Steel Structures

Design and Practice

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Contents

Foreword *v*
Preface *vii*
List of Symbols *xv*

Chapter 1 Structural Steel: Types, Properties, and Products 1

Introduction *1*
1.1 Historical Development *2*
1.2 Processes Used for Steel Making *2*
1.3 Heat Treatment of Steel *5*
1.4 Alloying Elements in Steel *5*
1.5 Weldability of Steel *6*
1.6 Chemical Composition of Steel *7*
1.7 Types of Structural Steel *8*
1.8 Mechanical Properties of Steel *8*
1.9 Resistance to Corrosion *18*
1.10 Fatigue Resistance *19*
1.11 Residual Stresses *19*
1.12 Stress Concentration *20*
1.13 Structural Steel Products *20*
1.14 High-performance Steel *29*
1.15 Stainless Steel *30*
1.16 Composite Construction *31*
1.17 Advantages of Steel as a Structural Material *31*
1.18 Types of Steel Structures *33*
1.19 Fabrication and Erection *40*
1.20 Aesthetics of Steel Structures *41*

Chapter 2 The Basis of Structural Design 45

2.1 Design Considerations *45*
2.2 Steps Involved in the Design Process *46*
2.3 Structural Systems *48*

2.4 Seismic Force Resisting Systems *59*
2.5 Structural Integrity *64*
2.6 Loading and Load Combinations *66*
2.7 Structural Analysis *84*
2.8 Codes and Specifications *87*
2.9 Design Philosophies *88*
2.10 Failure Criteria for Steel *101*

Chapter 3 Design of Tension Members 113

Introduction *113*
3.1 Types of Tension Members *114*
3.2 Slenderness Ratio *115*
3.3 Displacement of Tension Members *117*
3.4 Behaviour of Tension Members *117*
3.5 Modes of Failure *118*
3.6 Factors Affecting the Strength of Tension Members *121*
3.7 Angles Under Tension *125*
3.8 Other Sections *129*
3.9 Tension Rods *129*
3.10 Design of a Tension Member *130*
3.11 Lug Angles *131*
3.12 Splices *132*
3.13 Gussets *134*

Chapter 4 Plastic and Local Buckling Behaviour 154

Introduction *154*
4.1 Plastic Theory *154*
4.2 Plastic-collapse Load *158*
4.3 Conditions of Plastic Analysis *159*
4.4 Theorems of Plastic Collapse *160*
4.5 Methods of Plastic Analysis *160*
4.6 Plastic Design of Portal Frames *161*
4.7 Special Considerations *162*
4.8 Local Buckling of Plates *162*
4.9 Cross Section Classification *167*
4.10 Behaviour and Ultimate Strength of Plates *172*

Chapter 5 Design of Compression Members 193

Introduction *193*
5.1 Possible Failure Modes *196*
5.2 Classification of Cross Section *197*
5.3 Behaviour of Compression Members *197*
5.4 Elastic Buckling of Slender Compression Members *199*

5.5 Behaviour of Real Compression Members *201*
5.6 Development of Multiple Column Curves *201*
5.7 Sections used for Compression Members *204*
5.8 Effective Length of Compression Members *207*
5.9 Single Angle Struts *216*
5.10 Design of Compresssion Members *218*
5.11 Built-up Compression Members *220*
5.12 Compression Members Composed of Two Components Back-to-back *227*
5.13 Column Bases and Caps *228*
5.14 Displacement *235*

Chapter 6 Design of Beams 266

Introduction *266*
6.1 Beam Types *268*
6.2 Section Classification *269*
6.3 Lateral Stability of Beams *270*
6.4 Effective Length *275*
6.5 Buckling of Real Beams *280*
6.6 Design Strength of Laterally Supported Beams in Bending *281*
6.7 Design Strength of Laterally Unsupported Beams *283*
6.8 Shear Strength of Steel Beams *292*
6.9 Maximum Deflection *294*
6.10 Web Buckling and Web Crippling *297*
6.11 Purlins *299*
6.12 Design of Beams *303*

Chapter 7 Design of Plate Girders 339

Introduction *339*
7.1 Plate Girders *340*
7.2 General Considerations *344*
7.3 Preliminary Design Procedure *346*
7.4 Web Panel Subjected to Shear *350*
7.5 Behaviour of Transverse Web Stiffeners *358*
7.6 Design of Plate Girders using IS 800 : 2007 Provisions *358*
7.7 Welding of Girder Components *366*
7.8 Proportioning of the Section *367*

Chapter 8 Design of Gantry Girders 393

Introduction *393*
8.1 Loading Considerations *396*
8.2 Maximum Load Effects *400*

8.3 Fatigue Effects *402*
8.4 Selection of Gantry Girder *402*
8.5 Design of Gantry Girder *407*

Chapter 9 Design of Beam-columns 420

Introduction *420*
9.1 General Behaviour of Beam-columns *422*
9.2 Equivalent Moment Factor C_m *425*
9.3 Nominal Strength—Instability in the Plane of Bending *426*
9.4 Interaction Equations for Local Capacity Check *430*
9.5 Code Design Procedures *431*
9.6 Design of Beam-columns *434*
9.7 Beam-columns Subjected to Tension and Bending *435*
9.8 Design of Eccentrically Loaded Base Plates *436*

Chapter 10 Bolted Connections 458

Introduction *458*
10.1 Rivets and Riveted Connections *461*
10.2 Bolted Connections *462*
10.3 Behaviour of Bolted Joints *470*
10.4 Design Strength of Ordinary Black Bolts *473*
10.5 Design Strength of High Strength Friction Grip Bolts *480*
10.6 Simple Connections *485*
10.7 Moment Resistant Connections *495*
10.8 Beam-to-Beam Connections *506*
10.9 Beam and Column Splices *508*

Chapter 11 Welded Connections 547

Introduction *547*
11.1 Welding Processes *548*
11.2 Welding Electrodes *550*
11.3 Advantages of Welding *551*
11.4 Types and Properties of Welds *553*
11.5 Types of Joints *559*
11.6 Control of Shrinkage and Distortion *562*
11.7 Weld Symbols *563*
11.8 Weld Specifications *564*
11.9 Effective Area of Welds *567*
11.10 Design of Welds *570*
11.11 Simple Joints *572*
11.12 Moment Resistant Connections *579*
11.13 Continuous Beam-to-Column Connections *587*
11.14 Beam and Column Splices *589*

Chapter 12 Design of Industrial Buildings 619

Introduction *619*
12.1 Selection of Roofing and Wall Material *619*
12.2 Selection of Bay Width *624*
12.3 Structural Framing *624*
12.4 Purlins, Girts, and Eave Strut *626*
12.5 Plane Trusses *628*
12.6 End Bearings *644*

Appendix A: Properties of Structural Steel Sections *662*
Appendix B: Properties of Soils *684*
Appendix C: Computer Programs *689*
Appendix D: Design Aids *717*
Appendix E: Conversion Factors *749*
Bibliography *751*
Index *763*

CHAPTER 1

Structural Steel: Types, Properties, and Products

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.

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.

The main advantages of structural steel as a building material are its strength, speed of erection, prefabrication, and demountability. They are 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.

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.

A brief introduction to the loads to be considered during the analysis of steel structures and a discussion about the methods of analysis are also provided.

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).

Structural 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 till 1980. 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.

Riveting was used as a fastening method until around 1950 when it was superseded by welding. 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 Section 1.4). The electric arc furnace is used to make special steels such as stainless steel.

1.2 Processes Used for Steel Making

Currently steel is produced largely by the *basic oxygen steel making* (BOS) process and the *electric arc method*. Steel production is basically a batch process and involves reducing the carbon, sulphur and phosphorous levels and adding, when necessary, manganese, chromium, nickel or vanadium.

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.

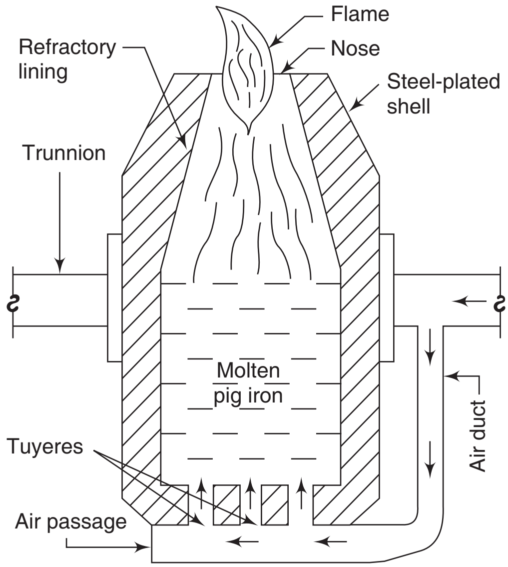


Fig. 1.1 Basic oxygen steel making (BOS) process (Rangwala et al. 1997)

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. 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*. 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 process is called *continious casting* or *concast method*.

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. Further processing of steel can include cold rolling, pickling (to remove oxides and mill scale from the surface of the steel), and coating.

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 schematic diagram showing the various stages of manufacturing of structural steel sections from the iron ore are shown in Fig.1.2.

