Chapter 8
Steel

The metal material is a general term for an alloy consisting of one or more metallic elements and some nonmetallic elements. Metal materials exhibit high strength, large elastic modulus, dense structure, and capability of casting, welding, assembling, and mechanical construction. Therefore, metal is an important building material. Metal materials for civil engineering are generally classified into ferrous metals and non-ferrous metals. Ferrous metals contain iron as their main constituent or base metal and are the most used metals in civil engineering. Non-ferrous metals are other metals except ferrous metals, such as aluminum, lead, zinc, copper, tin, and their alloys. The aluminum alloy is an important lightweight structural material.

8.1 Production

The use of iron dates back to about 3500 years ago when primitive furnaces were used to heat the ore in a charcoal fire. Ferrous metals were produced on a relatively small scale until the blast furnace was developed in the 1700s. Iron products were widely used in the late eighteenth century. Steel production started in the mid of the nineteenth century and advanced rapidly due to the development of the basic oxygen furnace and continuous casting methods in the late nineteenth century. China's annual steel production has ranked first in the world since 1996, and currently produces and uses 50% of the world's steel. The overall process of steel production consists of the following three phases:

(1) Iron making is to reduce iron ore to pig iron. Iron contains more carbon and other impurities. The carbon content of iron is more than 2.06%, while that of steel is less than 2.06%.
(2) Steel making is to refine pig iron and scrap steel from the recycling of steel.

Q. Dong et al. (eds.), *Civil Engineering Materials for Transportation Infrastructure*,
https://doi.org/10.1007/978-981-99-1300-8_8

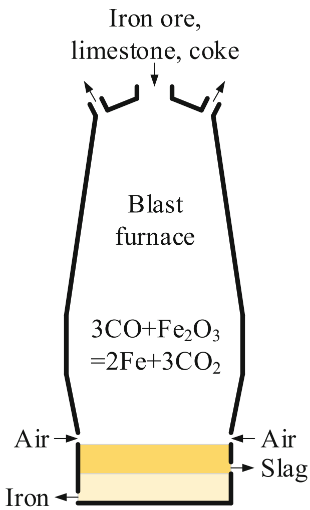


Fig. 8.1 Iron production in a blast furnace

(3) Steel rolling is to cast and roll steel into products including the bar, wire, pipe, sheet, etc.

8.1.1 Iron Production

Iron, which makes up 4.8% of the Earth's crust, is usually found in iron ore as a chemical compound. The iron ore includes hematite ore (Fe), magnetite (Fe_3O_4), siderite (($FeCO_3$), limonite ($Fe_2O_3 \cdot 2Fe(OH)_3$), and pyrite (FeS_2). Coal and limestone are also used to produce pig iron. The coal, after being transformed into coke, supplies carbon to reduce the amount of oxygen in the ore. Limestone is used to help remove impurities. The concentration of iron in the ore is increased by crushing and soaking the ore. The processed ore contains about 65% iron. Reduction of the ore to pig iron is accomplished in a blast furnace (Fig. 8.1), in which the oxygen in the ore reacts with carbon to form carbon oxides. A flux is used to help remove impurities. The molten iron is at the bottom of the furnace. The impurities and slag float on top of the molten iron.

8.1.2 Steel Production

Steel is produced by removing excess carbon and other impurities in iron. Refining pig iron to steel needs an oxygen furnace or arc furnace (Fig. 8.2). The basic oxygen

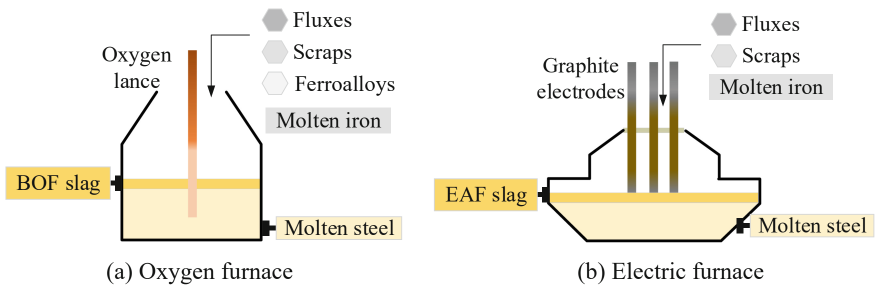


Fig. 8.2 Steel production, redrafted after Irem and Monica (2011)

furnaces remove excess carbon by reacting the carbon with oxygen. The steel production process is continued until all impurities are removed and the desired carbon content is achieved. Electric furnaces use an electric arc between carbon electrodes to melt and refine the steel. It can heat charged pig iron by an electric arc to 1800 °C.

8.2 Classification

Steel can be classified into different types based on its composition and physical properties.

8.2.1 Deoxygenation

During steel production, oxygen may be dissolved in the liquid metal. As steel solidifies, oxygen can react with carbon to form carbon monoxide bubbles that are trapped in the steel and cause fractures. Deoxidizing agents, such as aluminum, ferrosilicon, and manganese, can be used to eliminate the formation of carbon monoxide bubbles.

1. Rimmed steel

Rimmed steel does not have deoxidizing agents added to it during casting which causes carbon monoxide to evolve rapidly from the ingot. Rimmed steel has uneven composition and poor compactness, which influences the quality of steel. However, its cost is low and can be widely used in general building structures.

2. Killed steel

Killed steel is steel that has been completely deoxidized by the addition of an agent before casting so that there is practically no evolution of gas during solidification. Killed steel has better quality than rimmed steel, but costs more. It is mostly used in parts or joints bearing impact loads.

3. Semi-killed steel

Semi-killed steel is mostly deoxidized steel, but the carbon monoxide leaves blow-hole type porosity distributed in the ingot. Semi-killed steel is commonly used for structural steel with a carbon content between 0.15 and 0.25%.

8.2.2 Chemical Composition

Carbon steel is also known as plain steel. Carbon steel is an iron-carbon alloy with a carbon content of less than 1.35%, a silicon content of less than 0.4%, and a small amount of sulfur and phosphorus impurities. Carbon plays a major role in the performance of steel, while other elements, such as silicon, sulfur, and phosphorus, do not play decisive roles due to their low contents. According to the amount of carbon, carbon steel can be classified into low, medium, and high carbon steel.

(1) Low carbon steel has a carbon content of less than 0.25%. It is soft and easy to work with, but cannot be quenched and annealed. It is the main steel used in civil engineering.
(2) Medium carbon steel has a carbon content of 0.25–0.6%. It is hard, can be quenched and annealed, and is mostly used as mechanical parts.
(3) High carbon steel has a carbon content of higher than 0.6%. It is very hard, can be quenched and annealed, and is mainly used for tools.

According to the contents of phosphorus, sulfur, and other impurities in the steel, carbon steel can also be classified into:

(1) Plain carbon steel with phosphorus and sulfur content of less than 0.045 and 0.050%, respectively;
(2) Quality carbon steel with phosphorus and sulfur content of both less than 0.035%;
(3) High-quality carbon steel with phosphorus and sulfur contents both less than 0.025%.

Alloy steel is to add different alloy metals to carbon steel to alter its characteristics. According to the content of alloying elements, it is classified into:

(1) Low alloy steel with a total alloy content of less than 3.5%;
(2) Medium alloy steel with a total alloy content of 3.5–10%;
(3) High alloy steel with a total alloy content of higher than 10%.

8.2.3 Applications

According to different applications, steel can be classified into structural steel, tool steel, and special steel.

