3

STEEL

The use of iron dates back to about 1500 B.C. 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 18th century. Iron products were widely used in the latter half of the 18th century and the early part of the 19th century. Steel production started in mid-1800s when the Bessemer converter was invented. In the second half of the 19th century, steel technology advanced rapidly due to the development of the basic oxygen furnace and continuous casting methods. More recently, computer-controlled manufacturing has increased the efficiency and reduced the cost of steel production.

Currently, steel and steel alloys are used widely in civil engineering applications. In addition, wrought iron is still used on a smaller scale for pipes, as well as for general blacksmith work. Cast iron is used for pipes, hardware, and machine parts not subjected to tensile or dynamic loading.

Steel products used in construction can be classified as follows:

1. *structural steel* for use in plates, bars, pipes, structural shapes, etc. (Figure 3.1)
2. *fastening products* used for structural connections, including bolts, nuts and washers
3. *reinforcing steel* (rebars) for use in concrete reinforcement (Figure 3.2)
4. miscellaneous products for use in such applications as forms and pans

Civil and construction engineers rarely have the opportunity to formulate steel with specific properties. Rather, they must select existing products from suppliers. Even the shapes for structural elements are generally restricted to those readily available from manufacturers. While specific shapes can be made to order, the cost to fabricate low-volume members is generally prohibitive. Therefore, the majority of civil engineering projects are designed using standard steel types and structural shapes.

Even though civil and construction engineers are not responsible for formulating steel products, they still must understand how steel is manufactured

FIGURE 3.1 Truss made of structural steel for the structural support of a building.

and treated and how it responds to loads and environmental conditions. This chapter reviews steel production, the iron–carbon phase diagram, heat treatment, steel alloys, structural steel, steel fasteners, and reinforcing steel. The chapter also presents common tests used to characterize the mechanical properties of steel. The topics of welding and corrosion of steel are also introduced.

3.1 Steel Production

The overall process of steel production is shown in Figure 3.3. This process consists of the following three phases:

1. reducing iron ore to pig iron
2. refining pig iron to steel
3. forming the steel into products

The materials used to produce pig iron are coal, limestone, and iron ore. The coal, after transformation to coke, supplies carbon used to reduce iron

FIGURE 3.2 Steel rebars used to reinforce portland cement concrete wall.

oxides in the ore. Limestone is used to help remove impurities. Prior to reduction, the concentration of iron in the ore is increased by crushing and soaking the ore. The iron is magnetically extracted from the waste, and the extracted material is formed into pellets and fired. The processed ore contains about 65% iron.

Reduction of the ore to pig iron is accomplished in a blast furnace. The ore is heated in the presence of carbon. Oxygen in the ore reacts with carbon to form gases. A flux is used to help remove impurities. The molten iron, with an excess of carbon in solution, collects at the bottom of the furnace. The impurities, slag, float on top of the molten pig iron.

The excess carbon, along with other impurities, must be removed to produce high-quality steel. Using the same refining process, scrap steel can be recycled. Three types of furnaces are used for refining pig iron to steel:

1. open hearth
2. basic oxygen
3. electric arc

The open hearth and basic oxygen furnaces remove excess carbon by reacting the carbon with oxygen to form gases. Lances circulate oxygen through the molten material. The process is continued until all impurities are removed and the desired carbon content is achieved. Open hearth furnaces have been used since the early 1900s. Now, due to greater efficiency and productivity,

