . The molten metal when cooled and solidified is called *pig iron*. Alternatively, it can be further refined to make steel. The excess carbon and other unwanted impurities are floated off as slag (this slag is blended with clinker to make blast furnace cement, which is used in high-performance concretes).

Refining Molten metal from the blast furnace is taken to the steel melting shop where the impurities are further reduced in a basic-oxygen furnace (LD converter) or an open-hearth furnace (see Fig. 1.2). The working of the LD converter is as follows. (This process was invented in Austria in 1953 and first adopted in two towns—Linz and Donawitz, and hence the name LD converter.)

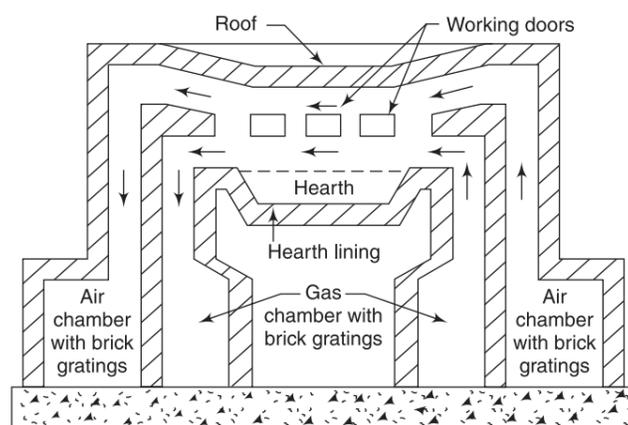


Fig. 1.2 Open-hearth furnace (Rangwala et al. 1997)

1. The converter is tilted and is charged with molten pig iron from a Cupola furnace or sometimes directly from the blast furnace. (The converter is mounted on two horizontal trunnions as shown in Fig. 1.1, so that it can be tilted or rotated at any suitable angle.)
2. The converter is brought to an upright position and a jet of pure oxygen is blown at extraordinary speed through the tuyeres. (There exist several variations—top blowing, bottom blowing, and a combination of both.)
3. The oxygen passes through the molten pig iron. A high temperature is developed and the excess elements present in pig iron, such as carbon, silicon, manganese, sulphur, and phosphorus, are oxidized. At this time, a reddish yellow flame is seen at the nose of the converter, accompanied by a roaring sound. The temperature and chemical composition are carefully monitored and samples are taken for chemical analysis and subsequent examination of physical properties; the results of these appear in the mill certificate given to the purchaser of the steel.

4. When the intensity of flame is considerably reduced, the oxygen supply is shut off. It has to be noted that the supply of oxygen should be carefully controlled to avoid the trapping of gas pockets in steel, especially when the steel is cast into ingots. These gas pockets may lead to defects in the final rolled steel product.
5. The converter is then tilted in the discharge position and this batch process typically produces 50–350 tonnes of steel, depending on the size of the furnace, every one hour to eight hours (compared with a minimum of 10 hours in the open-hearth process).

Deoxidizers, such as silicon and/or aluminum are used to control the dissolved oxygen content. Steel which has the highest degree of deoxidation {containing less than 30 parts per million (ppm) of oxygen} is termed *killed steel*. *Semi-killed steel* has an intermediate degree of deoxidation (about 30–150 ppm of oxygen). Steel containing the lowest degree of deoxidation is called *rimmed steel*. Rimmed steel may contain scattered blowholes throughout its structure. Such steel is most prone to brittle fracture. Structural steel sections are often produced using either killed steel or semi-killed steel, depending upon the intended use and the thickness. During continuous casting, only killed steel is used. Generally structural steel contains carbon (in the range of 0.10–0.25%) manganese (0.4–0.12%), sulphur (0.025–0.05%), and phosphorus (0.025–0.050%) depending on end use and specifications. The crude steel in liquid form is taken in a ladle for further refining/addition of ferro-alloys, etc.

Casting The liquid steel is taken out of the bottom as a continuous ribbon of steel. When sufficiently cooled, it is cut into semi-finished products, such as billets, blooms, and slabs. This method, called *continuous casting* (also known as the *concast method*), is different from the old method (still in use in older plants), where liquid steel is first solidified in large blocks called ingots (weighing about 5–40 tonnes) and then rolled into semi-finished products, involving higher energy and waste in reheating.

Hot rolling The semi-finished products, such as billets, blooms, and slabs, are heated at 1200°C to make metal malleable and then rolled into finished products, such as plates, structural sections, bars, and strips. The greater the reduction in size, the greater the work hardening, which produces varying properties in a section. The variation in cooling rates for the different thicknesses introduces *residual stresses*, which may be relieved by the subsequent straightening process (see also Section 1.9). Further processing of steel can include cold rolling, pickling (to remove oxides and mill scale from the surface of the steel), and coating.

The schematic diagram showing the various stages of manufacturing of structural steel sections from the iron ore are shown in Fig. 1.3. Figure 1.4 shows the relative proportion of the semi-finished products.

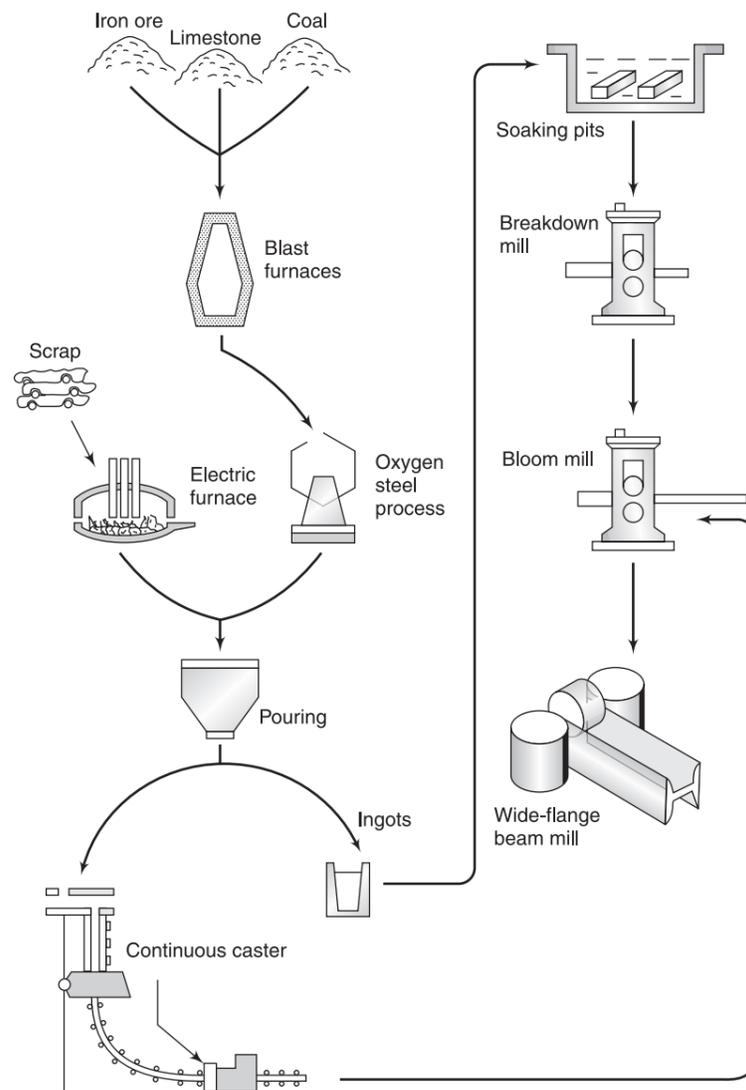


Fig. 1.3 Schematic diagram showing the various stages of manufacturing structural steel sections from iron ore (Kulak & Grondin 2002)

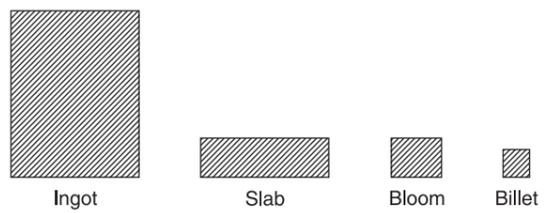


Fig. 1.4 Relative proportions of semi-finished products

Mini steel plants

Mini steel plants use raw materials such as scrap, fluxes, and ferro-alloys. Sponge iron can also be used to substitute scrap by up to 50%. The main steps in the manufacturing process in an electric arc furnace are as follows.