1. Structural steel

Structural steel is a type of steel that is used as a construction material. According to chemical composition, structural steel is classified into structural carbon steel and structural alloy steel.

(1) Structural carbon steel includes plain and superior structural carbon steel. Plain structural carbon steel contains carbon of less than 0.38%. They are used to produce bars, square steel, flat steel, angle steel, slot steel, steel plates, etc. Superior structural carbon steel contains fewer impurities. It has better performance and is commonly used for mechanical parts, tools, springs, etc. It can be further classified into pressure processing steel and cutting processing steel.
(2) Structural alloy steel includes low structural alloy steel and structural alloy steel. Low structural alloy steel is the plain structural carbon steel with a few additional alloys. It has high strength, resilience, and weldability. It is widely used to produce rebars and steel plates. Structural alloy steel includes spring alloy steel, ball bearing steel, manganese steel, chrome steel, nickel steel, boron steel, etc. They are mainly used to build machines and equipment.

2. Tool steel

Tool steel refers to a variety of carbon steel and alloy steel that are used to be made into tools. It has distinctive hardness, resistance to abrasion and deformation, and the ability to hold a cutting edge at elevated temperatures. Tool steel can be classified into carbon tool steel, alloy tool steel, and high-speed tool steel. It is used in various fields, such as cutting, molding, and measuring tools.

(1) Carbon tool steel typically has a carbon content of 0.65–1.35%. It is further classified into superior and advanced carbon steel according to the content of sulfur and phosphorus. Carbon tool steel can be used to produce steel brazing and hollow steel brazing.
(2) Alloy tool steel contains a higher content of carbon. It exhibits high hardness, abrasion resistance, and small heat deformation at high temperatures. Alloy tool steel is classified into measuring and cutting alloy tool steel, abrasion-resistant alloy tool steel, cold-rolled mold steel, and hot-rolled mold steel.
(3) High-speed tool steel has a high alloy content and has superior hardness and abrasion resistance to regular tool steel. It is mainly used for drilling and cutting tools such as the power-saw blades and drill bits.

3. Special steel

Special steel is mostly high alloy steel, including stainless steel, heat-resistant steel, abrasion-resistant steel, and electrical silicon steel.

8.2.4 *Steels in Civil Engineering*

1. Carbon structural steel

Carbon structural steel is widely used in civil engineering and can be used to produce various types of steel bars, wires, and sections. It is also directly used in the hot rolled process. Steel products are typically labeled with Chinese phonetic letters, element symbols, and numbers, indicating the grade, application, properties, and manufacture of the steel. In China, the grade for carbon steel includes four parts:

(1) Alphabet "Q" representing yield strength in Chinese.
(2) Yield strength value in the unit of MPa, including five levels, ranging from 195 to 275 MPa.
(3) The quality grades of A, B, C, and D. Grade A steel has the highest content of impurities. Grade D steel has the lowest amount of impurities.
(4) Deoxidation methods of F, B, and Z. F means rimmed steel, B means semi-killed steel, and Z means killed steel or completely deoxidized steel.

For example, "Q235AF" means a quality grade A rimmed carbon steel with 235 MPa yield strength. According to specification GB/T 700-2006 (2006), carbon structural steel includes five types: Q195, Q215, Q235, Q255 and Q275.

2. Superior carbon structural steel

Compared with normal carbon structural steel, superior carbon structural steel contains fewer harmful impurities such as sulfur and phosphorous and non-metallic inclusions. It has higher plasticity and toughness, can be strengthened by heat treatment, and is mostly used in more important structures. In civil engineering, it is often used to produce steel wires, steel strands, high-strength bolts, prestressed anchors, etc. The grade for superior carbon structural steel includes three parts:

(1) Two digits of carbon content in the unit of 0.01%.
(2) Deoxidation method in which none means killed steel, and F means rimmed steel.
(3) Manganese (Mn) content, in which none means content lower than 0.8% while Mn means 0.7–1.2%. With the increase of Mn content, the strength and hardness increase, while plasticity and toughness decrease.

For example, "50Mn" means quality carbon steel with 0.5% carbon and 0.7–1.2% Mn. According to specification GB/T 699-2015 (2015), there are 28 types of superior carbon structural steel with different carbon content (0.05–0.75%).

3. Low alloy structural steel

Low alloy structural steel is high-strength steel formed by adding usually less than 3% alloy to low carbon steel. The main alloy elements include manganese (Mn), silicon (Si), vanadium (V), titanium (Ti), niobium (Nb), and other rare elements (RE). Low alloy structural steel is widely used in bridges, vehicles, and rebar production because of its high strength, wear resistance, and corrosion resistance. The grade for low alloy structural steel includes three parts:

(1) Alphabet “Q” representing yield strength.
(2) Yield strength value in the unit of MPa.
(3) Quality grades, including A, B, C, and D. Grade A has the highest content of impurities such as sulfur and phosphorus, followed by B, C, and D.

For example, “Q295D” means quality grade D low alloy steel with 235 MPa yield strength. According to specification GB/T 1591-2018 (2018), there are eight types of low alloy structural steel, including Q355, Q390, Q420, Q460, Q500, Q550, Q620, and Q690.

4. Alloy structural steel

Due to the effect of alloy elements, the strength, toughness, and wear resistance of alloy steel are significantly improved. The alloy structural steel is widely used in high-strength bolts, gears, and other important structural components. Alloy structural steel usually requires heat treatment to obtain good mechanical performance. The grade for alloy structural steel includes 3 parts.

(1) Two digits of carbon content in the unit of 0.01%.
(2) An element symbol representing the major alloy.
(3) A number representing alloy content in the unit of 1% when it is higher than 1.6%.

For example, “20SiMn2MoV” means 2% carbon content alloy structural steel including 2% manganese as well as silica and molybdenum. According to specification GB/T 3077-2015 (2015), there are 86 types of alloy structural steel, including 40Mn2, 20SiMn2MoV, 40Cr, etc.

5. Bridge structural steel

Bridge structural steel is the steel used specifically for building bridges. Steel bridge structures can be built quicker due to their modular design. In most instances, steel beams and other small elements are made off-site and then transported to the jobsite. The grade of steel bridge is the same as quality carbon steel but ended with “q” representing it is for bridge use. According to specification GB/T 714-2015 (2015), the eight types of bridge structural steel include Q345q, Q370q, Q420q, Q460q, Q500q, Q550q, Q620q, and Q690q.

8.3 Chemical Composition

The properties of steel are mainly determined by its chemical composition. Steel is an alloy made up of iron with a little carbon and may contain other elements such as silicon, manganese, phosphorus, sulfur, oxygen, nitrogen, etc. Those elements have different influences on the properties of steel.

8.3.1 Influence of Elements

1. Carbon

Carbon is the most abundant element in steel except iron. As shown in Fig. 8.3, with the increase of carbon content, the hardness and strength increase while the plasticity, toughness, and cold bending properties decrease. When the carbon content increases to about 0.8%, the strength reaches the maximum. When the carbon content exceeds 0.8%, the strength decreases. Part of the carbon in the steel dissolves into iron as a solid solution, while the other part is combined with iron to form cementite. Carbon steel is a mixture of low hardness and high plasticity ferrite, and hard and brittle cementite. Therefore, the tensile strength and hardness of carbon steel increase linearly with the increase of the carbon content, while the plasticity of carbon steel decreases.

The influence of carbon on steel is not only related to the hardness and brittleness of cementite itself but also related to the distortion of the crystal lattice at the interface between cementite and ferrite. The grain interface between cementite and ferrite restraints the slip of ferrite and causes micro cracks. Therefore, the increase of cementite improves the grain interface and the deformation resistance, while decreases the plasticity.