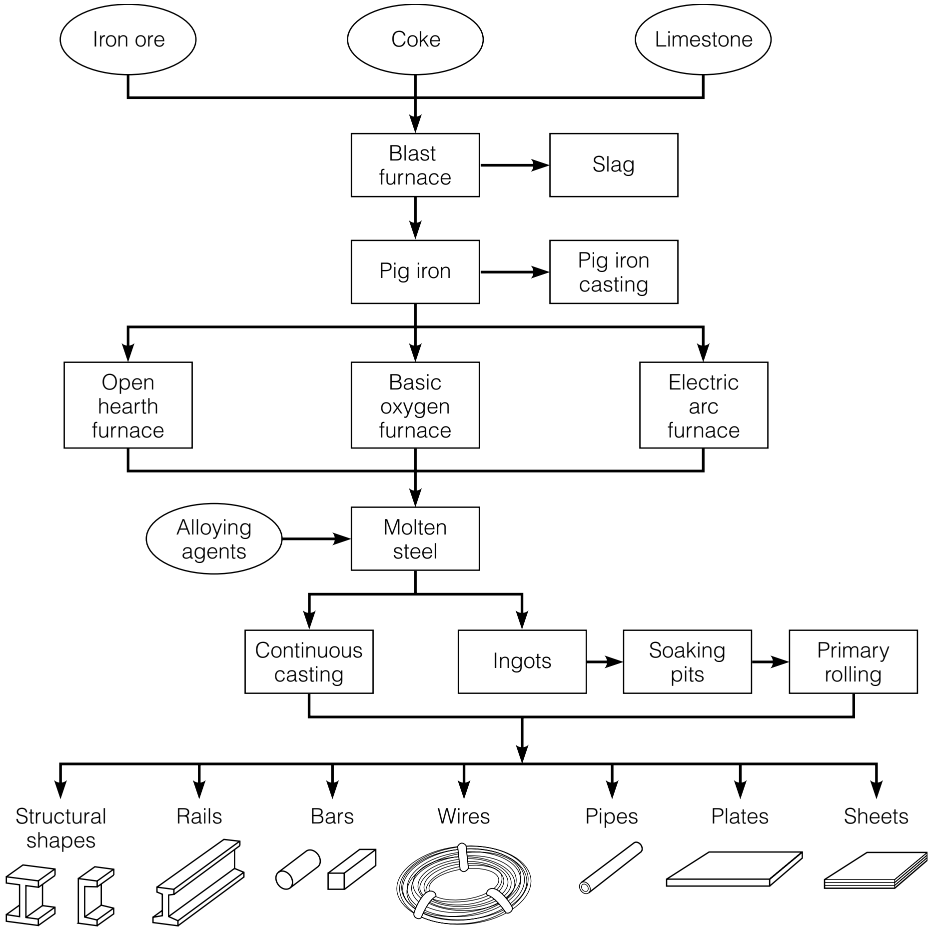

FIGURE 3.3 Conversion of raw material into different steel shapes.

basic oxygen furnaces are the industry standard for high-production mills. A basic oxygen furnace can refine 280,000 kg (300 tons) of steel in 25 minutes, compared with the eight hours it takes to refine the same quantity of steel in an open hearth furnace.

Electric furnaces use an electric arc between carbon electrodes to melt and refine the steel. These plants require a tremendous amount of energy and are primarily used to recycle scrap steel. Electric furnaces are frequently used in minimills, which produce a limited range of products. In this process, molten steel is transferred to the ladle. Alloying elements and additional agents can be added either in the furnace or the ladle.

During the steel production process, oxygen may become dissolved in the liquid metal. As the steel solidifies, the oxygen can combine with carbon to form carbon monoxide bubbles that are trapped in the steel and can act as initiation points for failure. Deoxidizing agents, such as aluminum, ferrosilicon and manganese, can eliminate the formation of the carbon monoxide bubbles. Completely deoxidized steels are known as *killed steels*. Steels that are generally killed include

- Those with a carbon content greater than 0.25%
- All forging grades of steels
- Structural steels with carbon content between 0.15 and 0.25 percent
- Some special steel in the lower carbon ranges

Regardless of the refining process, the molten steel, with the desired chemical composition, is then either cast into ingots (large blocks of steel) or cast continuously into a desired shape. Continuous casting is becoming the standard production method, since it is more energy efficient than casting ingots, as the ingots must be reheated prior to shaping the steel into the final product.