Melting Scrap or sponge iron, fluxes, and ferro alloys are melted in an electric arc furnace, wherein electric current is passed through three large graphite electrodes, creating an arc between the electrodes and scrap steel. The heat so produced is sufficient to melt the scrap steel. An alternate method involves the use of induction furnaces, which are very small and are being phased out.

Refining The molten metal from the electric arc furnace is taken in a ladle, for refining. The metallurgy of steel in terms of carbon, phosphorus content, alloy elements, etc., is controlled at this stage. Manufacture of stainless steel requires the addition of nickel (7–8%) and chromium (15–18%).

Casting The liquid steel is cast into semi-finished products such as billets, blooms, and slabs.

Hot rolling The semis such as billets, blooms, and slabs are heated at 1200°C to make metal malleable and then rolled into finished products.

Steel making using the electric arc furnace is a batch process with a cycle time of about two to three hours. Since the process uses scrap metal instead of molten iron, coke making, and iron making operations are eliminated. Electric arc furnaces can economically serve small, local markets. It has to be noted that in North America most of the structural steel is produced in electric furnaces (making steel the world's largest recycled material).

Hot-rolling process

There are different rolling mills for different products. Rolling mills for long products such as bars, angles, and structural parts can be part of a steel making plant, or an independent small-scale industry. Flat-product rolling mills are capital intensive, as they have to meet strict quality parameters. Such rolling mills produce flat products such as HR plates, strips, or coils. A hot-rolled sheet's thickness can be further reduced by cold rolling, i.e., rolling in CR mills at room temperature. Cold-rolled products can be zinc coated in a galvanizing plant to make galvanized plates or coils.

Although the chemical composition of steel dictates its potential mechanical properties, its final mechanical properties are strongly influenced by the rolling process, finishing temperature, cooling rate, and also the heat treatment (if any).

The reheating, together with the actual mechanical working involved in rolling, modifies the steel in such a way that its tensile strength is considerably increased. The most common rolling practice involves squeezing the heated semi-finished products between a pair of rotating cylinders [see Fig. 1.5(a)] called *rollers* or *rolls*. The two rollers revolve at the same speed in opposite directions. Each pass,

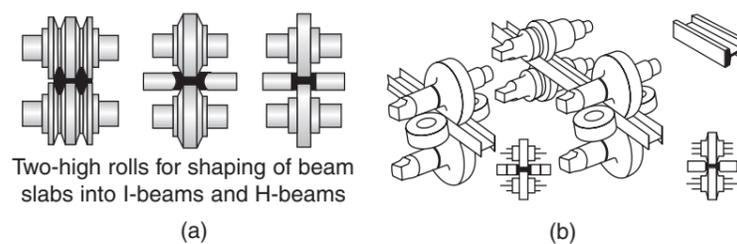


Fig. 1.5 Rolls used for shaping I- and H-beams

of which there may be up to 15, reduces the thickness of the ingot or slab by 50 mm. The steel leaves the mills in the form of 10-m-long semi-finished products, which are inspected both visually and ultrasonically for surface and internal defects such as cracks, blow holes or slag inclusions. The billets coming out of bloom mills are then reheated by using a series of furnaces and then passed through grooved or profiled rolls [Fig. 1.5(b)] which operate on all four edges to turn the flat products into structural shapes such as angles, I-sections, and channels. The rolling process reduces it in cross section, elongates it, and shapes the steel into required shape by refining the grain size of the material.

As per the International Iron and Steel Institute, the global production of crude steel during 2005 was estimated as 1129 mt and the consumption was 900 mt.

1.3 Iron and Steel in India

There are archaeological evidences of the use of iron in India during the Indus valley civilization. Two excellent examples are the iron pillar near Kutub Minar erected in the fifth century and the 14 m tall iron post in the Kodachadri village in Karnataka.

As early as in 1907, Jamsetji Nusserwanji Tata set up the first integrated steel manufacturing plant at Jamshedpur in Bihar. (It is significant to note that our country possesses enormous deposits of very rich iron ores, but they cannot be fully exploited because there are no coal mines in their vicinity.) During the first two five-year plans, Jawaharlal Nehru, the then Prime Minister of India, authorized the setting up of major steel plants at Bhilai, Rourkela, and Durgapur. In Karnataka, Sir Mokshakumdam Visweswarayya established the Bhadravathi steel plant. At the time of independence, India produced 1.3 million tonnes of steel per year. After the plants were set up at Durgapur, Bhilai, and Rourkela, the production of steel increased to 6.5 million tonnes in 1969–70 and to 21.3 million tonnes in 1995–96. The steel sector now consists of seven integrated plants (see Fig. 1.6) and about 180 mini steel plants and rerollers. (The mini steel plant requires less than one half man-hour per tonne of steel produced as against two man-hour per tonne in the most efficient integrated steel plant.) During the British rule several steel structures were constructed in India. The Howrah Bridge and second Hooghly cable-stayed bridge in Calcutta are examples of steel-intensive bridge construction. There are numerous bridges (built by the Railways) and industrial buildings exclusively using steel.



Fig. 1.6 Map of India showing locations of integrated steel plants

In 2000–05, the annual production of steel was about 38 million tonnes and is likely to increase in the future. At present, India is the tenth largest producer of steel in the world. However, the per capita consumption of steel in India is low, about 33 kg/person/year as compared to 220 kg in China and 300–600 kg in developed countries like the USA, Germany, the UK, and Japan. In India, a major part of steel is consumed in engineering applications, followed by automobiles and constructions.

The continuous casting method accounts for only 17% of the total steel produced. The remaining 83% is accounted for by the ingot route, which results in high energy costs. The productivity of our blast furnaces is around 50% of that of blast furnaces of world standard due to the low quality of indigenous coking coals and adoption of outdated technologies. Integrated steel plants in India consume 13 gigacalories per tonne of crude steel, whereas plants in other developed countries consume about 5 gigacalories or even less.

The National Mineral Development Corporation (NMDC), Kudremukh Iron Ore Co. (KIOCL), and Sesa Goa (Sesa) are the major merchant producers of iron ore. SAIL and Tata Steel have their captive iron ore mines. Pig iron is mainly produced by KIOCL, Sesa Goa, and Usha Ispat. In addition, there are many mini blast furnace pig iron producers. Even integrated steel plants such as SAIL and RINL produce significant amounts of pig iron. Gas-based sponge iron is produced by Essar Steel, Ispat Industries, and Vikram Ispat (a division of Grasim). SAIL, RINL, Tata Steel, and Jindal Vijayanagar (JVSL) are the largest primary steel producers. Essar steel, Ispat Industries, and Lloyds Steel are the largest secondary steel producers in India. In 2000-01, India produced 3.395 mt of pig iron, 5.481 mt of sponge iron, 26.5 mt of crude steel, and 29.5 mt of finished steel. India imported 1.433 mt and exported 2.911 mt of finished steel. As on October 2004, the price per tonne of mild steel angles, channels, and HR sheets, respectively, were Rs 24,200, Rs 23,700, and Rs 32,500.