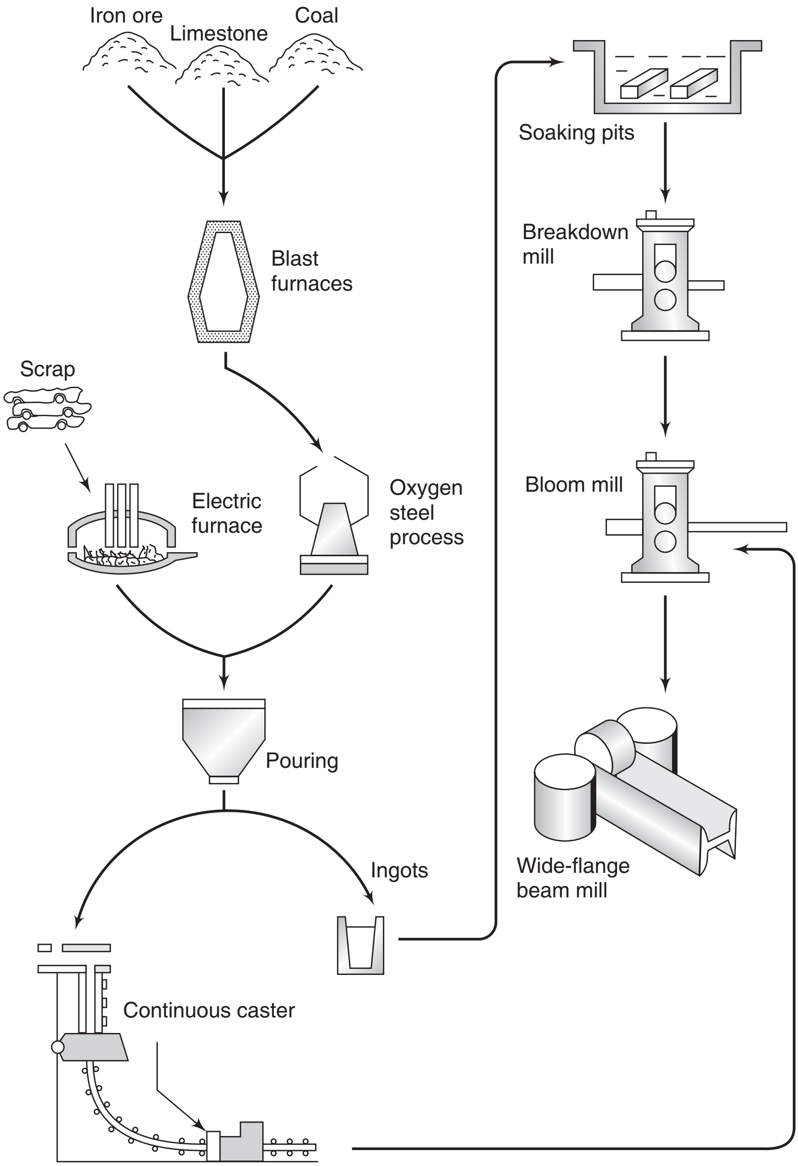


Fig. 1.2 Schematic diagram showing the various stages of manufacturing structural steel sections from iron ore (Kulak & Grondin 2002)

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.

As early as in 1907, Jamsetji Nusserwanji Tata set up the first integrated steel manufacturing plant at Jamshedpur in Bihar. Then major steel plants were constructed at Bhilai, Rourkela, Durgapur, and Bhadravati steel plant in Karnataka. The steel sector now consists of seven integrated plants and about 180 mini steel plants and rerollers. 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.

In 2004–05, the annual production of steel in India 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.

1.3 Heat Treatment of Steel

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. In the annealing process, the steel is heated to a temperature just greater than 910°C and held at that temperature to achieve uniformity of composition and temperature prior to slow cooling, usually in the furnace. Sufficient cooling time allows the carbon diffusion and transformation process to get completed. This refined pearlite + ferrite microstructure shows both increased strength and ductility.

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. 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.

Mild steel plates, structural sections, etc., show very good properties of strength with ductility in the normalized condition. Heat treatment is costly and in India the heat treated steels amount hardly to about 5% of the steel produced (Rangwala 1997).

1.4 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%). Structural steels normally have a carbon content less than 0.25%. 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.

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, mobium, 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 < 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%).

If the silicon content 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. 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.

1.5 Weldability of Steel

In most cases, members of steel are welded during fabrication. 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.

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).

$$C_{eq} = \frac{C + Mn}{6} + \frac{(Cr + Mo + V)}{5} + \frac{(Ni + Cu)}{15} \tag{1.1}$$

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 1.1.

Table 1.1 Types of steel and their relevant IS standards

Type of steel	Relevant IS standards
Structural steel	2062, 1977, 3502, 5517, 8500
Steel for tubes and pipes	1239, 1914, 806, 1161, 10748, 4923
Steel for sheets and strips	277, 1079, 12367, 513, 12313, 14246
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 filer 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 1.2. For details of chemical composition of other steels refer IS 1977 [structural ordinary (low tensile) quality], IS 8500 (medium and high strength quality).

Table 1.2 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	0.4	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/mm^2 or MPa

[b] K—killed steel, SK—semi-killed steel (explained in Section 1.2)

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

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 410 to 440 MPa and their specified minimum yield strength from about 230 to 300 MPa (see Table 1 of IS 800 : 2007).

High-strength carbon steel 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 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 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. 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.

Fire-resistant steels Also called thermomechanically treated steels, they perform better than ordinary steel under fire.

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. 1.3. 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 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.

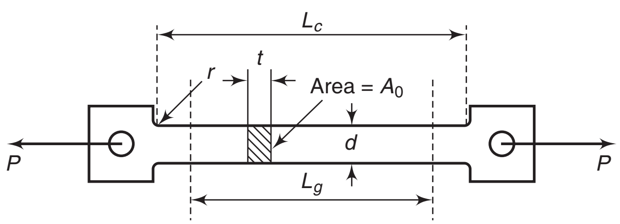


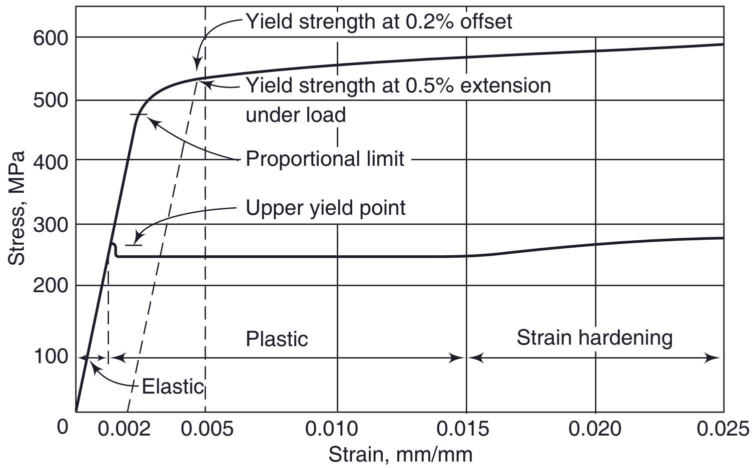
Fig. 1.3 Standard tensile test specimen as per IS 1608

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. 1.4(a) and the stress–strain curve of mild steel specimen is shown in Fig. 1.4(b).

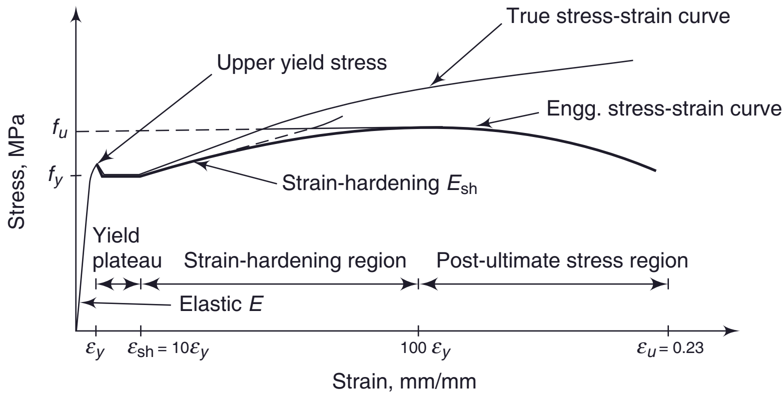
The ultimate tensile strength is the highest stress at which a tensile specimen fails by fracture and is given by

$$\text{Ultimate tensile strength} = \frac{\text{ultimate tensile load}}{\text{original area of cross section}} \quad (1.2)$$

Note that steel is specified in the code by the characteristic ultimate tensile strength, 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]. However, in some countries like the USA, steel is specified according to the (characteristic) yield strength.



(a)



(b)

Fig 1.4 Typical stress-strain curves of mild steel-(a) stress-strain curves of ordinary and high-streangth 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 1.3 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 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.

Table 1.3 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) Thickness (mm) <20	20–40	>40	Min. percentage elongation (gauge length = $5.65\sqrt{A_0}$)	Charpy V-notch impact energy (min.)
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	20	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	12×10^{-6}/°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

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*.

As shown in Fig. 1.4(a), initially the steel has a linear stress–strain curve whose slope equals Young's modulus of elasticity, E. Thus,

$$\text{Modulus of elasticity} = \frac{\text{stress within the proportional limit}}{\text{strain}} \quad (1.3)$$

This can be expressed as

$$E = \frac{f}{\varepsilon} \quad (1.4)$$

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 $\varepsilon_y = f_y/E$. 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 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 ε_y and 15 ε_y. The average value of 10 ε_y is taken as the yield plateau of structural steels. The value of ε_u is taken as 100 ε_y and that of ε_{br} as 0.23 mm/mm. The initial slope of the strain-hardening part of the curve is termed as 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. 1.4(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. 1.4(b) 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_{yl} 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). 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. 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 the yield stress 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.

(a) The yield plateau should extend for at least six times the strain at first yield.

(b) 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.)

(c) 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 1.5 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.)

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. 1.5). 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. 1.5. 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.

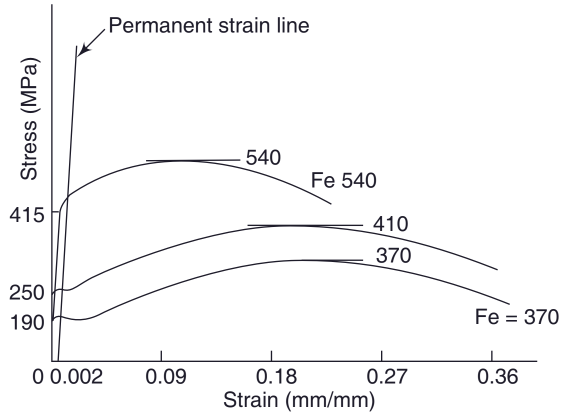


Fig. 1.5 Stress-strain curves of different types of steel produced in India

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. 1.6. 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.

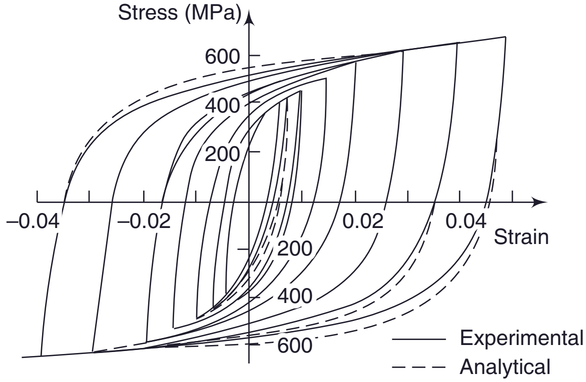


Fig. 1.6 Stress-strain curve of steel subjected to cycle loading

1.8.3 Characteristic Strength

Variations in material properties 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. 1.7.