2. Silicon

Silicon is added to the steel as a deoxidizer to capture oxygen from FeO and form oxides to reduce the oxygen content in the steel. Silicate can be further formed by oxides of silicon and basic oxides in molten steel as shown in Eqs. (8.1) and (8.2).

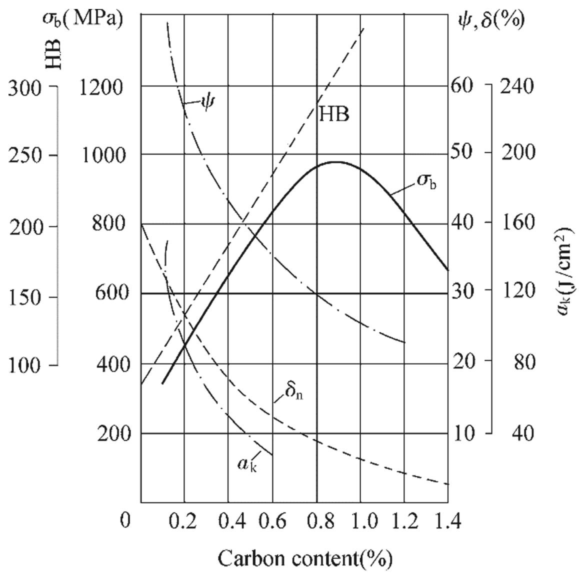


Fig. 8.3 Influence of carbon content on steel properties (HB = Brinell hardness, σ_b= tensile strength, δ_n = elongation at fracture (%), ψ = reduction of area at fracture (%), a_k= impact toughness), redrafted after Huang et al. (2020)

When the molten steel is poured, silicate impurities have no time to float into the slag and remain in the steel. It is easy to concentrate in the grain boundary during solidification, and the steel is easy to deform or fracture during pressure processing. The content of silicon in carbon steel is 0.1–0.4%. The incorporation of silicon into ferrite increases the strength and hardness of steel significantly although the silicon content in carbon steel is very low. When the content of silicon increases to 1–1.2% as an alloying element, the tensile strength of the steel can be increased by 15–20%, but the plasticity, toughness, and weldability decrease.

$$SiO_2 + CaO = CaSiO_3 \tag{8.1}$$

$$SiO_2 + Fe_2O_3 + C = CO \uparrow + Fe_2SiO_4 \tag{8.2}$$

3. Manganese

Manganese is added to steel as a deoxidizer as shown in Eq. (8.3). The content of manganese in carbon steel is 0.25–0.8%. When the content of manganese is less than 0.8%, the effect of Mn on the properties of steel is not significant. When manganese is added as an alloy to a content of 0.8–1.2% or higher, the mechanical properties of steel will be significantly improved. However, when the manganese content is greater than 1%, the corrosion resistance and weldability of steel decrease.

$$Mn + FeO = MnO + Fe \tag{8.3}$$

4. Phosphorus

When phosphorus is dissolved into ferrite, the strength, and hardness of steel increase, while the plasticity and toughness decrease significantly. When the content of phosphorus is higher than 0.3%, the steel becomes completely brittle and the impact toughness is close to zero. This phenomenon is called cold brittleness. Although the content of phosphorus is usually low, the phosphorus in the steel is easy to segregate during crystallization, causing the local area with a higher phosphorus content to become brittle. Therefore, the content of phosphorus is strictly controlled to be less than 0.045%. Phosphorus can improve the cutting performance of steel, and the cutting tool steel contains more phosphorus.

5. Sulfur

Sulfur can form ferrous sulfate. Ferrous sulfate and ferrite then can form eutectic at 985 °C and causing cracking above 1000 °C due to eutectic melting, which is called hot brittleness. The sulfur content is also strictly controlled to be less than 0.055%. The harmful influence of sulfur can be reduced by the addition of manganese to molten steel since manganese can capture sulfur from FeS as shown in Eq. (8.4). MnS melts at 1620 °C, and the hot working temperature of steel is 800–1200 °C. MnS has good plasticity and does not influence the hot working properties of steel.

$$Mn + FeS = MnS + Fe \tag{8.4}$$

6. Other elements

Impurities of N, O, and H are from the air in the production of steel. When molten steel cools down, these elements stay in ferrite as atoms. N increases the strength and hardness of steel while decreases toughness. Al reacts with N to generate AlN. When AlN particles are evenly distributed in the steel, the toughness, plasticity, and abrasion resistance of the steel are increased. When AlN particles are not evenly distributed, the mechanical properties and abrasion resistance of steel are decreased.

After the deoxidation with Mg, Al, and Si, there is still a little oxygen in steel in the form of Al_2O_3, FeO, MnO, and SiO_2, which exist in the steel as chains or strips, especially at the interface of crystals, decreasing the plasticity and toughness of steel.

After hot rolled and forged, atomic hydrogen will gather into a molecular state and appear in the steel. The pressure generated by hydrogen can crack the steel from the inside, forming almost circular flat fracture surfaces, which are called "white spots" or hydrogen blistering. In particular, some alloy steel, such as ingot steel, shackle steel, shackle inscribed steel, etc., are particularly sensitive to white spots. The hydrogen content can be controlled by using materials of low moisture or hydrogen content, avoiding late addition of lime during the smelting process, minimization of carry-over slag, efficient vacuum degassing, and intense purging.

8.3.2 Metallography

Similar to pure iron, carbon steel has a crystal structure. Crystal phases are defined as regions with the same chemical composition and crystal structure, and have a distinct interface with the surrounding medium. Several different crystalline structures make up the steel at different temperatures.

(1) Ferrite is a solid solution, stable at room temperature, and capable of containing up to only 0.008% carbon. Magnetic ferrite is sometimes called alpha iron.
(2) Cementite is an iron-carbon crystalline (Fe_3C). Cementite contains 6.67% carbon and can combine with ferrite to form pearlite.
(3) Austenite or gamma iron is capable of dissolving 2% carbon. While austenite is never stable in carbon steel at temperatures below 727 °C, additional alloys can make it stable at room temperature. Austenite is nonmagnetic and easily work-hardened.
(4) Pearlite is formed when thin and alternating layers of cementite and ferrite combine. During the slow cooling of an iron-carbon alloy, pearlite is also formed by a eutectoid reaction as austenite cools slowly. Pearlite contains 0.77% carbon, and it usually makes the steel more ductile.
(5) Bainite is hard with low ductility and is a combination of fine carbon needles in a ferrite matrix. It forms when the austenite is cooled at a rate lower than that is needed to form martensite.

(6) Martensite is formed by quenching of the austenite form of iron, in which carbon atoms do not have time to diffuse out of the crystal structure in large enough quantities to form cementite.

8.4 Mechanical Properties

Steel in civil structures is mainly subjected to tension, compression, bending, impaction, and other external loads. The strength, plasticity, bending performance, impact toughness, and hardness are the five important mechanical properties of steel.

8.4.1 Strength

Figure 8.4 illustrates a stress–strain curve of low carbon steel subjected to uniaxial tension. According to specification GB/T 228.1-2021 (2021), during the tensile test, a steel bar is placed in the upper and lower gripping device of the testing machine, and a tensile load is applied until the specimen breaks. The stress–strain curve can be divided into two parts: elastic deformation and plastic deformation.

1. Elastic deformation

The first section of the curve is the elastic deformation region where the relationship between the stress and strain is linear. The elastic deformation is totally reversible. The slope of the linear relationship is Young's modulus, E, and is approximately constant for all steels: around 200 GPa.