To produce one tonne of crude steel nearly 1.75 tonnes of iron ore, 1.35 tonnes of coal, 0.5 tonne of limestone, and 0.5 tonne of other materials (dolomite, manganese, and other alloy materials) are required. The primary energy requirement to produce one tonne of finished steel in UK is 35.9 GJ (Haseltine 1975). As iron ore and coal are heavy and bulky materials, iron and steel plants should be located close to the raw material source. Generally, large-scale deposits of iron ore and coal do not occur in close proximity to the market centre. Hence, the location of iron and steel plants is determined based on the calculation of the cost of transporting coal, iron ore, and the finished product to the market centre. In places like the UK and Japan, where imported ore is used, coastal locations are preferred.

1.4 Metallurgy of Steel

The metallurgy of steel is outside the scope of this book. However, since a little knowledge of it will help the structural engineer understand the ductile behaviour, welding, corrosion, and fire protection aspects of steel, a brief discussion of the metallurgical composition of steel is included in this section.

1.4.1 Crystalline Structure of Metals

The atoms of chemical elements consist of a central nucleus carrying a positive electrical charge, surrounded by a number of negatively charged electrons, which tend to move in layers or shells. The first shell is complete with only two electrons but if there are more electrons present, eight are required to completely fill an outer shell. Atoms combine with metallic bonding to form molecules or crystals in a variety of ways but are associated with the formation of stable units with complete shells of electrons. The strength, ductility, and toughness of metals are due to the properties of the metallic bond.

Solid metals such as iron consist of an aggregate of crystals or grains in which the atoms are arranged in a regular three-dimensional geometrical pattern called a

space lattice. In an ideal close-packed lattice arrangement, the unit cell is a *face-centred cubic unit* (fcc) or a *hexagonal close-packed structural cell*. The face-centred cubic unit has atoms at each corner of the cube and in the centre of each face [Fig. 1.7(a)]. The hexagonal structure cell has atoms at each corner, the centre of the top and bottom faces, and also three atoms within the unit cell [Fig. 1.7(c)]. With planes of slightly less dense packing, we have the body-centred cubic structure (bcc structure), which has an atom at each corner and one in the centre of the cube [Fig. 1.7(b)]. These are the three basic lattices occurring in common metals.

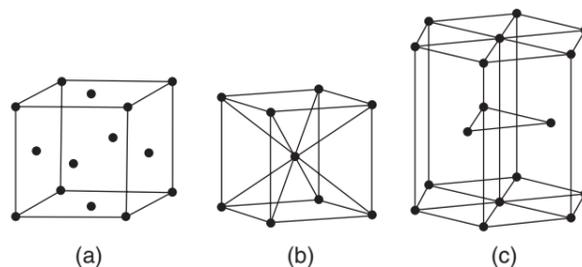


Fig. 1.7 The three most common crystal structures in metals and alloys— (a) Face-centred cubic, (b) body-centred cubic, and (c) hexagonal close-packed

Pure iron, when heated to its melting point, undergoes several crystalline transformations. Up to a temperature of 910°C , iron has a bcc crystalline structure and remains as ‘ferrite’ or ‘ α -iron’. (It has to be noted that the magnetic properties of iron decrease with increase in temperature and vanish at about 768°C , called the ‘Curie point’. The iron that exists between 768°C and 910°C and having a bcc structure is called ‘ β -iron’.) Between 910°C and 1400°C , it transforms to ‘austenite’ or ‘ γ -iron’, which has fcc structure. From 1400°C up to its melting temperature of about 1539°C , iron reverts to the bcc structure and is called ‘ δ -ferrite’. On cooling the molten iron back to room temperature, the transformations are reversed almost at the same temperature when heated. These different phases of iron are summarized in Table 1.3.

Table 1.3 Different phases of iron

Stable temperature range $^{\circ}\text{C}$	Form of matter	Phase	Identification symbol
> 2740	Gaseous	Gas	Gas
$1539\text{--}2740$	Liquid	Liquid	Liquid
$1400\text{--}1539$	Solid	bcc	δ -ferrite
$910\text{--}1400$	Solid	fcc	γ -austenite
< 910	Solid	bcc	α -ferrite

1.4.2 Structure of Steel

When carbon in small quantities is added to iron, steel is obtained. The crystallization of such alloys during solidification is generally similar to but more complex than

that of pure iron. The type of solid formed is governed by factors such as the chemical nature of the metals and the relative sizes of atoms. Different crystalline forms appearing in the structures are referred to as *phases* and appear to be homogenous although they may contain more than one type of atom. Solid structures may be described as substitutional (when atoms are within 14% of the same diameter of the base metal) or interstitial solid solutions. When iron combines to form a compound with elements such as carbon, the compound is interstitial due to the small size of the carbon atoms in comparison with that of the iron atoms. These small atoms enter the interstices or gaps between the atoms in the iron lattice. Figure 1.8 shows the equilibrium diagram for alloys of iron and carbon, containing 0 to 6.7% carbon.

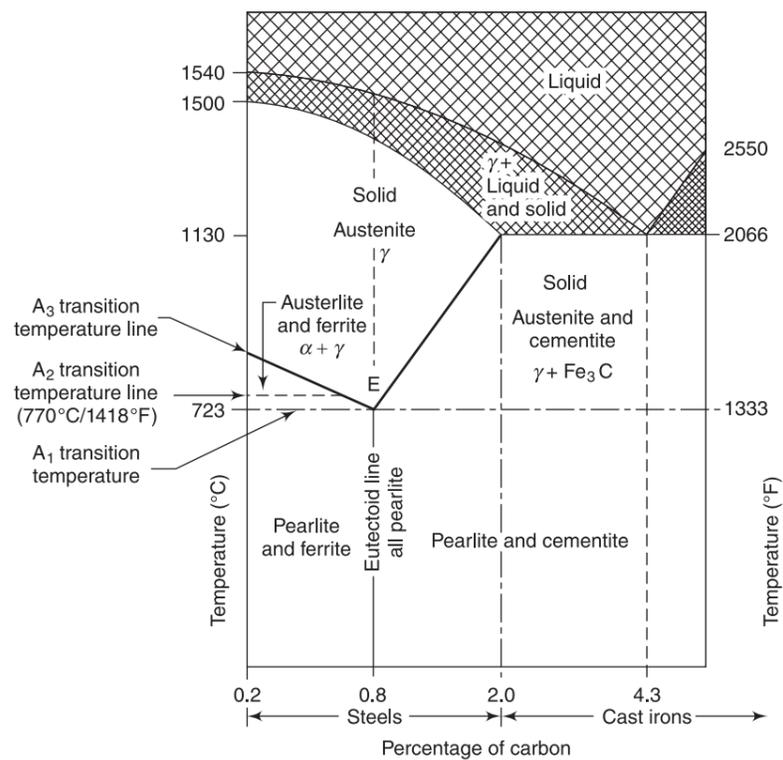


Fig. 1.8 Equilibrium diagram for alloys of iron and carbon

Ferrite or α -iron up to 910°C dissolves carbon in an interstitial solid solution to a maximum of 0.025%. γ -iron is capable of dissolving carbon to a maximum of 2%. Cementite or iron carbide is an interstitial compound of iron and carbon, containing 6.7% carbon, with the chemical formula Fe_3C . It is extremely hard and brittle. At *E* (0.8% carbon), the austenite solid solution reacts to form a fine laminated mixture of ferrite and iron carbide. This eutectoid mixture, known as pearlite, is hard and has low ductility. (Ductility is the ability of a substance to undergo large plastic deformation.) These metallurgical terms of iron are summarized in Table 1.4.