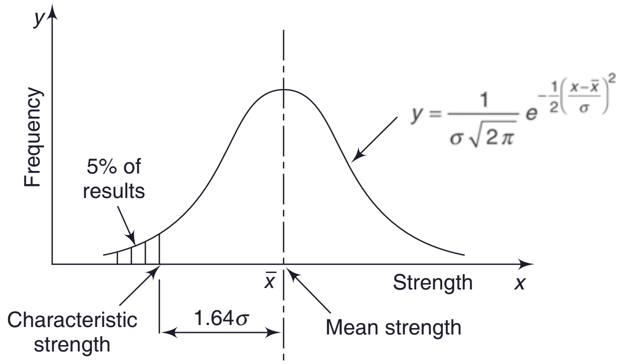


Fig. 1.7 The normal distribution curve

This curve can be mathematically expressed by the equation shown in Fig. 1.7, 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. 1.7, 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

$$f_k = f_{mean} - 1.64\,\sigma \tag{1.5}$$

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

$$\sigma = \left[\frac{\Sigma(f_{mean} - f)^2}{(n-1)}\right] \tag{1.6}$$

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.

$$\text{Gauge length} = 5.65\sqrt{A_0} \tag{1.7}$$

$$\text{Percentage elongation} = \frac{(\text{elongated length between gauge point} - \text{gauge length}) \times 100}{\text{gauge length}} \tag{1.8}$$

The measured elongation is influenced by the gauge length, strain rate of test, and failure within or outside the gauge length.

Values of 20% can be obtained for mild steel but are less for high-strength steel. By improper testing one may get percentage elongation values of 20–60 and hence the test houses should be careful with the testing process. A high value is advantageous because it allows the redistribution of stresses at ultimate load and the formation of plastic hinges. The minimum required percentage elongations of steel produced in India as per the code are given in Table 1.3(a) (also see Table 1 of IS 800 : 2007). For most standard mild steels, the values are greater than the minimum required. However, rerolled steel or improperly controlled steel may give higher strength but less percentage of elongation.

1.8.5 Low Temperature and Toughness (Brittle Fracture)

In structural steel design, toughness is a measure of the ability of steel to resist fracture under impact loading, i.e., the capacity to absorb large amounts of energy. Toughness can be an important design criterion, particularly for structures subject to impact loads (e.g., bridges) and for those subject to earthquake loads. Hence both strength and ductility contribute to toughness.

At room temperature, common structural steel is very tough and fails in a ductile manner. At temperatures below 0°C, steel structures sometimes fail suddenly and without warning. A right combination of low temperature, an abrupt change in section size (notch effect) or an imperfection, and the presence of tensile stress can initiate a failure called *brittle fracture*. This may begin as a crack, which may propagate and cause the member to fail. Most brittle fractures occur under static load at stress levels which are not excessive, but they may also be due to the dynamic application of a load or some overload.

One of the best known brittle fractures occurred in Boston in a riveted steel tank of diameter 27.5 m and height 15 m, which contained 7.57 million litres of molasses. The tank failed in an explosive manner on January 15, 1919. Similar sudden failures of steel water tanks, oil tanks, transmission lines, ships, plate girders, and bridges have occurred in the past (McGuire 1968). Most of these failures have occurred under normal service conditions, in welded structures, and at low temperatures. During the cold winter of 1977, several spectacular failures occurred in bridge structures in Illinois, Minnesota and Pennsylvania in the USA. On January 22, 1988, several brittle failures occurred in a bridge in Providence, Rhode Island, the USA (Gaylord et al. 1992).

The *Charpy V-notch test* (CVN test) is commonly used to evaluate the behaviour of metals as they are affected by an abrupt change in cross section (IS 1757). In this test, the temperature of the specimen is varied, the energy absorbed by each specimen is recorded, and the energy–temperature curve is plotted. From this curve, a transition temperature corresponding to some level of energy absorption (usually 20 or 27 J) is selected.

Structural steels vary greatly in toughness. Highly killed, fine grain steel with a suitable chemical composition or specially heat-treated steel exhibit considerable toughness. IS 2026 and IS 1757 codes allow the use of only those steels that exhibit a minimum energy absorption capacity at a predetermined temperature (e.g., 20 J at 23 ± 5°C). In addition to the chemistry of steel, size of plates, residual stress, and cold work also affect toughness. (Thick plates, large residual stress, and cold work are detrimental.)

1.8.6 Lamellar Tearing

Lamellar tearing is a form of brittle fracture that may occur in certain welded joints. For example, a tear can occur if a large weld (or welds from both sides) is placed on a thick plate, since the shrinkage strains from the welding operation will be large and restrained. The restraint may be developed due to the weld on the far side or due to the member thickness or due to a combination of both the factors.

Generally I-sections are adequately ductile when loaded either parallel or transverse to the rolling direction. A thin, stiffened column is susceptible to lamellar tearing, since the flange stiffeners that are welded to the column flange produce a restraint. A large overmatch of electrode and base metal in a full penetration butt weld also tends to increase the possibility of tearing.

The use of fillet welds, a joint design that allows weld shrinkage to occur in the rolling direction, and the sequence of welding to minimize shrinkage strains are practical methods used to avoid lamellar tearing.

1.8.7 High-temperature Effects

Steel is not a flammable material. However, its strength reduces with rise in temperature. The yield as well as tensile strength at 500°C are about 60–70% of that at room (about 21°C) temperature. The drop in strength is much higher at still higher temperatures (for example at 800°C it is only 15% of that at room temperature).

Hence, steel frames enclosing materials that are flammable require fire protection, to control the temperature of steel members for a sufficient time for the occupants to seek safety or for the fire be extinguished before the building collapses. In many cases, the building does not collapse even at high temperatures. But the members are deformed beyond acceptable limits, and hence have to be replaced.

The fire-resistance design of steel members, the methods to model real fire, and its effect on steel members are discussed in detail in Subramanian (2008).

1.8.8 Hardness

Hardness is a measure of the resistance of the material to indentations and scratching. Several methods are available to determine the hardness of steel and other metals. In all these methods, an 'indentor' is forced on to the surface of the specimen. On removal, the size of the indentation is measured using a microscope. Based on the size of the indentation, the hardness of the specimen is determined. Brinell hardness (typical value: 150–190) and Vickers hardness tests are used to determine hardness.

1.9 Resistance to Corrosion

Steel readily corrodes in moist air. Exposure to sea water, acid, or alkaline vapours hasten the process. It has been estimated that more than 0.075 mm of the thickness of steel members will be lost every year in an industrial environment in which sulphur dioxide is present. Hence, structural steel members should be protected effectively against corrosion.

The most common method of protecting a steel member involves the use of paint or metallic coating, or a plastic coat in the case of metallic sheeting. Steels with a copper content of 0.2–0.5% have improved resistance to atmospheric corrosion but still need to be protected. Paint systems consist of a zinc- or aluminium-based primary coat on which two or three layers of finishing coats are applied. Metallic coatings involve galvanizing and sheradizing (both of which use zinc), electroplating (usually applied to fasteners), and metal spraying using either zinc or aluminium. For the coating or painting to be effective, the surfaces of the steel members have to be cleaned effectively before treatment. Several methods are available and the usual one consists of blast cleaning the surface using small abrasive particles such as those of iron, which are directed to the surfaces of the members by using compressed air or an impeller. Instead of protective treatment, one can go in for special corrosion-resistant steel, which on exposure to weather forms a protective surface layer of oxide film. Such weathering steels contain a greater amount of phosphorus and some chromium and copper than normal steel. They cost 20% more than normal steel but this initial cost may be offset by savings in weight, protective treatment, and maintenance.

1.10 Fatigue Resistance

Fatigue is the term used in connection with the initiation and propagation of microscopic cracks into macrocracks by the repeated application of alternating stresses. The damage and failure of materials under cyclic loads is called *fatigue damage*. Fatigue need not be considered unless numerous significant fluctuations (usually taken as 2×10^6 to 5×10^6 cycles) of stress are anticipated. As per the code, stress reversals due to wind need not be checked for fatigue. Wind-induced oscillations have to be taken into account in special cases. For instances, oscillations of 2×10^6 cycles can be easily reached in a lighting mast. The code states that the designer should check the following members for fatigue assessment.

(a) Members supporting lifting or moving loads,
(b) Members subjected to wind-induced oscillations of a large number of cycles,
(c) Members subjected to repeated stress cycles from vibrating machinery, and
(d) Members subjected to crowd-induced oscillations.

Thus, fatigue effects are more likely to occur in bridges and gantry girders due to the cyclic nature of loading, which causes reversal of stresses. Welds are susceptible to a reduction in strength due to fatigue because of the presence of small cracks, local stress concentrations, and abrupt changes of geometry. It has to be noted that the incidence of fatigue and fatigue crack growth is independent of steel grade. Fatigue cracks are far more common than brittle fracture. Guidelines for the designer to take into account fatigue loads are discussed in detail in Subramanian (2008).

1.11 Residual Stresses

Higher temperatures in the range of 600–700°C are involved during the rolling of steel sections. Steel members are also subjected to high temperatures, to selected parts of cross-section, while members are fabricated by welding and also when material or members are cut by flame-cut. Cooling of these members or materials always takes place unevenly, for example, the flange tips of an I-section, cool faster than the flange-to-web junctions. Similarly the central portion of the web tends to cool faster than the junctions. Due to this uneven heating and cooling, structural members normally contain *residual stresses.* Residual stresses may also result from the cold straightening of bent members (Gaylord et al. 1992). Although it is possible to remove these stresses by subsequent reheating and slow cooling, this process is not attempted in normal structural engineering applications.

The typical distribution of residual stresses in a standard I-section is shown in Fig. 1.8(a). Residual stresses tend to increase in magnitude with increase in size of the element. The magnitude of tensile residual stresses may reach up to $0.3f_y$ and the compression residual stress up to $0.5f_y$ in rolled I-sections (Trahair et al. 2001).

A welded I-section fabricated from rolled plates has a different residual stress distribution from that of an I-section welded from plates flame-cut to width. The typical distribution of residual stresses in welded sections made of plates with rolled edges is shown in Fig. 1.8(b).