The area under the stress–strain curve in the elastic region is the energy that the material can absorb reversibly, and is known as resilience. The maximum stress in the elastic region is the yield strength, σ_s. The yield strength is an important parameter for structural design. In service, the steel must never undergo a stress level higher than the yield strength, otherwise, it will experience permanent deformation.

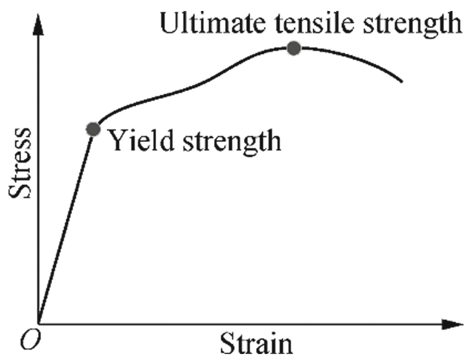


Fig. 8.4 Typical uniaxial tensile stress–strain curve for a steel bar

2. Plastic deformation

Once yield strength has been exceeded, the material enters the plastic deformation region where the relationship between the stress and strain is non-linear. The stress–strain curve then reaches the maximum point which is called the ultimate tensile strength (σ_b). This ultimate tensile strength represents the start of the rupture process, which leads to material fracture.

Once the ultimate tensile strength has been exceeded, micro cracks begin to appear inside the material and propagate, and deformation stops being uniform. The speed of deformation in the area where the cracks appear is greater than the speed of deformation in other parts of the specimen, due to the concentration of strain around the cracks, producing localized deformation. The area of localized deformation in a uniaxial tensile test is the necking, where the fracture takes place.

The area under the stress–strain curve is the toughness, which is the energy per unit of volume absorbed by the material from the start of deformation until fracture. Yield strength and ultimate tensile strength are the two important strength characteristics of steel. In structural design, steel members are required to work in an elastic range without plastic deformation. Thus, the yield strength of steel is considered as the design strength of the structure (σ_s). It is expected to use steel with high yield strength and the ratio of yield strength to tensile strength (σ_s/σ_b). Smaller σ_s/σ_b indicates higher reliability and safety factor. Usually, it is suggested to use a σ_s/σ_b value of 0.60–0.75. For some metals that do not have a significant yield point, the conditional yield point is typically defined at the 0.2% offset strain. The yield strength at 0.2% offset is determined by finding the intersection of the stress–strain curve with a line parallel to the initial slope of the curve and which intercepts the strain axis at 0.2%.

8.4.2 Plasticity

The ability of steel to undergo a specific permanent deformation before fracture when it is subjected to stress is called plasticity. Plasticity means non-reversible deformation in response to the applied force while ductility is the ability to deform under tensile stress. In Fig. 8.5, the left steel bar has low plasticity or ductility and is usually high carbon steel. The right one has better plasticity and is usually alloy steel. The plasticity of steel is of significance in civil engineering. In the manufacturing process, steel with high plasticity can withstand certain forms of external force process without damage. Steel with greater plasticity has better safety. During the service, occasional overload on steel with plasticity can produce plastic deformation to redistribute stress and avoid sudden failure.

Two values can be calculated based on the tensile strength test to evaluate the plasticity or ductility of steel. As shown in Fig. 8.6, elongation of the steel bar over the original length is used to evaluate the ability to withstand permanent deformation at fracture (Eq. 8.5). Reduction of area measures the maximum reduction of the necks

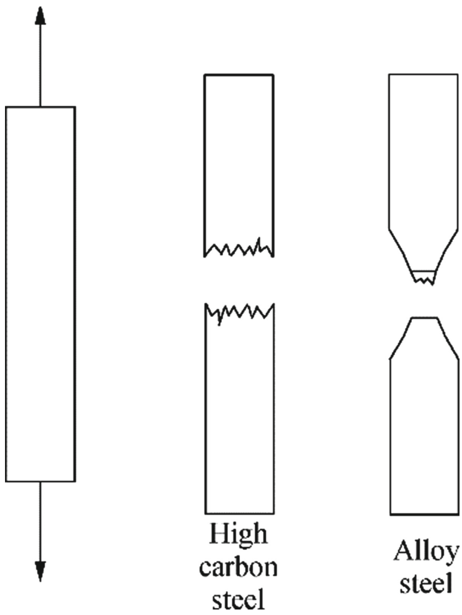


Fig. 8.5 Deformation of steel at a tensile fracture, redrafted after Ductility of Asphalt and Metals (2008)

in the cross-sectional area, which can also be used to evaluate the relative plasticity or ductility of steel at fracture (Eq. 8.6).

$$\delta_n = \frac{L_1 - L_0}{L_0} \times 100\% \tag{8.5}$$

$$\psi = \frac{A_0 - A_1}{A_0} \times 100\% \tag{8.6}$$

where δ_n = elongation at fracture (%);

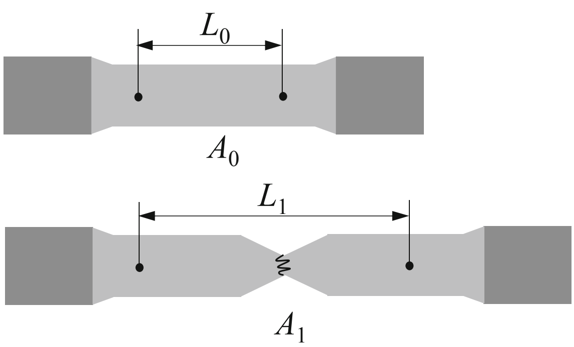


Fig. 8.6 Elongation and reduction of area

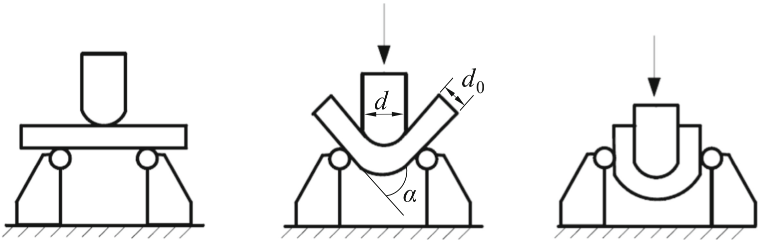


Fig. 8.7 Cold bending test, redrafted after Huang et al. (2020)

L_0 = gauge length (mm);
L_1 = gauge length after fracture (mm);
ψ = reduction of area at fracture (%);
A_0 = original cross-sectional area of the specimen (mm^2);
A_1 = cross-sectional area of the specimen after fracture (mm^2).

8.4.3 Cold Bending Property

The cold bending property of steel refers to its ability to withstand bending deformation at normal temperature. Most of the steel bars used in reinforced concrete need to be bent, so they must meet the requirements of cold bending properties. Cold bending tests, like elongation, indicate the plasticity of steel under static loads, but the elongation reflects the plasticity of steel under uniform deformation. Cold bending tests the plasticity or ductility of steel under bending deformation and determines whether there is uneven structure, defects, impurities, etc. It is a simple test measuring the ductility and soundness of steel, which is critical for structural steel.

According to specification GB/T 232-2010 (2010) the cold bending property of steel is expressed by the bending angle α and the ratio of diameter of the bending center d to the diameter (or thickness) of the specimen d_0 (Fig. 8.7). The larger the bending angle, the smaller the ratio of the bending diameter to the diameter (or thickness) of the specimen, the better the cold bending property of the steel specimen. After the bending test, the specimen should have no cracks, bedding, or fracture at the bending position.