Table 1.4 Metallurgical terms involving iron

Name	Metallurgical term	Percentage of carbon (max.)	Crystal structure
α -iron	Ferrite	0.02	bcc
Fe_3C	Cementite	6.67	—
Ferrite + cementite laminar mixture	Pearlite	0.80 (overall)	—
γ -iron	Austenite	2.0 (depends on temperature)	fcc

It has to be noted that as carbon dissolves in the interstices, it distorts the original crystal lattice of iron and provides increased mechanical strength. However, the addition of more carbon reduces ductility and causes problems during the welding process.

Structural engineers are interested in the portion of the phase diagram shown in Fig. 1.8 that has up to 2.2% carbon. This portion can be divided into two parts, one to the left of the eutectoid point (0.8% carbon), called hypo-eutectoid steel, and the other to the right of this point, called hyper-eutectoid steel. Iron containing very low carbon (up to 0.0025%) is called very low carbon steel, and has a 100% ferrite microstructure. It is very soft, ductile, and has low mechanical strength.

During manufacture, when the steel is cooled very slowly from a higher temperature, ordinary structural steel with a pearlite ferrite microstructure is formed. As mentioned previously, ferrite is soft and ductile, and pearlite is hard and hence imparts mechanical strength to steel. The higher the carbon content, the higher will be the pearlite content and hence the higher will be the mechanical strength. The amount of pearlite for a given carbon content is calculated according to the following formula.

$$\text{Volume fraction of pearlite} = \frac{\text{percentage of carbon}}{0.8\% \text{ of carbon}} \quad (1.1)$$

However, as the pearlite content increases, ductility is reduced. Steel with more than 0.85% carbon is of no great significance in civil engineering, though it is used in the manufacture of cutting tools, where high hardness is required. More details about the microstructure of steel may be found in Llewellyn and Hudd (1998) and Theling (1984).

1.4.3 Heat Treatment of Steel

Since changes occur in the solid state, it is possible to modify the structure of steel and improve the properties by heat treatment. *Heat treatment* involves the heating and cooling of steel under controlled conditions to change its structural and physical properties. *Annealing* and *normalizing* are the processes used to refine the structure of steel. A material that has not been cold worked can be annealed. This should not be confused with annealing as used to remove the effects of cold work. In the annealing process, the steel is heated to a temperature just greater than the A_3 temperature ($> 910^\circ\text{C}$, see Fig. 1.8) and held at that temperature to achieve

uniformity of composition and temperature prior to slow cooling, usually in the furnace. On heating, after the A_1 line is reached, pearlite changes to austenite, which has a very fine grain size. Cooling from A_3 to A_1 permits the separation of ferrite, which moves to the austenite grain boundaries because of the small grain size, and at the A_1 temperature, the remaining austenite changes to pearlite. Sufficient cooling time allows the carbon diffusion and transformation process to get completed. This refined pearlite + ferrite microstructure shows both increased strength and ductility. The yield strength of steel is related to the grain size by the following equation (Theling 1984)

$$f_y = f_0 + \frac{k}{\sqrt{d}} \quad (1.2)$$

where f_y is the yield strength, f_0 is the yield strength of very large isolated crystals (for mild steel it can be taken as 5 MPa), d is the grain size in millimetres, and k is a constant (assumed as 38 for mild steel). Equation (1.2) clearly shows that decreasing grain size enhances the yield strength.

Normalizing is a process similar to annealing, except that in normalizing the steel is removed from the furnace and allowed to cool in still air. The changes occurring are the same as during annealing but less time at high temperature and the faster cooling rate give a slightly finer grain structure and finer laminations in the pearlite, as shown in Fig. 1.9. These finer structures result in slightly improved properties compared to those obtained as a result of annealing. Normalizing is cheaper than annealing since the steel is kept in the furnace for less time. However, it can only be used for fairly uniform sections, where air cooling is unlikely to cause distortion due to differential cooling and contraction.

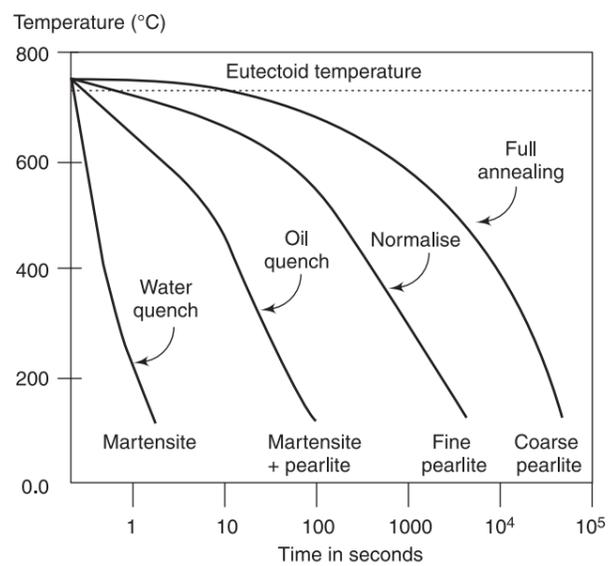


Fig. 1.9 Change in microstructure as a function of cooling

Mild steel plates, structural sections, etc., show very good properties of strength with ductility in the normalized condition. Heat treatment is costly and hence for many purposes the exposure of normalizing can be avoided, provided the finishing temperature during the hot rolling of steel is appropriate. A finishing temperature for hot rolling, which is only slightly above the A_3 temperature (refer to Fig. 1.8), gives a very fine austenite grain size and, on air cooling, a microstructure very similar to that obtained by normalizing. It may be noted that in India the heat treated steels amount hardly to about 5% of the steel produced (Rangwala 1997).

1.4.4 Quenching and Tempering

When small sections of steel are water quenched from the γ -region, the cooling rate is too great to allow the separation of ferrite and formation of pearlite by the nucleation and growth process. The fcc austenite is unstable, however, and the change to a bcc structure similar to ferrite cannot be prevented. This structure, known as martensite, is extremely hard and brittle, owing to the distortion produced in the lattice by the carbon retained in the supersaturated solution. It is also seen from Fig. 1.9 that oil quenching, where the cooling rate is slightly slower, results in a mixture of martensite and pearlite. Martensite is not used in structural steel construction due to its brittle nature and because it is difficult to weld. However, it is used in high-strength bolts.

When martensite is heated to a temperature of 600°C, it results in steel with strength and ductility superior to those in normalized steel. This process of reheating martensite is called *tempering*. Quenching and tempering are principally applied to higher-carbon steels to get high hardness or to alloy steels to achieve high strength and toughness.

1.5 Alloying Elements in Steel

The physical properties of steel such as ductility, elasticity, strength, toughness, etc., are greatly influenced by the following factors.

- (a) Carbon content,
- (b) Heat-treatment process, and
- (c) Alloying elements.

We have already discussed the first two factors in the previous sections. Depending upon the carbon content, the steel is designated as low-carbon steel (carbon content 0.10–0.25%), medium-carbon steel (carbon content 0.25–0.60%) and high-carbon steel (carbon content 0.60–1.10%). Table 1.5 shows various uses of steel of each category. Structural steels normally have a carbon content less than 0.6%. As already discussed, increasing the carbon content increases the hardness, yield, and tensile strength of steel. However, it decreases the ductility and toughness. Carbon also has greater influence on weldability. Mild steel is widely used for structural work and will be discussed in detail in the later sections of this chapter.