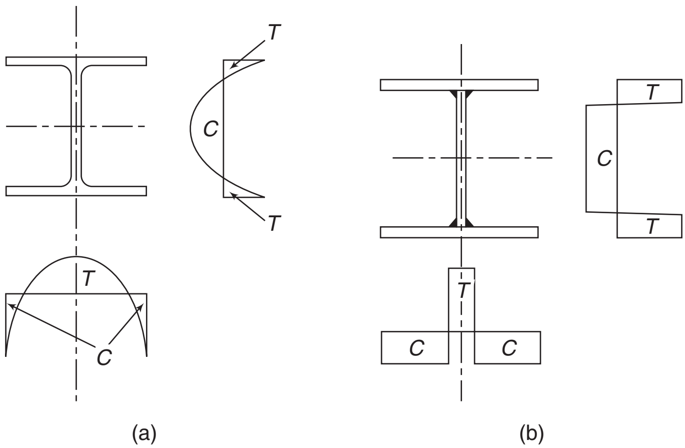


Fig. 1.8 Residual stress distribution in standard and welded I-beams

Fabricating operations such as cambering and straightening by cold bending also induce residual stresses. These stresses are superimposed on the thermal residual stresses. Because residual stresses must themselves be in equilibrium, their effect on structural behaviour is limited. However, residual stresses play an important role in the design of compression members (columns), since under compressive stress, the regions that contain residual compressive stress yield earlier (at loads which produce an applied stress less than f_y). Similarly, members in bending (beams) also yield early and hence tend to deflect more (Tall 1974). Residual stresses are also to be considered in the design of members subject to fluctuating loads (fatigue).

1.12 Stress Concentration

Steel structures often have connected elements which may have abrupt change in geometry and may contain holes for bolts. These features produce *stress concentrations*, which are localized stresses, greater than the average stress in the member (tensile stresses adjacent to a hole are often three times the average tensile stress).

The stress concentration at the holes is usually neglected in structural design and it is assumed that the stress is uniformly distributed over the net area of cross section. Since structural steel is sufficiently ductile to equalize the stress over the area, this assumption is justified in most cases. However, if the average stress in a member is high, the stress concentration effect should not be ignored. Stress concentration effects have been found to be critical in the webs of plate girders. Stress concentrations are also associated with fatigue and can also affect brittle fracture.

1.13 Structural Steel Products

Structural steel products of interest to designers can be divided into the following categories.

(a) Flat hot-rolled products—plates, flat bars, sheets, and strips,
(b) Hot-rolled sections—rolled shapes and hollow structural sections,

(c) Bolts,
(d) Welding electrodes, and
(e) Cold-rolled shapes.

1.13.1 Hot-rolled Sections

The hot-rolled sections and products consist of the following (see Fig. 1.9).

- Rolled beams
  - Junior beams (ISJB, meaning Indian Standard Junior Beams)
  - Lightweight beams (ISLB)
  - Medium-weight beams (ISMB)
  - Wide-flange beams (ISWB)
  - Heavyweight beams/columns (ISHB)
  - Column sections (ISSC)
- Channels: Junior, light, and medium and parallel flange (ISJC, ISLC, ISMC, ISMCP)
- Equal angles (ISEA or ISA)
- Unequal angles (ISA)
- T sections (ISJT, ISLT, ISST, ISNT and ISHT)
- Rolled bars
  - Round (ISRO)
  - Square (ISSQ)
- Tubular sections (ISLT, ISMT, ISHT)
- Plates (ISPL)
- Strips (ISST)
- Flats (ISFl)

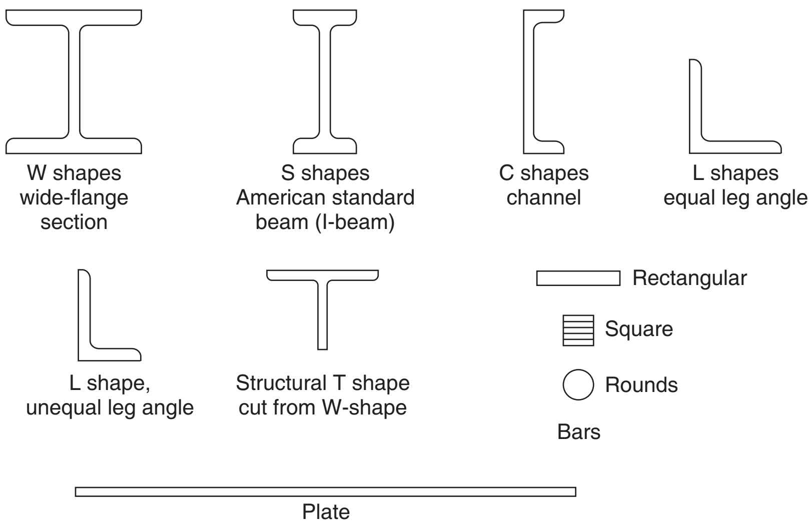
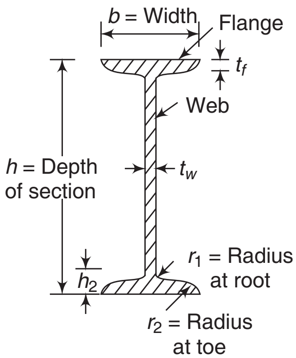
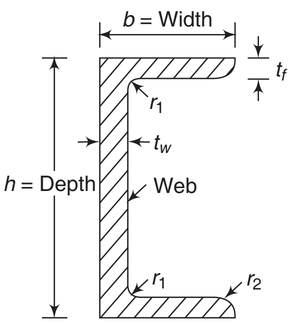
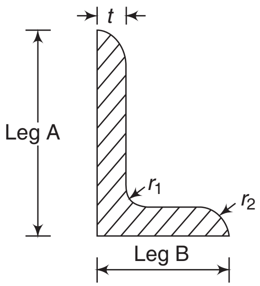


Fig. 1.9 Types of hot-rolled sections produced by steel producers

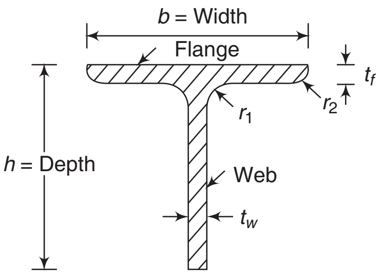
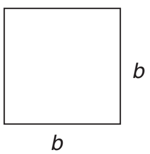
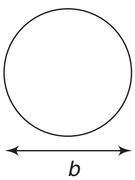
The standard rolled steel shapes and the nomenclature used in relation to them are mentioned in Table 1.4. Such nomenclature should be properly understood since it will be followed in the subsequent chapters.

Table 1.4 Rolled-steel structural shapes

<table>
<tr><th>Rolled section</th><th>Indian standard designation</th><th>Remarks</th></tr>
<tr><td>
</td><td>ISJB
ISLB
ISMB
ISWB
ISHB</td><td>A beam section referred to as ISMB 400 at 0.616 kN/m is an ISMB with a depth of 400 mm and a weight of 0.616 kN per metre length.</td></tr>
<tr><td>
</td><td>ISJC
ISLC
ISMC</td><td>Channel sections are referred to, for example, as ISMC 200 at 0.221 kN/m.</td></tr>
<tr><td>
</td><td>ISA</td><td>Angles are equal or unequal.
For equal angles, $A = B$.
For unequal angles $A > B$. Angles are referred to, for example, as ISA 60 × 60 × 6, indicating equal angles with legs 60 mm each and thickness 6 mm. An example of an unequal angle is ISA 100 × 75 × 6.</td></tr>
</table>

(*contd*)

(*contd*)

Rolled section	Indian standard designation	Remarks
	ISNT ISHT ISST ISLT ISJT	Tee sections are referred to, for example, as ISNT 100 at 0.147 kN/m, indicating that the depth of the section is 100 mm.
Plates	$t \geq 5$ mm	Plates are referred to in terms of width × thickness, e.g., 900 × 10 indicates a plate 900 mm wide and 10 mm thick.
Strips	$t < 5$ mm	Strips are referred to in terms of width × thickness.
Flats	$t \geq 5$ mm $b \leq 250$ mm	Flats are referred to in terms of $b \times t$.
		A square bar is referred to in terms of its sides, e.g., a 20-mm square bar.
		A round bar is referred to in terms of its diameter, e.g., a 20-mm diameter bar.

Steel tubes are designated in terms of their nominal bore in millimetres and self-weight. Rolled-steel circular or square rods are designated, respectively, in terms of diameter or side (e.g., ISRO 10 mm or ISSQ 10 mm).

IS Handbook No. 1 and IS 808, published by the Bureau of Indian Standards, provide the dimensions, weights, and geometrical properties of steel beam, column, channel and angle sections. Since these publications do not contain the plastic modulus and shape factor for steel I-beams, they are provided in Annex H of IS 800 : 2007.

Choice of section

The design of steel sections is governed by the cross-sectional area, *section modulus*, and *radius of gyration*. Though IS 808 and IS Handbook No.1 list the properties of various sections, due to the limitations of rolling mills only a few sections are available in the market. Therefore, design is governed by not only sectional properties but also the availability of the section. Another factor governing choice is the ease with which sections can be connected. In India ISMB beams are the most commonly produced. So are limited number of ISHB sections. Also, only medium channels are available. Only a limited number of unequal angles are available in the market. Also, not all the equal-angle sections are available readily in the market. Hence it will be a good idea to get a list of the available sections from steel producers like SAIL and plan the design accordingly. Appendix A gives the sectional properties of some of the sections manufactured in India.

Channels are used mainly as purlins in industrial buildings and angles in trusses and towers. The structural tee is commonly used for chord members in trusses, though in India double angles are also used for the purpose.

IS 1852 specifies allowable rolling tolerances, including amount of flange and web warping, and the deviation of web depth permitted for the section to be satisfactory. Designers should be careful about these tolerances, especially while using smaller sections which may be produced by small rerollers. It is because the designed cross-sectional properties may not match with the actual cross-section properties. Also, as mentioned previously, the rerolled sections may tend to have higher strength at the risk of reduced ductility.

Though the latest IS 800 : 2007 code has removed the minimum thickness requirements, it is advisable to use a minimum thickness of 6 mm for the main members and 5 mm for secondary members exposed to the atmosphere, especially in coastal areas.

1.13.2 Wide-flange Sections

As mentioned in Section 1.13.1, ISMB sections are the only I-sections that are normally produced in India on account of the calibre rolling method. These sections are used for beams as well as columns. Such sections have relatively narrow and sloping flanges and a thick web compared to wide-flange sections (see Fig. 1.10). ISMB beams are not economical, especially for compression members, because of excessive material in the web and the lack of lateral stiffness due to the narrow flanges. Also, since the available sections are limited, when a section is slightly inadequate, the choice is limited to either the next available section (which may be 25–45% heavier in weight) or built-up sections through welding, using which involves extra time and cost.

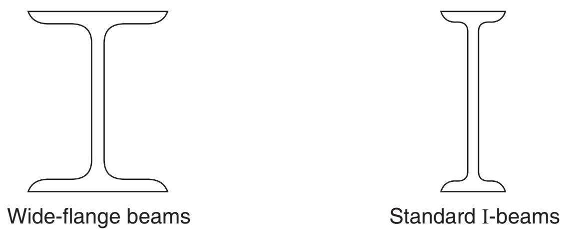


Fig. 1.10 Wide-flange sections

The main features of wide-flange beams which make them more popular than Indian standard I-beams are the followings.