3.2 Iron–Carbon Phase Diagram

In refining steel from iron ore, the quantity of carbon used must be carefully controlled in order for the steel to have the desired properties. The reason for the strong relationship between steel properties and carbon content can be understood by examining the iron–carbon phase diagram.

Figure 3.4 presents a commonly accepted iron–carbon phase diagram. One of the unique features of this diagram is that the abscissa extends only to 6.7% rather than 100%. This is a matter of convention. In an iron-rich material, each carbon atom bonds with three iron atoms to form iron carbide, Fe_3C, also called cementite. Iron carbide is 6.7% carbon by weight. Thus, on the phase diagram, a carbon weight of 6.7% corresponds to 100% iron carbide. A complete iron–carbon phase diagram should extend to 100% carbon. However, only the iron rich portion, as shown on Figure 3.4, is of practical significance (Callister 2003). In fact, structural steels have a maximum carbon content of less than 0.3%, so only a very small portion of the phase diagram is significant for civil engineers.

The left side of Figure 3.4 demonstrates that pure iron goes through two transformations as temperature increases. Pure iron below 912°C has a BCC crystalline structure called ferrite. At 912°C the ferrite undergoes a polymorphic change to a FCC structure called austenite. At 1394°C, another polymorphic change occurs, returning the iron to a BCC structure. At 1539°C the iron melts into a liquid. The high and low temperature ferrites are identified as δ and α ferrite, respectively. Since δ ferrite occurs only at very high temperatures, it does not have practical significance for this book.

Carbon goes into solution with α ferrite at temperatures between 400°C and 912°C. However, the solubility limit is very low, with a maximum of 0.022% at 727°C. At temperatures below 727°C and to the right of the solubility limit line, α ferrite and iron carbide coexist as two phases. From 727°C to 1148°C, the solubility of carbon in the austenite increases from 0.77% to

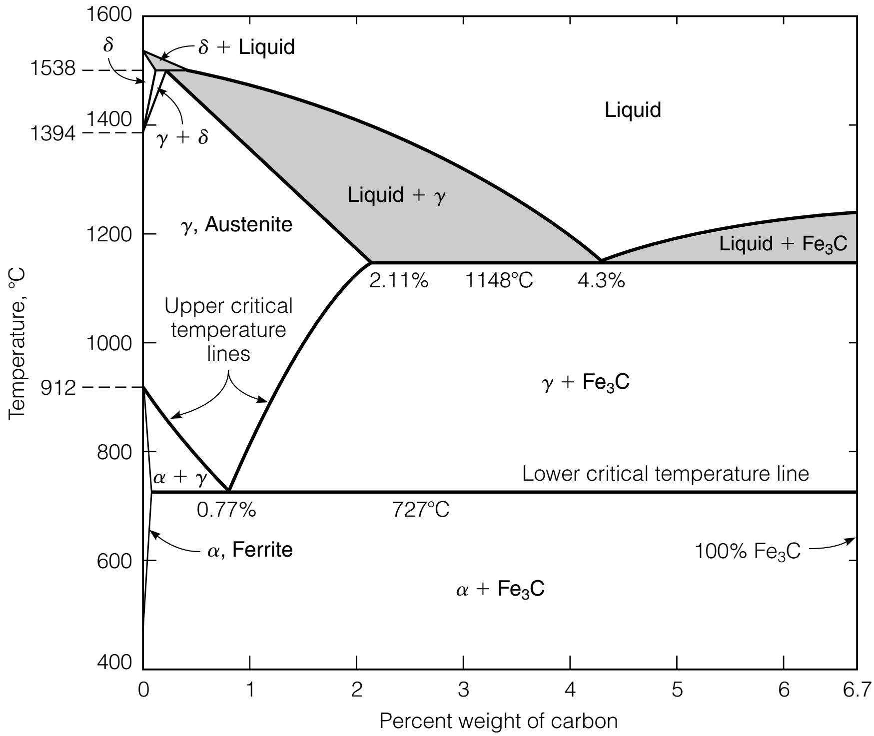

FIGURE 3.4 The iron–iron carbide phase diagram.