Table 1.5 Uses of steel

Type of steel	Carbon content	Uses
Mild steel	Up to 0.10%	Steel sections used in buildings, bridges, etc.
Medium-carbon steel	Up to 0.25%	Boiler plates, structural steel, etc.
	Up to 0.45%	Rails, tires, etc.
	Up to 0.60%	Hammers, large stamping and pressing dies, etc.
High-carbon steel or hard steel	Up to 0.75%	Sledgehammers, springs, stamping dies, etc.
	Up to 0.90%	Miner's drills, smith's tools, stone mason's tools, etc.
	Up to 1.00%	Chisels, hammers, saws, wood working tools, etc.
	Up to 1.10%	Axes, cutlery, drills, knives, punches, etc.

Manganese, silicon, sulphur, phosphorus, copper, vanadium, nickel, chromium, columbium, molybdenum, and aluminium are some of the other elements that may be restricted in, or added to, structural steel. In recent years, microalloyed steels or high-strength low-alloy (HSLA) steels have been developed. They are basically carbon manganese steels in which small amounts of aluminium, vanadium, niobium, etc., are used to control the grain size. Molybdenum is also added (up to 0.5%) to refine the lamellar spacing in pearlite and to make it evenly distributed. Alloy steels are termed as low-alloy steels (total alloy content < 0.5%), medium-alloy steels (total alloy content 5–10%) and high-alloy steels (total alloy content > 10.0%). Based on manganese content, steels are also classified as carbon manganese steels ($Mn > 1\%$) and carbon steels ($Mn < 1\%$). (It has to be noted that the atomic diameter of manganese is larger than that of iron. Hence manganese exists as a substitutional solid solution in the ferrite crystal, by displacing the smaller iron atoms.)

If the silicon content is less than 0.2%, it has no appreciable effect on the physical properties of steel. If it is raised to about 0.30 to 0.40%, the elasticity and strength of steel are considerably increased without serious reduction in ductility. More than 2% of silicon causes brittleness.

If the sulphur content is between 0.02 and 0.10%, it has no appreciable effect on the ductility or strength of steel. The sulphur content, however, decreases malleability (malleability is the ability of materials, both in cold and hot states, to be bent or pressed to different shapes without fracture) and weldability of hot metals. A sulphur content of more than 0.10% decreases the strength and ductility of steel.

It is desirable to keep the phosphorus content of steel below 0.12%. It reduces the shock resistance, ductility, and strength of steel. If present in quantities between 0.30 and 1.00%, manganese helps to improve the strength and hardness of mild steel in more or less the same way as carbon; it also increases the toughness of steel. However, when its content exceeds 1.50%, it increases the formation of martensite and hence decreases ductility and toughness.

1.5.1 Weldability of Steel

In most cases, members of steel are welded during fabrication. Hence, steels must not only possess high strength but must also be suitable for welding. For good

weldability, steel should not show high hardness in welded parts, but should have adequate elongation and notch toughness even in the *heat-affected zone* adjacent to a weld. Since weldability is affected by the kinds and amounts of alloying elements present in the steel, it is important to restrict both to the extent possible.

A major factor in weldability is the carbon equivalent, C_{eq} , of the chemical components in steel. The smaller this value, the better is the weldability. The carbon equivalent may be calculated by an equation such as that shown below, in which each symbol refers to the proportion of weight of that particular element in percentage (IS 2062 : 1992).

$$C_{eq} = \frac{C + Mn}{6} + \frac{(Cr + Mo + V)}{5} + \frac{(Ni + Cu)}{15} \quad (1.3)$$

where C is carbon, Mn is manganese, Cr is chromium, Mo is molybdenum, V is vanadium, Ni is nickel, and Cu is copper.

High-strength steels tend to have a high carbon equivalent. When the carbon equivalent exceeds a certain limit ($C_{eq} = 0.30-0.43$), the loss of weldability is compensated by the reheating or post-heating of the weld zone. However, if the carbon content is less than 0.12%, then C_{eq} can be tolerated up to 0.45%.

1.6 Chemical Composition of Steel

Several varieties of steel are produced in India. The Bureau of Indian Standards (BIS) classifies structural steels into different categories based on the ultimate yield strength of the basic material and their use (see IS 7598). They are listed along with the appropriate codes of practice issued by BIS in Table 1.6.

Table 1.6 Types of steel and their relevant IS standards

Type of steel	Relevant IS standards
Structural steel	2062, 1977, 3502, 5517, 8500
Steel for rivets	1148, 1149, 7557, 1929, 2155, 2998
Steel for tubes and pipes	1239, 1914, 806, 1161, 10748, 4923
Steel for sheets and strips	277, 1079, 12367, 513, 12313, 14246
Steel for rerolling	2830, 2831
Steel for reinforced concrete	432, 1786, 2090
Steel for bolts, nuts, and washers	1363, 1364, 1367, 3640, 3757, 6623, 6639, 730, 4000, 5624, 6649, 8412, 10238, 12427
Welding	814, 1395, 816, 819, 1024, 1261, 1323
Steel for filler rods/wires, electrodes	1278, 1387, 7280, 6419, 6560, 2879, 4972, 7280
Steel casting	1030, 2708, 2644, 276

The chemical compositions of some typical steels specified by the Bureau of Indian Standards are listed in Table 1.7. For details of chemical composition of other steels refer IS 1977 [structural ordinary (low tensile) quality], IS 8500 (medium and high strength quality). A comparison of the chemical compositions of mild steels of different grades as given in international standards is shown in

Table 1.7 Chemical compositions (in percentage) of some typical structural steels

Type of steel	Designation	IS code	C (max.)	Mn (max.)	S (max.)	P (max.)	Si (max.)	Carbon equivalent	
Standard structural steel	Fe 410 A ^a	2062	0.23	1.5	0.050	0.050	—	SK ^b	0.42
	Fe 410 B	2062	0.22	1.5	0.045	0.045	0.4	SK	0.41
	Fe 410 C	2062	0.20	1.5	0.040	0.040	0.4	K	0.39
Micro-alloyed medium-/high-strength steel	Fe 440	8500	0.20	1.3	0.050	0.050	0.45		0.40
	Fe 540	8500	0.20	1.6	0.045	0.045	0.45		0.44
	Fe 590	8500	0.22	1.8	0.045	0.045	0.45		0.48

^a Fe stands for steel and the number after Fe is the tensile strength in N/mm² or MPa

^bK—killed steel, SK—semi-killed steel (explained in Section 1.2.2)

C = carbon, Mn = manganese, S = sulphur, P = phosphorus, Si = silicon

Table 1.8 A comparison of the chemical compositions of different steel-grade designations (Madhu Mohan et al. 2002)

Standard	Grade of steel	Maximum permissible limits (%)					
		C	Mn	S	P	Si	Ni
IS 2062	Fe410W A	0.23	1.50	0.05	0.05	—	—
		(±0.02)	(±0.05)	(±0.005)	(±0.005)		
ISO	Fe 430 A	0.24	—	0.05	0.06	—	—
BS 4360	40EE	0.16	1.50	0.03	0.04	0.50	
ASTM	A 36	0.15	0.60	0.06	0.04	0.30	1.0

Table 1.8. This table will be helpful if the structural engineer has to design a structure using a different code of practice.

1.7 Types of Structural Steel

The structural designer is now in a position to select structural steel for a particular application from the following general categories.

Carbon steel (IS 2062) Carbon and manganese are the main strengthening elements. The specified minimum ultimate tensile strength for these steels varies from about 380 to 450 MPa and their specified minimum yield strength from about 230 to 300 MPa (see Table 1 of IS 800 : 2007).