8.4.4 Impact Toughness

The impact toughness of metal is determined by measuring the energy absorbed in the fracture of the specimen. According to specification GB/T 229-2020 (2020), it is obtained by noting the height at which the pendulum is released and the height to which the pendulum swings after it has struck the specimen. Figure 8.8 shows

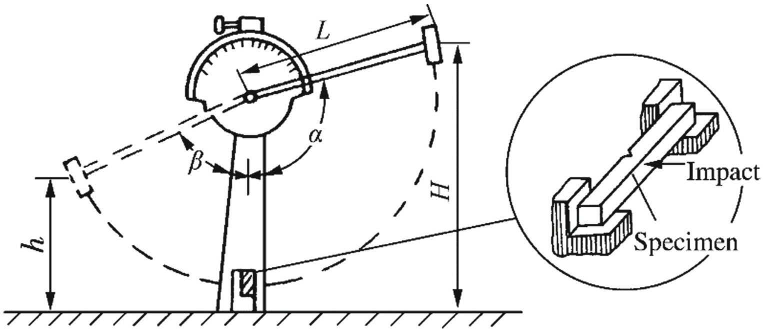


Fig. 8.8 Charpy V notch impact test, redrafted after Huang et al. (2020)

the Charpy V-notch impact testing machine and the specimen used for the impact toughness test.

The chemical composition, smelting, and processing quality of steel influence the impact toughness. The high content of phosphorus and sulfur, segregation, non-metallic inclusions, pores and micro-cracks formed in welding, etc., significantly reduce the impact toughness. In addition, the impact toughness of steel is greatly influenced by temperature, and the impact toughness decreases with the decrease of temperature. When the temperature falls below a value, the impact toughness drops sharply, and the steel may exhibit brittle fracture, which is called cold brittleness. Therefore, low-temperature impact toughness must be tested for the steel used in a cold environment, especially the important structure under dynamic loads.

8.4.5 Hardness

Hardness is the ability of steel to resist harder objects pressing into the steel surface. It is usually tested with the Brinell hardness apparatus (Fig. 8.9). The Brinell hardness (HB) test applies a predetermined force on a tungsten carbide ball of fixed diameter and holds for a predetermined time, and then removes it. The Brinell hardness number (BHN or HB) is related to the pressure on the indentation area and can be calculated by Eq. (8.7).

$$HB = 0.102 \times \frac{2P}{\pi D\left(D - \sqrt{D^2 - d^2}\right)} \tag{8.7}$$

where HB = Brinell hardness number;
P = applied specified load (N);
D = ball diameter (mm);
d = indentation diameter (mm).

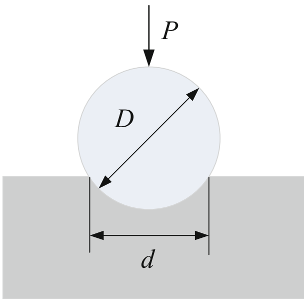


Fig. 8.9 Brinell hardness test, redrafted after Huang et al. (2020)

The diameter of the steel ball is 10, 5 or 2.5 mm. The load and the diameter of the steel ball follow the relationship: $P = 30D^2$. The Brinell hardness test is accurate and widely used but is not applicable for steel with HB higher than 450 and lower thickness. Hardness can also be utilized to estimate the tensile strength of steel as shown in Eq. (8.8).

$$\sigma_b = \begin{cases} 0.36HB, HB \leq 175 \\ 0.35HB, HB > 175 \end{cases} \tag{8.8}$$

8.5 Heat and Cold Treatment

8.5.1 Heat Treatment

Heat treatment is to heat the steel to a specific temperature, hold the temperature for a specified time, and then cool the material at a specified rate. It includes four types of treatment.

1. Annealing

Annealing is to heat the steel to a specific temperature and cool slowly. There are different types of annealing.

(1) Full annealing is to heat the steel to 50 °C above the austenitic temperature line, hold the temperature until all the steel transforms into either austenite or austenite-cementite, and then cool slowly in a furnace. Due to the slow cooling rate, the grain structure is coarse pearlite with ferrite or cementite, and the properties of steel are uniform. The steel is soft and ductile after treatment.
(2) Process annealing is to treat work-hardened parts made with low carbon steel. The material is heated to about 700 °C and held long enough to allow recrystallization of the ferrite phase. By keeping the temperature below 727 °C, there

is not a phase shift between ferrite and austenite, and the only change is the refinement of the size, shape, and distribution of the grain structure.

(3) Stress relief annealing is to reduce residual stresses in the cast, welded, cold-worked, and cold-formed parts. The steel is heated to 600–650 °C, held at temperature for about one hour, and then slowly cooled in still air.

(4) Spheroidization is an annealing process used to improve the ability of high carbon steel to be machined or cold worked. It also improves abrasion resistance.

2. Normalizing

Normalizing is similar to annealing with different heating temperatures and cooling rates. It is to heat steel to about 60 °C above the austenite line and then cool it in the air for a higher cooling rate. Normalizing produces a uniform, fine-grained microstructure. However, due to the higher cooling rate, the shapes with varying thicknesses result in less uniformity of the normalized parts than annealing. Since structural plate has a uniform thickness, normalizing is an effective process and results in high fracture toughness of the material.

3. Hardening

Hardening is to heat steel to a temperature above the transformation range and then quenched in water or oil for rapid cooling, resulting in high strength and hardness but very low plasticity and toughness. The rapid cooling causes the iron to change into martensite rather than ferrite. Martensite has a very hard and brittle structure. Due to the rapid cooling, the surface of the material is harder and more brittle than the interior of the element, creating non-homogeneous characteristics. Rapid cooling also causes steel pieces with sharp angles or grooves to crack immediately after hardening. Therefore, hardening must be followed by tempering.

4. Tempering

Tempering is after quenching, the steel is cooled to about 40 °C, then reheated, maintained at the elevated temperature for about two hours, and then cooled in still air to improve ductility and toughness. Heating causes carbon atoms to diffuse from martensite to produce a carbide precipitate and the formation of ferrite and cementite. Tempering is performed to improve ductility and toughness.

8.5.2 Welding

Welding is a technique for joining two metal pieces by applying heat to fuse the pieces. Many civil engineering structures such as steel bridges, frames, and trusses require welding during construction and repair. More than 90% of the connections are welded. There are many types of welding. Generally, arc welding uses an arc between the electrode and the grounded base metal to bring both the base metal and the electrode to their melting points. Gas welding uses an external shielding gas, which shields the molten weld pool and provides the desired arc characteristics.

Due to the high local temperature, steel forms an overheated area in the welding joint. The internal crystal structure changes and tends to produce hard and brittle structures around the welding joint. Materials with low weldability may crack due to the local stresses caused by heating at the weld joint. The weldability of steel is mainly influenced by its chemical composition. When the carbon content exceeds 0.3%, the weldability of steel is poor. The increase of other elements may also reduce the weldability. The welding quality can be improved by preheating before welding and heat treatment after welding, using the correct electrode, and proper operations.

During welding, a small volume of steel melts and cools quickly because of the rapid heat transfer. Complex and non-uniform changes occur, causing expansion, contraction, deformation, internal stress, changes in the crystal structure, and defects. The defects include cracks (thermal cracks), pores, and inclusions such as slag, deoxy products, and nitrous compounds. Defects in the heated zone include cracks (cold cracks) and coarse grains, and precipitate embrittlement. The carbon, nitrogen, and other atoms form carbide or nitrogen compounds, which precipitate and cause increased lattice distortion of the embrittlement. The welding joints require sufficient strength, plasticity, toughness, and fatigue resistance, and the welding quality should be carefully controlled.