2.11%. The solubility of carbon in austenite is greater than in a ferrite because of the crystalline structure of the austenite.

At 0.77% carbon and 727°C, a eutectoid reaction occurs; that is, a solid phase change occurs when either the temperature or carbon content changes. At 0.77% carbon, and above 727°C, the carbon is in solution as an interstitial element, within the FCC structure of the austenite. A temperature drop to below 727°C, which happens slowly enough to allow the atoms to reach an equilibrium condition, results in a two-phase material, a ferrite and iron carbide. The α ferrite will have 0.022% carbon in solution, and the iron carbide will have a carbon content of 6.7%. The ferrite and iron carbide will form as thin plates, a lamellae structure. This eutectoid material is called pearlite.

At carbon contents less than the eutectoid composition, 0.77% carbon, *hypoeutectoid* alloys are formed. Consider a carbon content of 0.25%. Above approximately 860°C, solid austenite exists with carbon in solution. The austenite consists of grains of uniform material that were formed when the steel was cooled from a liquid to a solid. Under equilibrium temperature drop from 860°C to 727°C, α ferrite is formed and accumulates at the grain boundaries of the austenite. This is a proeuctoid ferrite. At temperatures slightly above 727°C, the ferrite will have 0.022% carbon in solution and austenite will have 0.77% carbon. When the temperature drops below 727°C, the austenite will transform to pearlite. The resulting structure consists of grains of pearlite surrounded by a skeleton of α ferrite.

When the carbon content is greater than the eutectoid composition, 0.77% carbon, hypereutectoid alloys are formed. Iron carbide forms at the grain boundaries of the austenite at temperatures above 727°C. The resulting microstructure consists of grains of pearlite surrounded by a skeleton of iron carbide.

The lever rule for the analysis of phase diagrams can be used to determine the phases and constituents of steel.

Sample Problem 3.1

Calculate the amounts and compositions of phases and constituents of steel composed of iron and 0.25% carbon just above and below the eutectoid isotherm.

Solution

At a temperature just higher than 727°C, all the austenite will have a carbon content of 0.77% and will transform to pearlite. The ferrite will remain as primary ferrite. The proportions can be determined by using the lever rule:

Primary α: 0.022% C,

$$\text{Percent primary } \alpha = \left[\frac{0.77 - 0.25}{0.77 - 0.022}\right] \times 100 = 69.5\%$$

$$\text{Percent pearlite} = \left[\frac{0.25 - 0.022}{0.77 - 0.022}\right] = 30.5\%$$

At a temperature just below 727°C, the phases are ferrite and iron carbide. The ferrite will have 0.022% carbon, so we have

$$\text{Percent ferrite, } \alpha\text{: } (0.022\%\ C) = \left[\frac{6.67 - 0.25}{6.67 - 0.022}\right] \times 100 = 96.6\%$$

$$\text{Percent pearlite} = \left[\frac{0.25 - 0.022}{6.67 - 0.022}\right] = 3.4\%$$

Figure 3.5 shows an optical photomicrograph of a hot-rolled mild steel plate with a carbon content of 0.18% by weight that was etched with 3% nitol. The photomicrograph is magnified at 50×. The light etching phase is proeutectiod ferrite and the dark constituent is pearlite. Note the banded structure resulting from the rolling processes. Figure 3.6 shows the same material as Figure 3.5, except that the magnification is 400×. At this magnification, the alternating layers of ferrite and cementite in the pearlite can be seen.