(a) Wide-flange beams provide excellent sectional performance, with high bending and buckling resistance due to the H-shaped arrangement of flanges and the web.

(b) The use of such beams reduces fabrication difficulties—since there is no taper in the H-beam flange, no tapered washer is necessary for bolting, and the gussets can be welded to the inner surface of the beam flange. Unlike tapered-flange beams, H-beams can be readily butt welded, and a sound welding is assured.

(c) Since H-beams have a higher section modulus for the same weight, using them is economical. (A saving of the order of 10–24% can be achieved.)

Using a new manufacturing technology, it is now possible to have beams with the same depth but with different flange and web thickness, and also flange width. This facilitates simple design and improves fabrication efficiency. These wide parallel-flange beams and columns are manufactured in India by M/s Jindal Steel and Power Limited (JSPL) at Raigarh, Chhattisgarh. The sectional properties of some of these beams are discussed in detail in Subramanian (2008).

1.13.3 Welded and Hybrid Sections

Hot-rolled plates or flame-cut plates can be welded together to form I-sections or box girders (see Fig. 1.8). Such built-up sections can also be made by using riveting or bolting. Welded I-beams with top and bottom plates and welded stiffeners are often used as plate girders. Welding makes it possible to combine any structural shape to get the desired properties. *Tapered girders* are fabricated either by welding two flange plates to a tapered web plate or by cutting a rolled I-beam lengthwise along its web at an angle, turning one half end for end, and then welding the two halves back together again along the web as shown in Fig. 1.11(a). Tapered girders are widely used in the framing of roofs over large areas, where it is desirable to minimize the number of interior columns or to eliminate them altogether.

Similarly, *castellated beams* (also called *cellular beams*) can be made economically by flame-cutting a rolled I-beam web in a zigzag pattern along its centreline [see Fig. 1.11(b) and (c)]. One of the two equal halves is turned end for end and is welded to the other half. The result is a deeper beam, stronger and stiffer than the original. Castellated beams have more section modulus and moment of inertia and result in greater economy. Figure 1.12 shows a parking structure with castellated beams, that led to significant savings in construction costs. Properties of castellated beams made of ISMB beams and channels are discussed in detail in Subramanian (2008).

Since the web of a beam or a plate girder contributes only a little to the bending resistance and because its strength in shear depends on its slenderness ratio h/t, it is economical to have the web of a lower-strength steel than the flange. Beams with stronger steel in the flanges than in the web are called *hybrid beams*. Such beams are often fabricated by welding plates of different steel strengths.

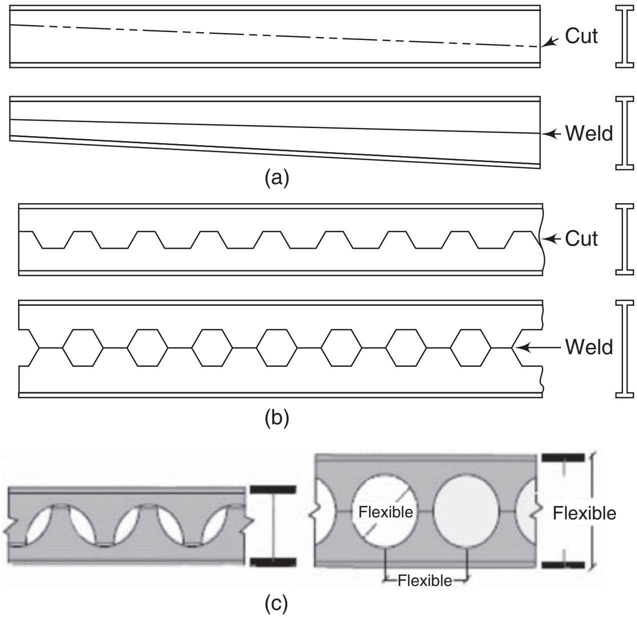


Fig. 1.11 Tapered girders and castellated beams

Fig. 1.12 Cellular beams over Rangers FC, an indoor training facility in Scotland (Courtesy: ASD Westok Ltd, UK)

With the development of high-performance steels (see Section 1.14), it is now possible to fabricate built-up I-beams with corrugated webs. The corrugations can have a trapezoidal shape or a sine-wave cross section. Corrugated webs allow deeper girders that are not susceptible to web stability problems, resulting in thinner webs and smaller flanges.

1.13.4 Hollow Steel Sections

Tubular members are being used extensively in plane and space trusses as tubes are more efficient in compression. The advent of welding has made the connection between tubular members using gusset plates possible and resulted in the widespread use of tubular sections. Welded connections without gusset plates require proper planning for profiling and welding the ends, and have to be executed carefully. Recently, square and rectangular tubes have been introduced in India and these, of course, are much easier to connect because of their flat surfaces. With square or rectangular hollow sections, the smaller tube can be simply sawed with a single cut at the required angle and welded to the bigger tube.

Flowdrill and Hollo-bolt Systems

The use of standard bolt is often impossible in steel hollow sections, as there is no access to the inside of the tube to allow for tightening. The use of gusset plates and brackets overcomes this problem but is not aesthetically pleasing. Several techniques have been developed which permit bolt installation and tightening from one side of the connection only; they are called *blind bolts*. Commercially available examples include Flowdrill and Hollo-bolt.

Flowdrilling is basically a thermal drilling process which makes a hole through the wall of an SHS without removing the metal normally associated with a drilling process. The formed hole is then threaded by the use of a special tool, leaving a threaded hole which will accept a standard fully threaded bolt. In the flowdrill system, the tungsten carbide bit of the Flowdrill is brought into contact with the RHS wall, where it generates sufficient heat to soften the steel. The bit is then advanced through the wall and when it is done, the metal 'flows' to form an internal bush. The tool also removes any surplus material which may arise on the outside of RHS section. In the next stage, the flowdrill bush is threaded with a coldform flowtap so that the connection can be made with bolts. The complete cycle is shown in Fig. CS1. Note that the Flowdrill method cannot be used with pre-galvanized sections.

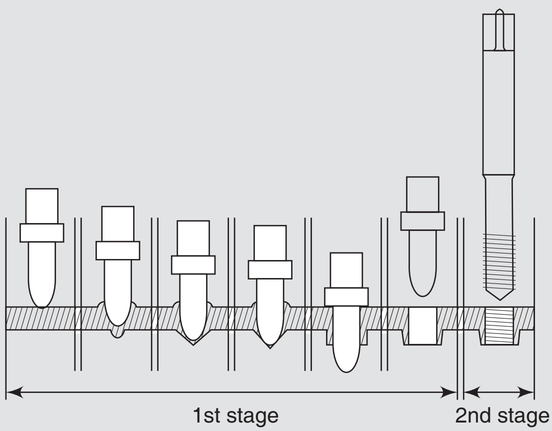


Fig. CS1

In the hollo-bolt system, a pre-assembled unit is inserted through normal tolerance holes in both the RHS and attachment plate. As the bolt is tightened, the cone is drawn into the body, spreading the legs, and forming a secure fixing. After installation, the hollo-bolt head and collar only are visible as shown below.

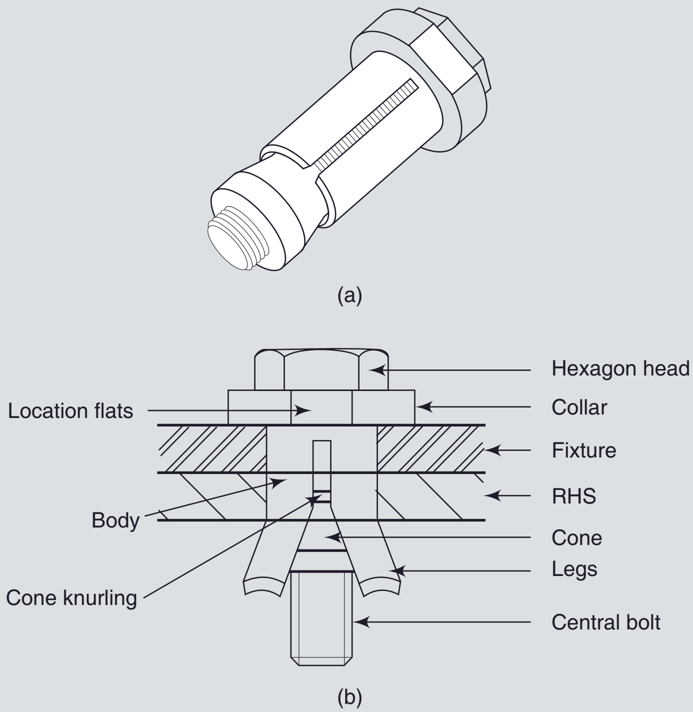


Fig. CS2 (a) Hollo-bolt and (b) hollo-bolt assembly

In India, till recently only two grades of RHS, i.e., f_y = 210 MPa (f_u = 330 MPa) and f_y = 240 MPa (f_u = 450 MPa) were produced. Now, HSS as per the specifications given in IS 4923 with f_y = 310 MPa (f_u = 450 MPa) are also available.

As per IS 1161, tubes for structural purposes are available in three grades of steel (see Table 1.5) in light, medium, and heavy categories. The yield stress of Yst 240 is the same as that of mild steel and this is often the grade (medium-section) available in the market. The properties of hollow sections and tubes are given in Appendix A. Yst 310 grade tubes are also available ranging in diameter from 15 mm (NB) to 300 mm (NB).

Table 1.5 Strength of steel used for circular tubes as per IS 1161

Grade	Ultimate tensile stress, f_u (MPa) (min.)	Yield stress, f_y (MPa) (min.)
Yst 210	330	210
Yst 240	410	240
Yst 310	450	310

It has to be noted that tubes having less than 3.25 mm have to be carefully welded. If the tubes and hollow sections are not plugged at the ends properly, they retain the moisture inside and corrosion starts from the inside, which will not be noticed at the early stages.

1.14 High-performance Steel

A new grade of steel, called high-performance steel, HPS-485W was developed by a cooperative program between the Federal Highway Administration, the American Iron and Steel Institute, and the Department of the Navy in August 1994. Three grades of HPS are available now: HPS-345W, HPS-485W, and HPS-690W, out of which HPS-485W (yield strength = 485 MPa), is widely used. The benefits related to HPS include enhancements in weldability, toughness, corrosion resistance, ductility, fatigue and fire resistance, formability, and strength. These factors combined led to construction elements of higher economic efficiency, ease of maintenance, and longer service life.