8.5.3 Cold Working

Cold working is to draw or roll steel to produce plastic deformation at room temperature, improving strength and surface finishing. After cold-drawn, steel bars are stored at room temperature for 15–20 days which is natural aging, or heated to 100–200 °C and kept for a specific time which is artificial aging. After cold working, the yield strength increases, while the plasticity, toughness, and elastic modulus decrease. As shown in Fig. 8.10, the yield strength of the cold-drawn without aging is just a little higher than that of the original steel. However, the cold-drawn steel with aging significantly improves both the yield and ultimate strength of steel after cold-drawn treatment. The proper cold tensile stress and aging treatment measures are usually chosen through tests. Generally, natural aging has more significant effects on the steel bar with lower strength but has less significant effects on the steel bar with higher strength, for which artificial aging must be used.

As shown in Fig. 8.11, low carbon cold-drawn steel wire is made by letting a round steel bar pass through a smaller area. The cold drawing effect is stronger than the pure drawing action. The cold-drawn wire is not only pulled but also squeezed. Through one or more times of cold drawing, the yield strength can be increased by 40–60%, but the toughness reduces. According to specification GB 50204-2015 (2015), cold-drawn steel wire can be classified into two levels based on strength: Class B for non-prestressed steel wire and Class A for prestressed steel wire.

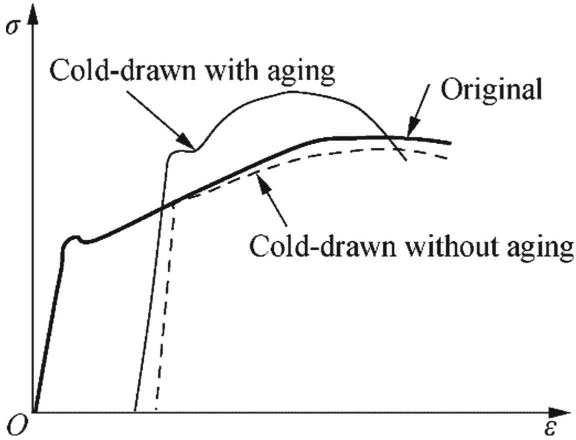


Fig. 8.10 Cold-drawn with and without aging, redrafted after Huang et al. (2020)

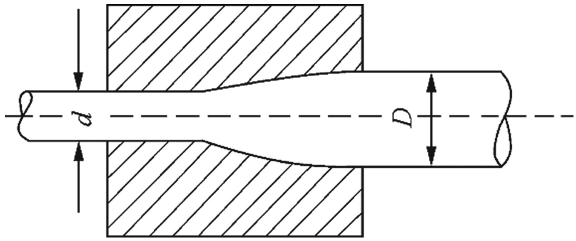


Fig. 8.11 Low carbon cold-drawn steel wire, redrafted after Huang et al. (2020)

8.6 Typical Structural Steel

Structural steel includes the steel plate, steel beam, and section steel. Structural stel used in concrete is generally the steel bar, steel wire, and steel stranded wire for reinforced concrete and prestressed concrete. Specifically, they are the hot-rolled plain steel bars for steel-reinforced concrete (GB/T 1499.1-2017, 2017), hot-rolled ribbed steel bars for steel-reinforced concrete (GB/T 1499.2-2018, 2018), steel wires for prestressed concrete (GB/T 5223-2014, 2014), medium-strength steel wires for prestressed concrete (GB/T 30828-2014, 2014), steel stranded wires for prestressed concrete (GB/T 5224-2014, 2014), cold-rolled ribbed steel bars (GB/T 13788-2017, 2017), cold-drawn steel bars (GB/T 3078-2019, 2019) and cold-drawn low carbon steel wires (JGJ 19-2010, 2010). The properties of various steels depend mainly on the type of steel used and the manufacturing method.

8.6.1 Hot-Rolled Steel Bar

The hot-rolled steel bar is one of the most commonly used steel in civil engineering, which can be classified into different types according to its mechanical properties (Table 8.1). There are mainly two types of hot-rolled steel bars: hot-rolled plain bar (HPB) and hot-rolled ribbed bar (HRB). The label is: "HPB" or "HRB" + yield strength. The "E" at the end means it is anti-earthquake.

(1) The HPB is made of Q235 carbon structural steel. It has low strength, but high plasticity and elongation, and is easy for cold working and welding. It is widely used as reinforcing bars in medium- and small-size reinforced concrete structures and tie rods in wood structures. It can be used as the base metal for cold-rolled ribbed steel bars and cold-drawn low carbon steel wires.

(2) The HRB is also used as reinforcing steel (Fig. 8.12). It exhibits high strength, good plasticity, and good weldability. On the surface of HRB, the longitudinal ribs and uniformly distributed transverse ribs are ribbed to enhance the bonding between the steel bar and concrete. The ribs include the crescent, contour, herringbone, spiral shapes, etc. Steel can be saved by 40–50% when using HRB as the load-bearing bars in concrete compared to HPB. Therefore, it is widely utilized as the main steel bar in large- and medium-size reinforced concrete structures.

Table 8.1 Hot-rolled steel bar (GB/T 1499.1-2017, 2017; GB/T 1499.2-2018, 2018)

Types	Labels	Nominal diameter d_0 (mm)	Min. yield strength (MPa)	Min. tensile strength (MPa)	Min. elongation at fracture (%)	Min. elongation at yield (%)	Diameter d of 180° cold bending test
Hot-rolled plain steel bar	HPB300	6–22	300	420	25	10.0	d_0
Hot-rolled ribbed steel bar	HRB400 HRBF400	6–25 18–40 40–50	400	540	16	7.5	4 d_0 5 d_0 6 d_0
	HRB400E HRBF400E				–	9.0	
	HRB500 HRBF500E	6–25 18–40 40–50	500	630	15	7.5	6 d_0 7 d_0 8 d_0
					–	9.0	
	HRB600	6–25 18–40 40–50	600	730	14	7.5	6 d_0 7 d_0 8 d_0

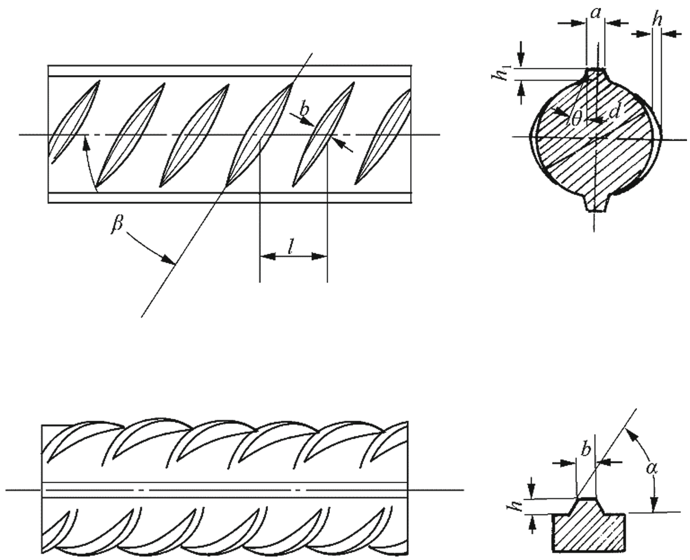


Fig. 8.12 The hot-rolled ribbed bar with crescent ribs, redrafted after Huang et al. (2020)

8.6.2 Cold-Rolled Ribbed Bar

A cold-rolled ribbed bar (CRB) is formed by reducing the diameter of the hot-rolled bar through cold rolling. Its label is "CRB" + yield strength. "H" at the end means high ductility. The chemical composition and mechanical properties of CRB should satisfy specification GB/T 13788-2017 (2017) as shown in Table 8.2. The CRB has high strength, good plasticity, and stable quality. Grade 550 steel bars are mainly used for reinforced concrete structures, especially the main load-bearing bars of slab members and the non-prestressed steel bars in prestressed concrete structures.