High-strength carbon steel As discussed already, such steel has a high carbon content and hence shows reduced ductility, toughness, and weldability. This steel is specified for structures such as transmission lines and microwave towers, where relatively light members are joined by bolting. Such steels have a specified ultimate tensile strength, ranging from about 480–550 MPa, and a minimum yield strength of about 350–400 MPa.

Medium- and high-strength microalloyed steel (IS 8500) Such steel has a low carbon content but achieves high strength due to the addition of alloys such as niobium, vanadium, titanium, or boron (total microalloying elements restricted to less than 0.25%). Such steel has a specified ultimate tensile strength ranging from 440 to 590 MPa and a minimum yield strength of about 300–450 MPa.

High-strength quenched and tempered steels (IS 2003) These steels are heat treated to develop high strength. Though they are tough and weldable, they require special welding techniques. They have a specified ultimate tensile strength between 700 and 950 MPa and a minimum yield strength between 550 and 700 MPa.

Weathering steels These are low-alloy atmospheric corrosion-resistant steels, which are often left unpainted (see Section 15.3 for the details of these steels). They have an ultimate tensile strength of about 480 MPa and a yield strength of about 350 MPa.

Stainless steels These are essentially low-carbon steels to which a minimum of 10.5% (maximum 20%) chromium and 0.50% nickel is added. More details about stainless steel are given in Section 1.15.

Fire-resistant steels Also called thermomechanically treated steels, they perform better than ordinary steel under fire. More details about these steels are given in Section 16.10.

1.8 Mechanical Properties of Steel

The mechanical properties of steels depend upon the following factors:

- (a) chemical composition,
- (b) rolling methods,
- (c) rolling thickness,
- (d) heat treatment, and
- (e) stress history.

The important mechanical properties of steel are ultimate strength (also called tensile strength), yield stress (also called proof stress), ductility, weldability, toughness, corrosion resistance, and machinability.

The last four properties are often associated with the fabrication of steel structures and are important for the durability of the material.

1.8.1 Ultimate Strength or Tensile Strength

Ultimate strength, which is the minimum guaranteed *ultimate tensile strength* (UTS) at which the steel would fail, is obtained from a tensile test on a standard specimen, generally called a *coupon*. A typical specimen as per IS 1608 is shown in Fig. 1.10. In this test, the gauge length L_g and the initial cross-sectional area A_0 are important parameters. The dimensions of the specimens are established to ensure that failure occurs within the designated gauge length. The test coupons are actually

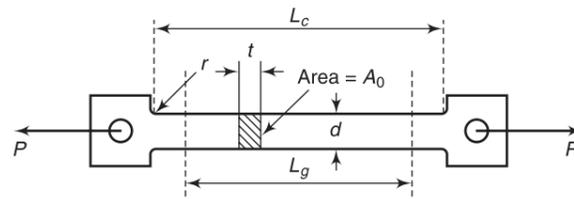


Fig. 1.10 Standard tensile test specimen as per IS 1608

cut out from a specified portion of the member for which the tensile strength is required. The initial gauge length is taken as $5.65\sqrt{A_0}$ in the case of a specimen with a rectangular cross section and five times the diameter in the case of a circular specimen.

The coupon is fixed in a tensile testing machine, with specified distances between the grips, and tested under uniaxial tension. The loads are applied through the threaded ends. A typical stress–strain curve of ordinary and high-strength steel specimen subjected to a gradually increasing tensile load is shown in Fig. 1.11(a) and the stress–strain curve of mild steel specimen is shown in Fig. 1.11(b).

The ultimate tensile strength is the highest stress at which a tensile specimen fails by fracture and is given by

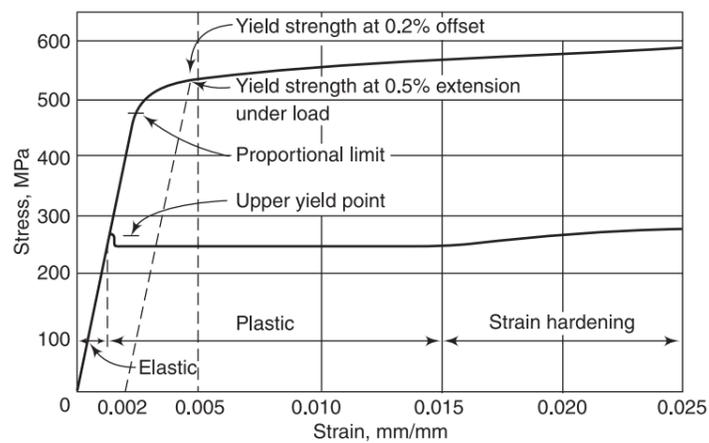
$$\text{Ultimate tensile strength} = \frac{\text{ultimate tensile load}}{\text{original area of cross section}} \quad (1.4)$$

The ultimate tensile strength or stress is called the engineering ultimate tensile stress and is different from the true or absolute ultimate stress. As a specimen is subjected to tension, the area of cross section of the specimen decreases due to Poisson's effect, and the true stress is obtained by considering the actual area of cross section at that instant instead of the original area of cross section. Thus it is calculated by the following formula.

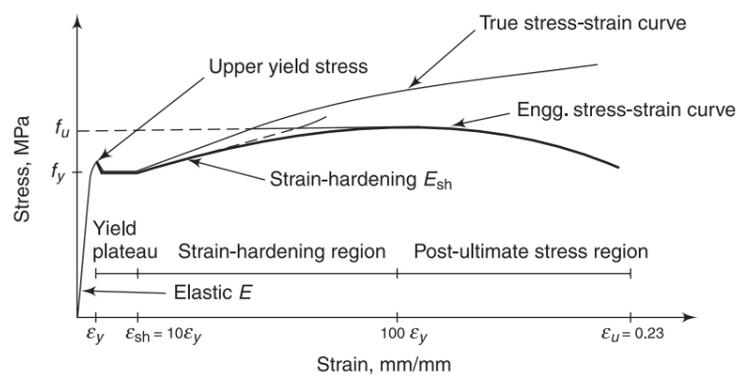
$$\text{True stress} = \frac{\text{ultimate tensile load}}{\text{actual area of cross section}} \quad (1.5)$$

In most engineering structures, the stress in the members in service conditions does not cause any appreciable change in the cross section. Moreover, it is extremely difficult to determine the area of cross section at various stages of loading. Hence in all design calculations, only the original area of cross section is considered.

Note that steel is specified according to the guaranteed ultimate tensile stress designated in the code as the characteristic ultimate tensile stress, f_u [which is defined as the minimum value of stress below which not more than a specified percentage (usually 5%) of corresponding stresses of samples tested are expected to occur]. See the next section for a discussion of characteristic strength. However, in some countries like the USA, steel is specified according to the (characteristic) yield strength.