The Nebraska Department of Transportation was the first to use HPS 485W in the design and construction of the 45-m simple span Snyder bridge, a welded plate girder (1.37 m) bridge, which opened to traffic in October 1997. In April 2002, there were 21 HPS 70W steel bridges in service and 13 more bridges are under various stages of construction in the USA alone. More details about HPS may be found in Jamshidi et al. (1997), and Gross and Lwin (2002).

High-performance Steel Bridge in Tennessee, USA

The bridge in Tennessee is a two-span continuous structure located on State Route 53 over the Martin Creek in Jackson County. The structure provides an 8.5-m wide roadway over two spans, both 72 meters long. This bridge consists of three continuous welded plate girders, fabricated from HPS-485W, 2-m deep, and spaced at 3.2 m centers. These plate girders act compositely with a cast-in-place concrete deck slab of thickness 212.5 mm.

The bridge is jointless, having integral, pile-supported abutments. The design was fully optimized for the 485-MPa steel, using the AASHTO Load and Resistance Factor (LRFD) Bridge Design Specifications. In the positive moment region, the top flanges are 450 mm wide and vary from 25 to 50 mm thickness in four increments. In the negative moment region, the top flanges vary in four

increments of 28 mm by 450 mm to 62.5 mm by 750 mm. The webs vary from 11 mm by 1800 mm in the positive moment region to 12.5 mm by 1800 mm over the negative moment region.
Cost estimates prepared by the Tennessee Department of Transportation indicate that the steel weight was reduced by almost 25% compared to the original grade 345W design. Because HPS-485W costs slightly more than grade 345W steel, this resulted in a 16% reduction in the total cost to fabricate and erect this bridge.

1.15 Stainless Steel

Stainless steel is essentially a low-carbon steel to which chromium has been added. It is this addition of chromium, in amounts greater than 10.5% by weight, that gives the steel its unique 'stainless' corrosion-resistant properties.

Of the various available grades, SS 304, SS 304L, SS 306, SS 409, and SS 430 are suitable for structural applications. The stainless steel production in India was only 20,000 tonnes in 1978; it increased to around 1.7 million tonnes in 2006.

The advantages of stainless steel include its aesthetic appearance, corrosion resistance, high tensile strength, high toughness, impact, and heat resistance. Hence, several countries have developed separate guidelines for the design of stainless steel structural members (Euro Inox 1994, ASCE/ANSI-8-90, ENV 1993-1-4). But Indian Code provisions for the design of stainless steel members are not available. This is one of the reasons, in India, for the non-application of stainless steel members in engineering structures.

The first application of stainless steel in a space frame roof, designed by the author, is at the entrance of M/s. Jindal Strips Limited at Hissar, Haryana (Subramanian, 2002), and is shown in Fig.1.13

Fig. 1.13 Stainless steel double-layer grid roof at Hissar, Haryana

In addition to the above different products, *cold formed steel sections*, made from light-gauge steel strips of thickness 2 to 4 mm thick (20-8 B.G.) are also available. Cold-rolled C, Z, and Sigma sections are often used as purlins and are economical than hot-rolled channels. They are designed using IS 801 code (which is under revision), and is outside the scope of this book. Details of design may be found in Yu (2000) and the IS handbook on light gauged sections (SP 6.5).

1.16 Composite Construction

The properties of reinforced concrete (strong in compression, greater rigidity) can be advantageously combined with the properties of structural steel to produce *composite constructions.* These constructions include (a) concrete–encased steel columns, (b) concrete-filled steel columns, (c) concrete-encased steel beams, and (d) steel beams supporting concrete slabs. Composite construction results in savings in time and material.

The design of composite construction is done by using IS 11384-1985, and is outside the scope of this book. The details of design may be found in Nethercot (2001), Martin and Purkiss (1992), and Kulak and Grondin (2002).

1.17 Advantages of Steel as a Structural Material

Structural steel offers several advantages over other competing materials. These advantages are as follows.

High strength The high strength of steel per unit weight means that structures made of steel sections weigh less than those made of other materials.

High ductility In structures built with structural steel, occasional human errors such as accidental overloading do not cause problems, due to the ductility of steel. Steel building are preferred in earthquake zones due to their greater ductility.

Uniformity The quality of steel-intensive construction is invariably superior, when compared with that of construction involving other materials. This is especially important in India, where quality control in construction sites is poor (resulting in poor performance, especially in concrete structures where water–cement ratio and curing are not controlled properly at site). Moreover, the properties of steel do not change appreciably with time as do those of reinforced concrete.

Environment-friendly Structural steel is recyclable and environment-friendly. Over 400 million tonnes of steel are recycled annually worldwide, which represents 50% of all steel produced. Steel is the world's most versatile material to be recycled. Another characteristic of a steel structure is that it can readily be disassembled at the end of its useful life. It means that the steel components can be reused in future structures without the need for recycling, resulting in the saving of energy and avoidance of CO_2 emitted from the steel production processes.

Versatility Using structural steel, it is possible to fasten different members together by simple connection techniques such as welding, bolting, and riveting. Steel members can also be rolled into a wide variety of sizes and shapes.

Prefabrication Often, steel components are manufactured at the factory (which means that they are produced using strict supervision and quality control), transported to the site, and erected using bolting and a minimum amount of welding. The prefabrication of steel structures results in the proper planning of construction, saving in time and money, speedy erection, and better quality of finished structures. Lighter steel members facilitate easy handling and erection.

Permanence Steel frames that are properly maintained last indefinitely. Several structures are available to testify the durability of steel structures (e.g., the Eiffel Tower and the Railway Bridge across the Firth of Forth, both built in 1890). Under certain conditions, weathering steels do not require any painting or maintenance. In Belgium and Japan, it has been found that steel bridges outlast prestressed concrete bridges by 15–26 years.

Additions to existing structures The repair and retrofit of steel members and their strengthening at a future date (for example, to take into account enhanced loading) is simpler than in concrete members. Thus, new bays or even entire new wings, can be added to existing steel-frame buildings, and steel bridges may often be widened. Of course, special precautions have to be taken while welding on a member already carrying loads.

Least disturbance to the community Steel-intensive construction causes the least disturbance to the community in which the structure is located. Fast-track construction techniques developed in recent years have demonstrated that steel structures cause the least disruption to traffic and minimize financial losses to the community and business. Such construction also results in far less environmental pollution.

Fracture toughness Due to its toughness and ductility, steel members can be subjected to large deformations during fabrication and erection without fracture, thus allowing them to be bent, hammered, sheared, and have holes punched in them without visible damage.

Elasticity Steel behaves closer to design assumptions than most materials because it follows Hooke's law up to fairly high stresses.

Though steel has several advantages, it also has the following disadvantages.

Maintenance costs Most steels are susceptible to corrosion when freely exposed to air and water, and must therefore be periodically painted. However, the use of weathering steels and modern coatings tend to eliminate/reduce this cost. Steel members in the interior of buildings (not exposed to rain) do not corrode quickly.

Fireproofing costs Although structural steel members are incombustible, their strength is tremendously reduced at temperatures commonly reached in fires when other materials in a building burn. Furthermore, since steel is an excellent heat conductor, non-fireproofed steel members may transmit enough heat from a burning section or compartment of a building to ignite materials which come into contact with them in adjoining sections of the building. Due to these factors, the steel frame of a building may have to be protected by materials with certain insulating characteristics. In addition, the building may have to include a sprinkler system, in order to meet the building code requirements.

Susceptibility to buckling The longer and more slender the compression members, the greater is the danger of buckling. Though steel has a high strength per unit of weight, steel columns have to be stiffened against buckling.

Fatigue Another undesirable property of steel is that its strength may be reduced if it is subjected to a large number of stress reversals or several variations of tensile stress. (There are fatigue problems only when tension is involved.) Hence we often reduce the estimated strengths of such members if more than a prescribed number of cycles of stress variation are anticipated.

1.18 Types of Steel Structures

The structural engineer will be concerned with the design of a variety of structures, which may include the following.

Buildings These may include rigid, semirigid, or simple connected frames, load-bearing walls, cable-stayed and cantilevered structures. Buildings may be simple or multi-storeyed, with single or many spans. For multi-storeyed buildings, several lateral bracing systems have been developed, such as trussed, staggered truss, rigid central core, etc. (see Chapter 2 for more details on these structural systems). Buildings are also classified according to use, such as residential, commercial, office, industrial, etc. These buildings may include a steel frame as shown in Fig. 1.14 or have a steel roof supported by load-bearing walls. The steel skeleton of the buildings may be rigid or pinned, a two- or three-hinged arch or a truss-on-column system. The truss also may be rigid or pin-connected, and may assume various shapes or have several bracing systems (see Chapter 12).

The building frame is actually a three-dimensional skeletal system, but in practice it is usually taken as rigid in only one plane. Some buildings are rigid in the *XY* as well as *YZ* planes, but this type of frame will not be considered in this text [see Subramanian (1999) for the details of three-dimensional frameworks]. The planar frame resulting from considering only the principal frame elements and/or the rigidity is termed as a *bent* and may have one or several stories. The spacing between bents in the third dimension is called the bay or *bay width. Spandrels* or floor beams are used to span the bays in multistoryed buildings with girders (usually heavier members than floor beams) spanning between columns or bents.

Figure 1.15 illustrates additional terms or members used in one-storey industrial buildings, where lateral bracings are often provided only in selected bays.