8.6.3 Hot-Rolled Reinforcing Bar for Prestressed Concrete

The hot-rolled reinforcing bar for prestressed concrete is made by quenching and tempering the hot-rolled low alloy steel bar (Table 8.3). The rebar can be classified into the rounded steel bar, the spiral groove steel bar, the spiral rib steel bar, and the ribbed steel bar. This steel bar is usually rolled into a flexible wire rod with a diameter of greater than 2.0 m. Each wire rod consists of one steel wire with a weight of larger than 700 kg. It features high strength, high toughness, and grip strength, which is mainly employed in prestressed concrete. It should meet the requirements in specification GB/T 5223.3-2017 (2017). The design strength of the hot-rolled reinforcing bar for prestressed concrete is 80% of the standard strength. The tensile

Table 8.2 Mechanical properties of CRB (GB/T 13788-2017, 2017)

Types	Labels	Min. plastic deformation strength $R_{p0.2}$ (MPa)	Min. tensile strength R_m (MPa)	Min $R_m/R_{p0.2}$	Min. elongation at fracture (%)		Min. elongation at yield (%)	Diameter d of 180° cold bending test	Bending times	Initial stress for stress relaxation
					A	A_{100mm}	A_{gt}			Min 1000 h, %
Steel for reinforced concrete	CRB550	500	550	1.05	11.0	–	2.5	3 d_0	–	–
	CRB600H	540	600	1.05	14.0	–	5.0	3 d_0	–	–
	CRB680H	600	680	1.05	14.0	–	5.0	3 d_0	4	5
Steel for prestressed concrete	CRB650	585	650	1.05	–	4.0	2.5	–	3	8
	CRB800	720	800	1.05	–	4.0	2.5	–	3	8
	CRB800H	720	800	1.05	–	7.0	4.0	–	4	5

Table 8.3 Properties of the hot-rolled reinforcing bar for prestressed concrete (GB/T 5223.3-2017, 2017)

Nominal diameter (mm)	Grades	Min. yield strength (MPa)	Min. tensile strength (MPa)	Min. elongation at fracture (%)
6	40Si2Mn	1325	1476	6
8.2	48Si2Mn			
10	45Si2Cr			

stress in the pre- and post-tensioning methods is 70 and 65% of the standard strength, respectively.

8.6.4 Cold-Drawn Low Carbon Steel Bar

The cold-drawn low carbon steel bar and wire are widely used cold-drawn steel (Table 8.4). The mechanical properties and surface finishes are both improved after cold drawing. After cold drawing under the required elongation and cold bending property, the low carbon steel and low alloy high strength steel have increased yield strength, ultimate strength, and plasticity. However, it should be noted that the steel bar must be cold-drawn after welding; otherwise, the cold-drawn hardening effect will disappear due to the influence of high temperature during welding.

Table 8.4 Mechanical properties of the cold-drawn steel bar (GB/T 3078-2019, 2019)

Labels	Cold-drawn			Annealed		
	Min. tensile strength (MPa)	Min. elongation at fracture (%)	Min. area reduction (%)	Min. tensile strength (MPa)	Min. elongation at fracture (%)	Min. area reduction (%)
10	440	8	50	295	26	55
15	470	8	45	345	28	55
20	510	7.5	40	390	21	50
25	540	7	40	410	19	50
30	560	7	35	440	17	45
35	590	6.5	35	470	15	45
40	610	6	35	510	14	40
45	635	6	30	540	13	40
50	655	6	30	560	12	40
15Mn	490	7.5	40	390	21	50
50Mn	685	5.5	30	590	10	35
50Mn2	735	5	25	635	9	30

Table 8.5 Mechanical properties of cold-drawn low carbon steel wire (JGJ 19-2010, 2010)

Nominal diameter (mm)	Min. tensile strength (MPa)	Min. elongation at fracture (%)	Bending times	Diameter *d* of 180° cold bending test (mm)
3	550	2.0	4	7.5
4		2.5		10
5		3.0		15
6				15
7				20
8				20

The cold-drawn low carbon steel wire is produced by one or multiple cold-drawn treatments. The mechanical properties of cold-drawn low carbon steel wire are shown in Table 8.5. During the cold-drawn process, the strength of low carbon steel is increased and its elongation rate is decreased because the dislocation in steel increases and prevents the slip of lattice in steel. Therefore, the strength of cold-drawn low carbon steel wire depends on the original strength of hot-rolled steel wire and total deformation after cold-drawn. The time of cold-drawn should be controlled to ensure strength and ductility.

8.6.5 Prestressed Steel Wire, Indented Steel Bar and Steel Strand

The prestressed steel wire is made of carbon steel of high quality by isothermal quenching and drawing. The diameter of the prestressed steel wire is 2.5–5 mm, and the tensile strength is 1500–1900 MPa. The surface of the prestressed steel wire can be deformed to enhance the bond with concrete, then into a carved steel wire. The prestressed steel wire has high strength, good plasticity, high corrosion resistance, etc., and is used in prestressed concrete.

The indented steel bar and steel strand are all cold-worked reinforced steel, and there is no obvious yield point, so the material inspection can only be based on the tensile strength. Its strength is almost twice that of the hot-rolled grade IV steel bar, and it has good plasticity and can be cut to the required length when used. The design strength is determined by the statistical value of the conditional yield point. The prestressed steel wire, scratched steel wire, and strand steel wire all have the advantages of high strength, high plasticity, and no need for joints. They are applicable to the prestressed concrete structure with a large load, large span, and curved reinforcement.

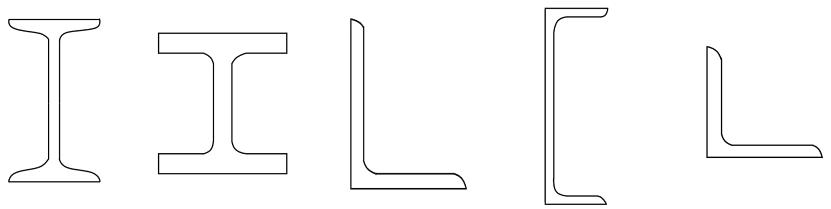
8.6.6 Steel Sections

Steel structures in civil engineering usually use different types of steel sections or plates. For example, thin-walled steel structures use thin-walled steel sections, round steel sections, and section angles. Steel sections are well-designed and manufactured steel members to bear specific bending or compressive loads, and can be directly used and assembled in the steel structure quickly and cost-effectively. The steel sections can be connected by bolting, welding, or riveting. Rivets have historically been used as a connecting medium; however, they have largely been replaced by bolts. Usually, steel sections with thick walls (0.35–200 mm) are hot-rolled, while steel sections with thin walls (0.2–5 mm) are cold-rolled.