(a)



(b)

Fig. 1.11 Typical stress–strain curves of mild steel—(a) stress–strain curves of ordinary and high-strength steel, (b) stress–strain curve of a mild steel specimen

Thus, steel is designated in India as Fe 310, Fe 410 WA, Fe 540 B, Fe 590, etc., where Fe stands for the steel and the number after Fe is the characteristic ultimate tensile stress in megapascals. The letter A, B, or C indicates the grade of steel. The letter W denotes that the steel is weldable. (Copper-bearing quality is designated with a suffix Cu, e.g., Fe 410 Cu-WA.) Table 1.9 indicates the minimum ultimate tensile stress and other important mechanical properties of steel produced in India. Grade A steel specified by IS 2062 is intended for use in structures subject to normal conditions and for non-critical applications (for parts not prone to brittle fracture). Grade B is intended for use in structures subject to critical loading applications, where service temperature does not fall below 0°C. Grade B steel is generally specified for those structural parts which are prone to brittle fracture or

Table 1.9 Mechanical properties of some typical structural steels
(a) Ultimate tensile strength, yield strength, and percentage elongation

Type of steel	Designation	UTS (MPa)	Yield strength (MPa)			Min. percentage elongation (gauge length = $5.65\sqrt{A_0}$)	Charpy V-notch impact energy (min.)
			Thickness (mm)				
			<20	20–40	>40		
Standard structural steel (IS 2062)	Fe 410 A	410	250	240	230	23	—
	Fe 410 B	410	250	240	230	23	27
	Fe 410 C	410	250	240	230	23	27
			<16	16–40	41–63		
Micro-alloyed medium-/high-strength steel (IS 8500)	Fe 440 B	440	300	290	280	22	30
	Fe 540 B	540	410	390	380	20	25
	Fe 490 B	490	350	330	320	22	25
	Fe 590 B /570 B	590/570	450	430	420	30	20

(b) Other mechanical properties as per IS 800 : 2007

Property	Value
Modulus of elasticity (E)	2×10^5 MPa
Shear modulus (G)	$E/[2(1 + \mu)] = 0.769 \times 10^5$ MPa for $\mu = 0.3$
Poisson's ratio (μ)	
(i) Elastic range	0.3
(ii) Plastic range	0.5
Unit mass of steel, ρ	7850 kg/m ³
Coefficient of thermal expansion, α_t	$12 \times 10^{-6}/^\circ\text{C}$
Brinell hardness number	150–190
Vickers hardness number	157–190
Approximate melting point	1530°C
Thermal conductivity	0.14 cal/cm ² s/1°C/cm

are subjected to severe fluctuations of stress (for example members in bridges). Naturally, such steel is also specified for structural parts prone to both conditions. Grade C steel has guaranteed low temperature (up to -40°C) and impact properties. Grade C steel is used in members or structures where the risk of brittle fracture requires consideration due to their design, size and/or service conditions. A comparison of the mechanical properties of mild steel as given in international codes is given in Table 1.10.

After reaching the ultimate tensile stress, a localized reduction in area, called *necking*, begins, and elongation continues with diminishing load until the specimen breaks. After failure, the fractured surface of the two pieces is found to form a cup-and-cone arrangement. Cup-and-cone fracture is considered as an indication of *ductile fracture*.

Table 1.10 Comparison of mechanical properties of different steel grade designations (Madhu Mohan et al. 2002)

Standard	Grade of steel	Tensile strength (f_u), MPa	Yield strength, (f_y) MPa		
			$t < 20$ mm	$20 < t < 40$ mm	$t > 40$ mm
IS 2062	Fe 410W A	410	250	240	230
EN 10027-1	S 235	360	235	235	215
BS 4360	43 EE	430	275	265	255
ASTM	A 36	400	248	—	—

As shown in Fig. 1.11(a), initially a specimen of steel has a linear stress–strain curve whose slope equals Young’s modulus of elasticity, E . Thus,

$$\text{Modulus of elasticity} = \frac{\text{stress within the proportional limit}}{\text{strain}} \quad (1.6)$$

This can be expressed as

$$E = \frac{f}{\epsilon} \quad (1.7)$$

where f is the uniaxial stress below the proportional limit, and ϵ is the strain corresponding to the stress f .

The values of E vary in the range 200,000–210,000 MPa and an approximate value of 200,000 MPa is assumed in the code. The steel obeys *Hooke’s law* in this linear range. That is, it remains elastic and recovers to the original shape perfectly on unloading. The limit of the elastic behaviour is often closely associated with the yield stress f_y , and the corresponding yield strain $\epsilon_y = f_y/E$. Beyond this limit, the steel flows plastically without any increase in stress until the ‘strain hardening’ strain ϵ_{sh} is reached. This *plastic range* is usually considerable, and accounts for the ductility of steel. The stress increases above the yield stress f_y , when the ‘strain hardening’ strain ϵ_{sh} is exceeded, until the ultimate tensile stress f_u is reached. As indicated earlier, at this stage, large local reductions in the cross section occur, and the load capacity decreases until tensile failure takes place.

The yield strain for mild steel is of the order of 0.00125 or 0.125%. Depending on the steel used, ϵ_{sh} generally varies between $5 \epsilon_y$ and $15 \epsilon_y$. The average value of $10 \epsilon_y$ is taken as the yield plateau of structural steels. The value of ϵ_u is taken as $100 \epsilon_y$, and that of ϵ_{br} as 0.23 mm/mm. The initial slope of the strain-hardening part of the curve is termed the *strain-hardening modulus*, E_{sh} . It is much less steep than the elastic part, with E_{sh}/E being typically between 1/30 and 1/100 (Alpsten 1973). The strain-hardening range is not consciously used in design, but some of the buckling limitations are conservatively derived to preclude buckling even at strains well beyond onset of strain hardening.

Yielding is sometimes accompanied by an abrupt decrease in load, as shown in Fig. 1.11(a), which results in upper and lower yield points. The upper yield point (f_{yu}) is influenced by the shape of the test specimen and by the testing machine itself, and is sometimes completely suppressed. The lower yield point (f_{yl}) is much

less sensitive and is considered to be more representative. The stress–strain curve shown in Fig. 1.11(a) is typical of low-carbon (mild) steel. Note that the upper as well as lower yield points tend to increase with increase in speed of loading (strain rate). Typical values of the ratio f_{yu}/f_{y1} for normal structural steel range from about 1.05 to 1.10. The term *yield stress* is commonly used to mean either yield point or yield strength when it is not necessary to make the distinction. Steel in compression has the same modulus of elasticity as in tension. The lower yield stress is also the same for tension and compression and there is about the same length of level yielding (contraction).

Parameters that influence yield stress

The strain rates used in tests to determine the yield stress of a particular steel type are significantly higher than the nearly static rates often encountered in actual structures (McGuire 1968 and Alpsten 1973). The increase in tensile and yield strength at higher strain rates is shown in Fig. 1.12. The lower yield stress at zero strain rates is called the *static yield level* and may be 10% to 15% lower than the yield stress reported in the rolling mill acceptance test (Gaylord et al. 1992).

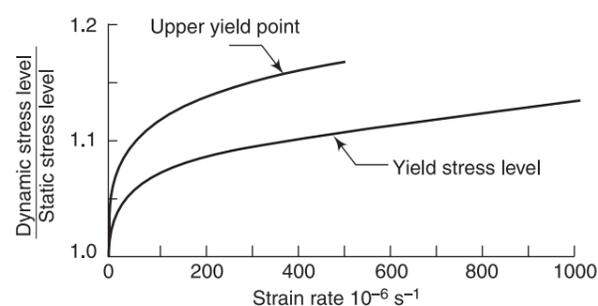


Fig. 1.12 Effect of strain rate on upper yield point and yield stress of structural steel (Alpsten 1973)

However, since the values obtained from the majority of these mill tests are not more than 10% higher or lower than the static rate values, the net effect, when averaged over a complete design, may not be significant (Nethercot 2001). At higher temperatures, the reverse takes place (i.e., at higher strain rates there is reduction in yield strength). This fact needs to be considered only in blast-resistant design. This is of less practical importance in earthquake engineering applications since the strain rate will be well within the range. Mild steel and medium-strength steels have clear yield points and should not be stressed beyond the yield point as the deformation will be large and uncontrollable beyond yield. At strain rates characteristic of seismic response (0.01–0.10/s), steel exhibits a significant increase in yield strength (10–20%) above static test values. However, under cyclic straining, i.e., straining under cyclic loads, the effective strain rate decreases, minimizing this effect.