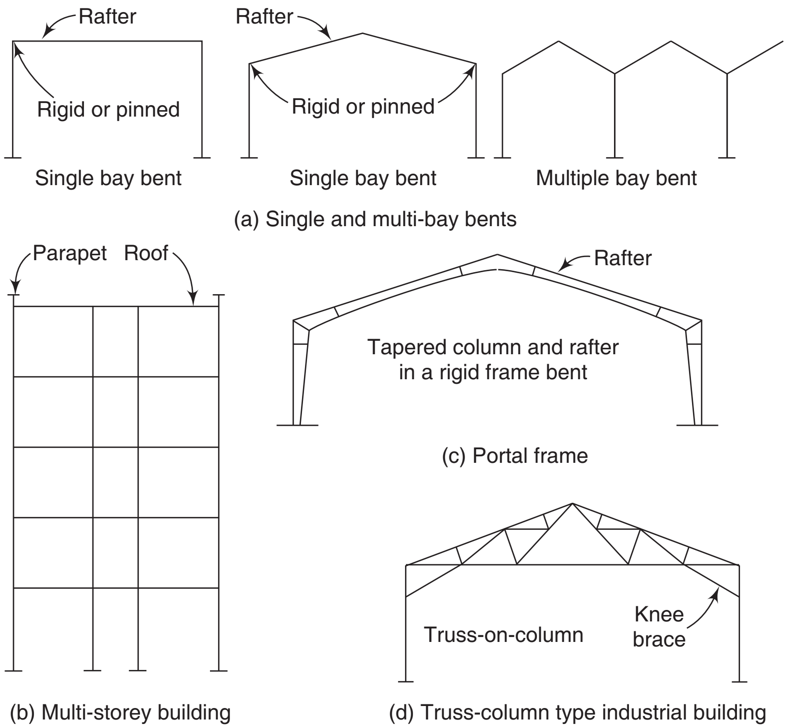


Fig. 1.14 Types of steel structures

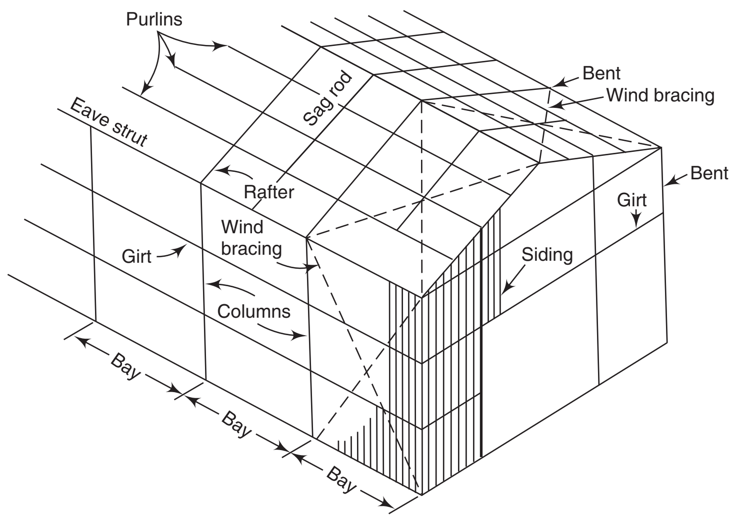


Fig. 1.15 Different structural members in industrial buildings

The roof systems of all buildings consist of a framing, some kind of decking, and a waterproof covering. The main roof framing consists of the *rafters* or the *truss* in any bent. Spanning the bay width are *purlins* spaced at about 0.6–2 m at centres, depending on the type of roof decking or sheeting used. *Sag rods* are provided as additional support for the purlins used on sloping roofs. Purlin design is rather complex for sloping roofs due to the unsymmetrical bending (see Section 6.11). The roof deck rests on purlins and may be a metal deck, precast concrete slabs, wood planking, gypsum sheets, GI sheets, polycarbonate sheets, fibre-glass sheets, or asbestos (which has been banned in several countries due to health hazards).

The siding may be made up of metal sheets, metal sandwich sheets (sometimes called curtain walls) consisting of two metal sheets with some insulating filler, brick, and precast or poured concrete, or asbestos sheets. A lightweight siding is carried by girts and spandrel beams in high-rise buildings and by *eaves struts* and *girts* in industrial buildings (see Fig. 1.14). Note that a spandrel beam is similar to a girt and is located at floor level (as the most exterior floor beam), and carries a proportion of live load. It also carries a part of the load acting on the siding. If the siding is heavy (e.g., brick or concrete blocks), built-up sections (using channels or angles depending on the load) can be used for the spandrel beam. It is necessary to establish the floor framing system very early in the design process, so that the load flow is identified and the sizes of different members are approximately fixed for computer analysis.

Bridges Bridges may be classified as truss, plate-girder, arch, cantilever, cable-stayed, or suspension (using cables as principal load-carrying members). The truss and plate-girder bridges are commonly adopted for small to moderate spans and cable-stayed and suspension bridges for long spans. Many types of trusses like Pratt, Warren, Parker, Baltimore, K-type, Whipple truss, etc., are used in bridges. The truss types include both deck (traffic on top of truss) and through types (traffic passes between the trusses of the bridge). The deck type is preferred if the clearance below the truss is not a critical factor, because the piers could be made shorter. Many truss bridges combine both types. A combination of trusses (for long spans) and girders (for shorter or approach spans) is also adopted in practice. Bridges may also be classified as railroad, highway, or road and pedestrian bridges, depending upon use.

Towers Towers may be of different types, such as lighting towers, power transmission towers, observation towers, towers for radar and TV installation, telephone relay towers, and windmill towers. Towers may be self-supporting or cable-stayed. Most towers are made of steel angles or tubes, which are bolted at site.

Water tanks They may be rectangular, circular, or spherical. They can be used to store oil or water. They may rest on the ground or be elevated on a staging.

Other structures Silos, bunkers, domes, folded plates, offshore platforms, chimneys, cooling towers.

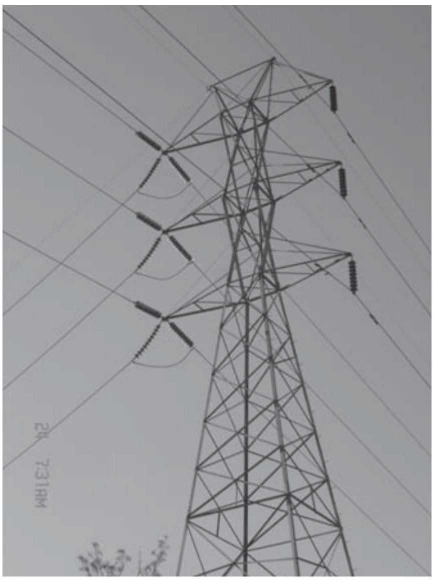
In addition to these structures, the structural engineer may be called upon to design ships, parts of various machines and other mechanical equipment, and automobiles (bus and car bodies, chassis), etc. Figure 1.16 shows the photographs of some different types of steel structures.

(a) The 2,065-m long Pamban railway bridge, on the Palk Strait, connects Rameswaram to mainland India. Constructed in 1914, it is still in good condition and considered as one of the marvels of engineering. The double-leaf bascule bridge section shown in this picture can be raised to let ships pass under the bridge. The bridge is located at the world's second highly corrosive environment (next to Miami, US), which is also a cyclone-prone, high wind velocity zone.

(b) The 110-stories high, 442-m tall Willis Tower (formerly known as Sears Tower), in Chicago, Illinois, USA. Designed by architects, Skidmore, Owings, and Merrill and structural engineer Fazlur Khan, and completed in 1973, it is the tallest building in the western hemisphere. The superstructure consisting of nine interlocking rigid steel framed tubes that terminate at different heights, efficiently counteract all lateral and gravity loads.

(c) Beijing National Stadium, also known as Bird's Nest, built for 2008 Summer Olympics in Beijing, China, and is the world's largest steel structure. This 91,000-seat stadium was designed by Swiss architects Herzog and de Meuron, ArupSport, and China Architectural Design & Research Group. It is 330-m long, 220-m wide, 69.2-m tall and contains 110,000 tonnes of steel.

(d) A typical pre-engineered building for the American Royal Exhibition Hall and Arena, Kansas City, MO. They are adopted for low-rise buildings with an eave height of up to 30 m and can be very economical and speedy. (Photo: www.butlermfg.com)



(e) Transmission line towers are often made of steel angles and bolted at site (Photo: Binod Therat)

(f) Steel-elevated water tanks are used to store water and provide pressure in the water distribution system. A tank elevated to 21 m creates about 0.207 MPa of discharge pressure, which is sufficient for most applications. The shapes of the tanks and their surface appearance can be varied according to the needs.

Fig. 1.16 Photographs of some of the different types of steel structures

In this book, we will confine our attention to the design of elements which are encountered in buildings. The various structural members used in buildings can be classified into the following according to the method by which they transmit forces in the structures (see Fig. 1.17).

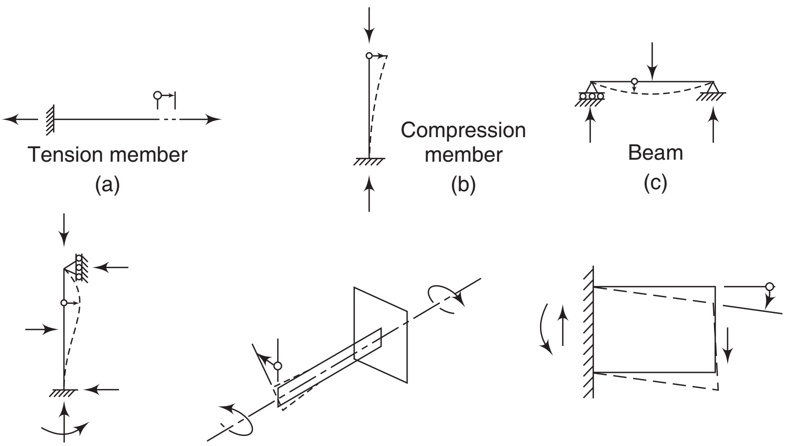


Fig. 1.17 Various types of structural members

Beams *Beams* (also called *girders*) primarily carry bending stresses which are the largest at the extreme fibre. Thus, most of the material of the beam remains understressed, and is not fully utilized, especially if it is of rectangular section. Also the bending moment reduces towards the support and if the beam section is uniform, even the extreme fibres carry smaller stresses. Thus, the overall efficiency of the use of material in beams is low. Yet beams are used so commonly because they give flat floors and roofs, are readily available, and require less fabrication at site. The design of beams is covered in Chapters 6 to 8.

Tension members or ties *Tension members* are structural elements that are subjected to direct axial forces, which try to elongate the members. They occur as components of trusses, hangers and cables for floors or roofs, in bracing systems, as tie rods, and similar members. An axially loaded tension member carries uniform stress and hence would give 100% efficiency in the use of materials. But in practice the efficiency is below 100% because the effective area of a tension member is less than the gross area due to the presence of rivet/bolt holes, shear lag effect, etc. A suspension cable, however, has a structural efficiency of 100% since it is flexible and can carry only tension. However, the use of a cable may require strong anchorage, and a stiffening arrangement to check large deformation under load, vibration due to wind, and other effects. The design of tension members is covered in Chapter 3.

Compression members (columns and struts) *Compression members* are those members in a structure that are subjected to loads that tend to decrease their length. Such members are used as the vertical load-resisting elements of a building structure, called columns, as the posts that resist compressive components of a load in a truss, and as bridge piers. In a building structure, forces and moments are transmitted to the columns through beams at each floor or the roof level of the structure. If the column is required to resist a load acting concentric to the original longitudinal axis of the member, it is termed an *axially loaded column* or simply a *column*. Even axially loaded columns will not be able to use 100% of the material, due to the phenomenon of *buckling*. The design of compression members is discussed in Chapter 5 and that of beam columns (which carry bending moments in addition to compressive forces) in Chapter 9.