1. Hot-rolled steel sections

The commonly used section steels of the steel structure include the I-beam, H-beam, T-beam, Z-beam, channel steel, equal-leg angle steel, unequal-leg angle steel, etc. (Fig. 8.13). Characteristics of those hot-rolled steel sections include:

(1) I-beam is widely used in various building structures and bridges. It is mainly used for members bearing in the plane of the web, but it should not be used alone as the axial compression member or two-way bending member.
(2) Compared with I-beam, H-beam optimizes the distribution of loads and has a wide flange, large lateral stiffness, strong bending resistance, parallel flange surfaces, and a convenient connection structure. It is often used in large buildings with large bearing capacity and good section stability. H-beam with the wide and middle flange is suitable for axial compression members such as steel columns and H-beam with the narrow flange is suitable for bending members such as steel beams.
(3) Channel steel can be used as members bearing axial force, beams bearing transverse bending, and connecting members. It is mainly used in building structures, vehicle manufacturing, etc.
(4) Angle steel is mainly used as a member and supporting member bearing axial force, and can also be used as a connecting part between stressed members.



(a) I-beam (b) H-beam (c) L-beam (d) Channel (e) Equal-leg angle

Fig. 8.13 Typical steel sections, redrafted after Huang et al. (2020)

The steel types and grades for the steel structure are mainly selected according to the importance of the structure and member, the type of loads (static or dynamic loads), the connection method (welding or bolting connection), working conditions (ambient temperature and surrounding environment), etc. Carbon structural steel and low alloy steel are mainly used as hot-rolled steel sections. The carbon steel Q235A, low alloy steel Q345 (16Mn), and Q390 (15MnV) are the most widely used. The former is applicable for most steel structures, and the latter can be used for long-span steel structures for dynamic loads. Labels of the hot-rolled steel sections include types, dimensions, steel types, and related specifications.

2. Cold-formed thin-walled steel section

Cold-formed thin-walled steel sections are usually formed by cold bending of 2–6 mm thin-walled steel plates. They include angle steel, channel steel and hollow thin-walled sections with square and rectangle shapes, and are mainly used in light steel structures.

3. Steel plate

The steel plates can be classified into hot-rolled and cold-rolled steel plates. According to the thickness, they can be classified into thick steel plates (thickness > 4 mm) and thin steel plates (thickness $\leq$ 4 mm). Thick plates are produced by hot rolling. Thin plates can be produced by hot-rolling or cold-rolling. Most of the thin plates used in civil engineering are hot rolled.

Steel plates mainly use carbon steel, and some long-span bridges use low alloy steel. Thick steel plates are mainly used for load-bearing members. Thin steel plates are mainly used for roofs, floors, and walls. In steel structures, a single steel plate cannot work independently. Several plates must be connected into I-shaped and box structures to bear the load.

4. Steel pipe

Steel pipes are mostly used to make trusses, tower masts, concrete-filled steel tubes, etc. They are widely used in high-rise buildings, plant columns, tower columns, penstocks, etc. According to the manufacturing process, the steel pipes used for steel structures are classified into hot-rolled seamless steel pipes and welded steel pipes.

(1) The hot-rolled seamless steel pipe is made of high-quality carbon steel and low-alloy structural steel. It is mostly produced by the hot-rolling, cold-drawing, or cold-rolling process. The cost of the latter is high. It is mainly used for penstocks and some specific steel structures.
(2) The welded steel pipe is made of high-quality or ordinary carbon steel plates by cold-welding. According to the welding forms, there are straight seam electric welding steel pipes and spiral welding steel pipes, which are suitable for various structures, transmission pipelines, and other purposes. The welded steel pipe has low cost and is easy to process, but the compressive performance is poor.

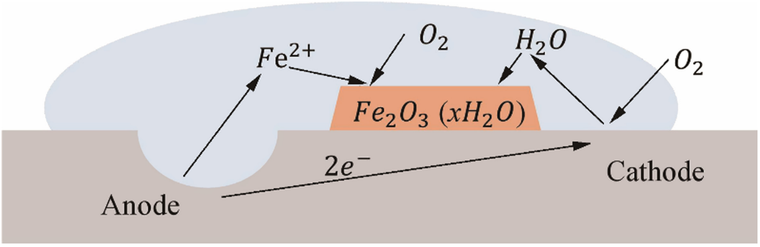


Fig. 8.14 Corrosion of steel, redrafted after Pravin et al. (2014)

8.7 Corrosion and Protection

8.7.1 Corrosion

Steel corrosion is the destruction of its surface by a chemical reaction with the surrounding medium. Corrosion can occur in humid air, soil, and industrial waste gas. The temperature increases, and the corrosion accelerates. Corrosion is critical for all steel structures. When serious corrosion occurs during storage, the cross-sectional area of steel and the quality are reduced. The rust removal work is very costly or can only obtain scrapped steel. If the steel has corrosion in service, the local rust pit can cause stress concentration, accelerating the early damage of the structure. Under repeated loads, corrosion fatigue occurs and the fatigue strength is greatly reduced.

According to different effects of the steel surface and the surrounding environment, corrosion can be classified into two types. Chemical corrosion is the chemical reaction of steel with the surrounding media (such as oxygen, carbon dioxide, sulfur dioxide, and water), generating porous hematite ferrite III oxide (Fe_2O_3). Electrochemical corrosion is the contact between the steel and the electrolytic solution that produces an electric current, forming a galvanic cell that causes corrosion. It is the most common type of corrosion. Electrochemical corrosion requires four elements: an anode where corrosion occurs, a cathode to form a corrosion cell, a conductor for electrons to flow, and a liquid electrolyte supporting the flow of electrons (Fig. 8.14). Steel contains anodes and cathodes and is also an electrical conductor. Preventing contact with moisture is critical for the prevention of rust.

8.7.2 Protection

Coating or painting is usually used to prevent the corrosion of steel. Commonly used primers in the paint include red lead, epoxy zinc-rich paint, and iron red epoxy primer. The topcoats include grey lead oil and phenolic enamel. For thin steel products, hot-dip galvanized coating is very effective while costly.

Concrete is strong alkalinity, with a pH value of around 12.5, forming alkaline protection on steel. There are several reasons for the corrosion of steel bars in concrete. Concrete contains voids and micro cracks, and the thickness of the protective concrete layer might be thin or heavily carbonized. In particular, when chloride iron content is too high, the corrosion of steel is severe. To improve the corrosion resistance of reinforced concrete, barrier coating or sacrificial primers are applied. Besides, the water-cement ratio and cement content should be controlled. The concrete should also be thick enough to prevent steel corrosion. It is also important to control the chloride content in additives for concrete.

Prestressed steel bar is susceptible to corrosion as it has a high content of carbon and is subjected to deformation and cold-drawn process. In particular, the prestressed steel after high strength hot-treated tends to produce corrosion. Thus, for a prestressed loading structure, the quality of raw materials should be strictly controlled and chloride should be avoided.

To prevent corrosion of the reinforced steel bar, it is suggested to use a rust inhibitor. Moreover, galvanization, cadmium, and nickel coating can also effectively enhance the corrosion resistance of the reinforced steel bar.

Questions

1. What is the effect of carbon and other elements on the mechanical properties of steel?
2. What is the typical maximum percentage of the carbon in the steel?
3. Define yield strength and ultimate tensile strength of steel.
4. What is the hardness of steel and can we use hardness instead of strength?
5. Why is impact toughness important for steel? What's the effect of temperature on the impact toughness?
6. How to measure the plasticity of steel?
7. Define the alloy steel. Explain why alloys are added to steel.
8. Discuss the procedures and objectives of the four heat treatment.
9. What is the effect of cold-drawn treatment?
10. How to prevent the corrosion of steel?

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