Yield stress may also be influenced by the position from which the test coupons are taken. For example, the webs of the I-section are thinner than those of the

flanges and hence tend to possess a slightly finer grain structure as a result of faster cooling after rolling. Due to this the yield stress at the web will be higher than that at the flange (Alpsten 1973). It has to be noted that in most situations, the flanges of I-sections contribute most to their load-carrying capacity, since most of the area is concentrated in the flanges. Hence, structural designers must be careful in selecting the appropriate value for material strength for use in their calculations. In order to use plastic design or in earthquake-resistant structures, the steel should satisfy the following criteria.

- The yield plateau should extend for at least six times the strain at first yield.
- The ultimate/yield stress ratio must be greater than 1.25. (To develop an inelastic rotation capacity, a structural member needs adequate length of yield region along the axis of the member. The larger the ultimate to yield ratio, the longer is the yield region.)
- The minimum elongation must be 15% on a gauge length of $5.65\sqrt{A_0}$.

It is also preferable that the actual yield strength based on the tensile test of steel does not exceed the specified yield strength by more than 120 MPa. Figure 1.13 shows the stress–strain curves of different types of steel produced in India and the permanent strain line. Fe 410 grade mild steel is the most commonly used in structural applications. Fe 370 grade steel is used in less important works. (Fe 310 mild steel is used primarily for furniture, doors, windows, etc.)

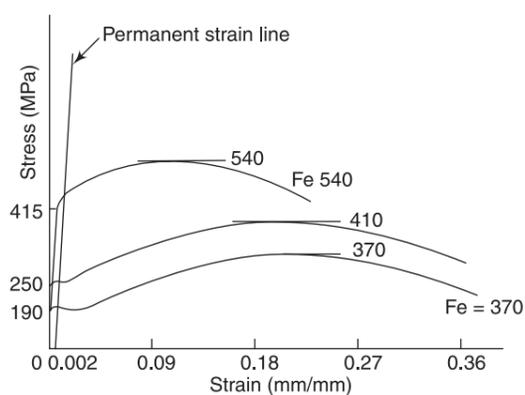


Fig. 1.13 Stress–strain curves of different types of steel produced in India

High-carbon steels do not usually have a pronounced yield point. Instead, after a range of linear elastic behaviour, which ends at a point called the *proportional limit*, the rate of increase in stress begins to drop till the tensile strength is reached (the upper curve of Fig. 1.13). In this case, yielding is arbitrarily defined by a yield strength which is usually taken to be that stress which leaves the specimen with a permanent set (plastic elongation) of 0.2% when the specimen is unloaded. It is obtained by drawing a line parallel to the elastic portion at 0.2% strain, which intercepts the stress–strain curve, as shown in Fig. 1.13. However some standards (e.g., ASTM specification, A370) define the yield stress as the stress corresponding to a 0.5% elongation under load. The allowed permanent set in higher tensile bolt is around 0.006.

The yield stress f_y also varies significantly with the chemical constituents of the steel (e.g., the percentage of carbon and manganese), the heat treatment used, and with the amount of working which occurs during the rolling process. Thus, thinner plates which are more worked have higher yield stresses than thicker plates. The yield stress is also increased by cold working.

1.8.2 Inelastic Cyclic Response

The stress–strain response of most materials under cyclic loading is different from that under single (monotonic) loading. For fatigue analysis, it is necessary to consider the cyclic material behaviour for strength and life calculations.

When steel is subjected to cyclic loading in the inelastic range, the yield plateau is suppressed and the stress–strain curve exhibits the *Bauschinger effect*, in which non-linear response develops at a strain much lower than the yield strain, as shown in Fig. 1.14. As seen from this figure, as the amplitude of response increases, the stress level for a given strain also increases and can substantially exceed the stress indicated by the monotonic stress–strain curve.

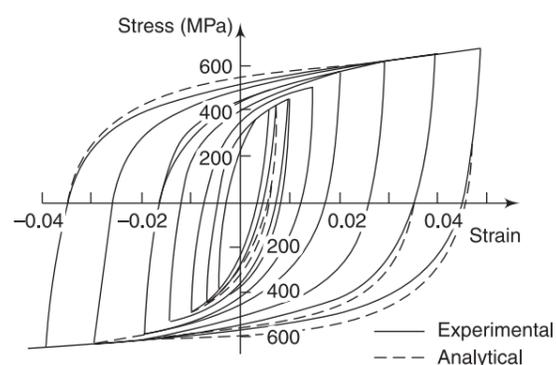


Fig. 1.14 Stress–strain curve of steel subjected to cyclic loading

1.8.3 Characteristic Strength

Variations in material properties (due to the non-uniform molecular structure of the material, and variations and inconsistencies in the manufacturing process, which depend on the degree of control, etc.) should be recognized and taken into consideration in the design process. The material properties that are of greatest importance in the design of structures using steel are yield strength, maximum percentage elongation, and Young's modulus. Other properties that are of less importance are hardness, impact resistance, and melting point.

If a number of samples are tested for a particular property (e.g., yield strength) and the number of specimens with the same strength (frequency) are plotted against the strength, then the results approximately fit a *normal distribution curve*, as shown in Fig. 1.15.

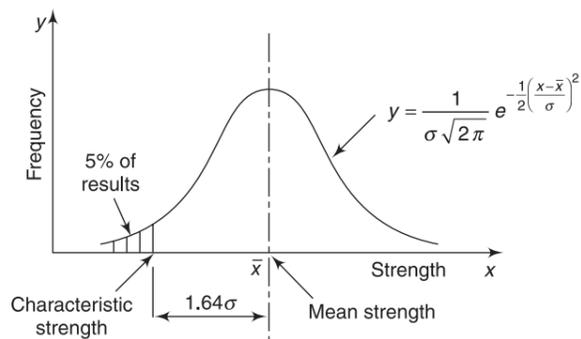


Fig. 1.15 The normal distribution curve

This curve can be mathematically expressed by the equation shown in Fig. 1.15, which can be used to define 'safe' values for design purposes. When defined, this safe value of yield strength, is called *characteristic strength*. If the characteristic strength is defined as the mean strength, then from Fig. 1.15, 50% of the material has a characteristic strength below this value and hence is not acceptable. Hence a characteristic value which has a particular chance (often 95%) of being exceeded in any standard tension test is chosen.

Thus, the characteristic strength is calculated from the equation

$$f_k = f_{\text{mean}} - 1.64 \sigma \quad (1.8)$$

where σ is the standard deviation for n samples, and is given by

$$\sigma = \left[\frac{\sum (f_{\text{mean}} - f)^2}{(n-1)^{0.5}} \right] \quad (1.9)$$

The characteristic strength of steel is the value obtained from tests at the rolling mills, but by the time the steel becomes part of the finished structure, its strength might have been reduced (e.g., by corrosion or accidental damage). The strength to be used in design calculations is therefore the characteristic strength divided by a partial safety factor. The value of the partial safety factor adopted for steel is given in Table 5 of IS 800 : 2007 as 1.10 for yielding resistance.

1.8.4 Ductility

Ductility may be described as the ability of a material to change its shape without fracture. In other words, the ductility of a structure or its members is the capacity to undergo large inelastic deformations without significant loss of strength or stiffness. The stress-strain curve of a material also indicates the ductility. It is the amount of permanent strain, i.e. strain exceeding proportional limit up to the point of fracture. The ductility of the tension test specimen is measured by determining the percentage elongation (comparing the final and the original lengths over a specified gauge distance). The specified gauge length according to the code is as follows.

$$\text{Gauge length} = 5.65 \sqrt{A_0} \quad (1.10)$$