Torsional members Such members are often encountered in shafts of machines. Of course, torsional effects should be considered in spandrel beams also. For design of members subjected to torsion, refer Subramanian (2008).

Plates Some built-up members and several light-gauge cold-formed members are made up of slender plate elements, which are liable to buckle locally. Local buckling is prevented by limiting the b/t ratios of plates.

Often, a combination of actions, such as bending and compression, bending and tension, compression bending and torsion, etc., occurs in frameworks where several members are joined together. In many cases, one action may be predominant and the other may be secondary. In the design, such secondary action is usually not taken into account. However, if the secondary action is considerable, the member has to be designed for the combined actions.

As already indicated, these members (beams, columns, tension members, etc.) are joined together in a framework by means of welding, bolting, or riveting. These fastening techniques and designs of connections are covered in Chapters 10 and 11.

1.19 Fabrication and Erection

According to the design of various members of a structure, the various required sections are procured and are fabricated at site or factory. Tolerances for the fabrication of steel structures should conform to IS 7215. The various activities in the fabrication shop include the following.

(a) Exact cutting of length by sawing, shearing, cropping, thermal cutting, or machining, based on the fabrication drawing of the structure,
(b) Straightening of members,
(c) Cambering of beams,
(d) Drilling or punching of holes,
(e) Welding of gusset plates,
(f) Machining of butt joints, caps, and bases,
(g) Surface preparation, such as shot blasting,
(h) Painting or galvanizing after pickling in acids,
(i) Marking,
(j) Shop assembly and erection,
(k) Inspection and testing, and
(l) Packing.

The numbered parts are then transported to the site and the structure is erected following the erection tolerances specified in IS 12843. The normal tolerances after erection are given in Table 33 of IS 800.

The straightness tolerances incorporated in the design rules are given in Table 34 of IS 800. When the actual curvature exceeds these values, the effect of additional curvature on the design calculations should be reviewed. A tension member should not deviate from its correct position by more than 3 mm.

After the structure is erected, the specified protective treatment should be applied on the surfaces of the steel members and joints. No painting should normally be used on the contact surfaces in the friction connection. More guidelines for the fabrication and erection of steel structures are given in Section 17 of IS 800 : 2007. Some recommendations for steel work tenders and contracts are also given in Annex G of the code.

1.19.1 Errors that Lead to Failures

To err is human but the consequences of an error in structural design can lead to loss of life and damage to property. Hence it is necessary to appreciate where errors can occur. Small errors can occur due to rounding of figures but these generally do not lead to failures. The majority of structural failures (whether it is the collapse of the structure or functional failure) are due to errors in design, construction, or operation. It has been reported that 85% of building failures occur due to human errors (Brown and Yin, 1988). Hence it is imperative for engineers and contractors to consciously avoid these errors.

The common errors that occur in the planning and design phase are due to the following (Martin and Purkiss 1992, and Subramanian 1984, 1989).

(a) Ignorance of the physical behaviour of the structure under load, which leads to errors in basic assumptions used in theoretical analysis
(b) Errors in selecting and estimating the loads, especially the erection forces
(c) Numerical errors in calculations—these could be eliminated by proof-checking; however when speed is of paramount importance, checking of calculations is often neglected
(d) Lack of consideration for certain effects such as fatigue, brittle fracture, residual stresses, etc.
(e) Insufficient allowances for temperature strains, tolerances, etc.
(f) Insufficient information about new materials, methods of analysis and design, detailing, erection procedures, etc.

Nowadays computer programs are being used as black boxes; that is, without knowing the limitations of these programs. Such usage leads to erroneous results. Errors that may occur during fabrication and erection are as follows.

(a) Using the wrong grade of steel or wrong types of electrodes for welding,
(b) Using the wrong weight of section,
(c) Errors in fabrication (holes not matching, oversized holes, lack of fit, improper welding, welding distortions, etc.), and
(d) Errors due to improper quality control.

Errors can also occur during the life of the structure, which affect the safety of its occupants. Such errors include

(a) overloading due to change of occupancy,
(b) loading which is not expected during the design stage (an earthquake of greater magnitude, flood, tsunami, etc.),
(c) alteration of the structural system (removal of the web of the flange to provide service ducts, addition of heavy partitions, balconies, etc.), and
(d) poor maintenance.

A study of the various types of failure has been provided by Levy and Salvadori (1992), Kaminetzky (1991), and Feld and Carper (1997). Case studies of building failures provide opportunities to learn from previous mistakes (Subramanian 1999, 2000; Subramanian & Mangalam 1997, 1998; Kevin et al. 2000). A few case studies of some important failures are also included in this book, which will help designers to avoid failures in their designs.

1.20 Aesthetics of Steel Structures

Although architects pay attention to the aesthetic qualities of structures like theatres, stadia, office buildings, residential units, etc., industrial buildings and non-habitat structures, which are made of steel members, are not aesthetically designed. It is very difficult to assess the aesthetic qualities of any structure, because taste differs from person to person. Aesthetics may be viewed as a composite impression of all visual aspects of design. In a normal building, aesthetic qualities may be judged with reference to its site, the physical layout and environment, the view from within and from without, and the appearance of the building with reference to its surroundings. Of course, these aesthetic factors should be considered in addition to functionalism, perfect manufacture, construction safety, stability, durability, disassembly, and reusability.

However, whether a person finds a structure beautiful depends upon whether it is able to evoke an emotion in him or her, which in itself is extremely complex in nature. The magnitude and combinations of the qualities listed previously obviously cannot be specified, since they evoke different responses in different individuals and are beyond the scope of our discussion. Nowadays, designers have moved away from notions of symmetry and order towards more expressive and dynamic structures, as seen in Fig. 1.18, which shows the Walt Disney Concert Hall in Downtown Los Angeles, USA. More details about aesthetic design may be found in Kavanagh (1975), Subramanian (1987, 2003), and Billington (1983).

Fig. 1.18 The Walt Disney Concert Hall in Downtown Los Angeles, California, designed by Architect Frank O. Gehry

Summary

This chapter begins with a brief historical review of steel. The steel making process along with the heat treatments given to steel is briefly outlined.

The chemical composition and mechanical properties of different kinds of steel are included. (It is quite important to specify the steel for the project at hand.) The important properties of structural steel are its ultimate and yield stress, ductility, toughness and weldability. We should remember that the yield stress, as measured by the tension coupons, is affected by several factors, such as the rate of loading and position from where the test coupons are taken. Variation in material properties can be incorporated in the design by the concept of characteristic strength. Ductility and toughness are very important when a steel structure is subjected to earthquake loads or impact loads. Special steels such as stainless steel and high-performance steel are also included.

In any design, the engineer's first task is to think about material selection. First, he or she should consider the working temperature range and form of the structure, and decide whether the components require thick material. A simple yardstick is that satisfactory performance against brittle fracture can be expected if the Charpy impact toughness exceeds 27 J at the lowest working temperature. Of course the quality of design, detailing, and fabrication are also equally important in the prevention of brittle fracture. One should avoid severe stress raisers to achieve smooth stress flow. In critical cases, this is as important as material selection.

Secondly, one must consider fatigue and ascertain whether the incidence of high levels of fluctuating stresses warrant further consideration. In general, this has to be checked in crane supporting structures, bridges, and structures supporting rotating machinery. Residual stresses and stress concentration effects should be properly accounted for in the design.

Though, mainly Fe 410 grade mild steel is used in India, it is prudent to check whether it is possible to use high-strength steel. Though the cost of high-strength steel may be 10–20% higher, its use may result in reduction in steel weight and subsequent foundation cost. Of course, while using high-strength steels, the deflection criteria may become critical due to the reduced section sizes. Other special types of steels are also available and may be specified, depending upon site conditions and cost considerations.

A brief introduction to corrosion, fire protection, and fatigue resistance of steel is also given. An overview of the different types of structures, types of sections (circular, I, angle, channel, hollow sections, etc.) and types of members (compression, tension, bending), is presented, which will be quite useful in understanding the concepts discussed in later chapters.

Review Questions

1. What are the properties of steel that make it better suited for structural applications?
2. Write a short note on the historic development of steel as a structural material.
3. Describe the production of structural steel in integrated steel plants.
4. What is the difference between killed and semi-killed steel?
5. What are the heat treatments employed to improve the properties of steel?
6. Differentiate between normalizing and annealing.
7. How does carbon content affect the properties of steel?
8. What is the relation between weldability and carbon equivalent?
9. List the IS codes that are used for the following applications:
   (a) material for structural steel,
   (b) welding,
   (c) ordinary bolts, and
   (d) high-strength bolts.

10. List the important factors that influence the mechanical properties of steel.
11. Describe the test to predict the tensile strength of steel.
12. Give the values of yield strength, Young's modulus, coefficient of thermal expansion, and ultimate tensile strength for mild steel as per IS 800.
13. Sketch the typical stress-strain curve of steel, indicating the three important regions.
14. What are the parameters that influence the yield stress of steel?
15. How the yield stress of high-carbon steels is determined for design purposes?
16. How the characteristic strength of steel is defined? What is the partial safety factor used with characteristic strength in the IS 800 code?
17. What is meant by ductility? Why and where is it important?
18. How the toughness of steel is measured?
19. What is brittle failure? How can it be controlled?
20. What is Charpy V-notch test? What is the CVN value that provides safety against brittle facture?
21. Write short notes on
    (a) lameller tearing,
    (b) effect of high temperature on steel,
    (c) corrosion resistance of steel,
    (d) hardness, and
    (e) fatigue resistance.
22. How are residual stresses induced in steel sections? Sketch the typical residual stress distribution in a rolled I beam and a welded I beam.
23. What is the effect of residual stress in compression members and beams?
24. What is meant by stress concentration? Where do we have to consider stress concentration effects?
25. Name and sketch some of the hot-rolled steel sections used in practice.
26. What are the problems associated with rerolled sections?
27. Are wide flange beams better than ordinary-rolled ISMB beams? Why?
28. What are castellated/cellular beams? How are they produced? What are the advantages of using them?
29. Write short notes on hollow steel sections and cold-formed steel sections.
30. Explain the flow-drill and hollo-bolt connection systems.
31. Write a short note on high-performance steel.
32. What are the advantages of using stainless steel?
33. State the main advantages of steel as a structural material.
34. List the types of structures that can be built using steel.
35. Discuss the following:
    (a) Fabrication and erection of steel structures,
    (b) Aesthetics of steel structures, and
    (c) Advantages of composite construction.