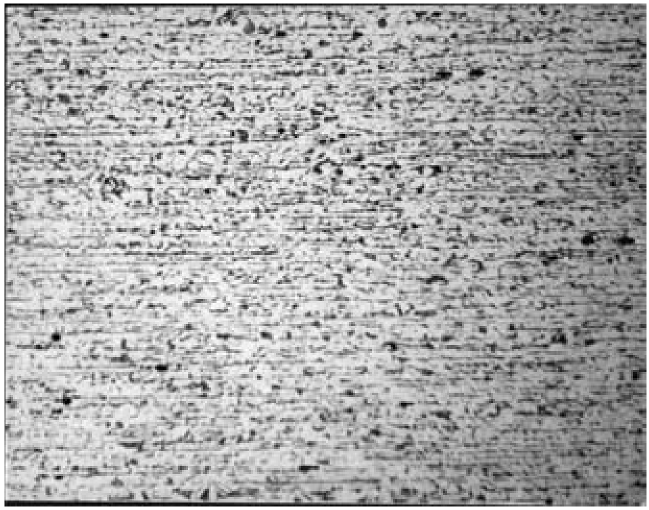

FIGURE 3.5 Optical photomicrograph of hot rolled mild steel plate (magnification: 50x).

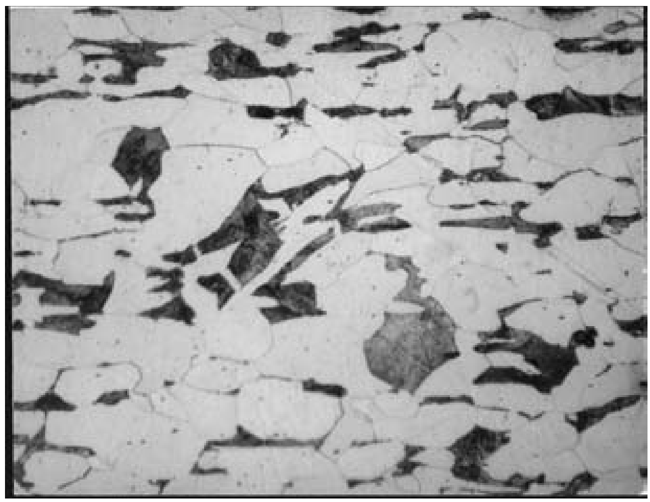

FIGURE 3.6 Optical photomicrograph of hot rolled mild steel plate (magnification: 400x).

The significance of ferrite, pearlite, and iron carbide formation is that the properties of the steel are highly dependent on the relative proportions of ferrite and iron carbide. Ferrite has relatively low strength but is very ductile. Iron carbide has high strength but has virtually no ductility. Combining these materials in different proportions alters the mechanical properties of the steel. Increasing the carbon content increases strength and hardness, but reduces ductility. However, the modulus of elasticity of steel does not change by altering the carbon content.

All of the preceding reactions are for temperature reduction rates that allow the material to reach equilibrium. Cooling at more rapid rates greatly alters the microstructure. Moderate cooling rates produce bainite, a fine-structure pearlite without a proeuctoid phase. Rapid quenching produces martensite; the carbon is supersaturated in the iron, causing a body center tetragonal lattice structure. Time–temperature transformation diagrams are used to predict the structure and properties of steel subjected to heat treatment. Rather than going into the specifics, the different types of heat treatments are described.

3.3 Heat Treatment of Steel

Properties of steel can be altered by applying a variety of heat treatments. For example, steel can be hardened or softened by using heat treatment; the response of steel to heat treatment depends upon its alloy composition. Common heat treatments employed for steel include annealing, normalizing, hardening, and tempering. The basic process is to heat the steel to a specific temperature, hold the temperature for a specified period of time, then cool the material at a specified rate. The temperatures used for each of the treatment types are shown in Figure 3.7.

3.3.1 Annealing

The objectives of annealing are to refine the grain, soften the steel, remove internal stresses, remove gases, increase ductility and toughness, and change

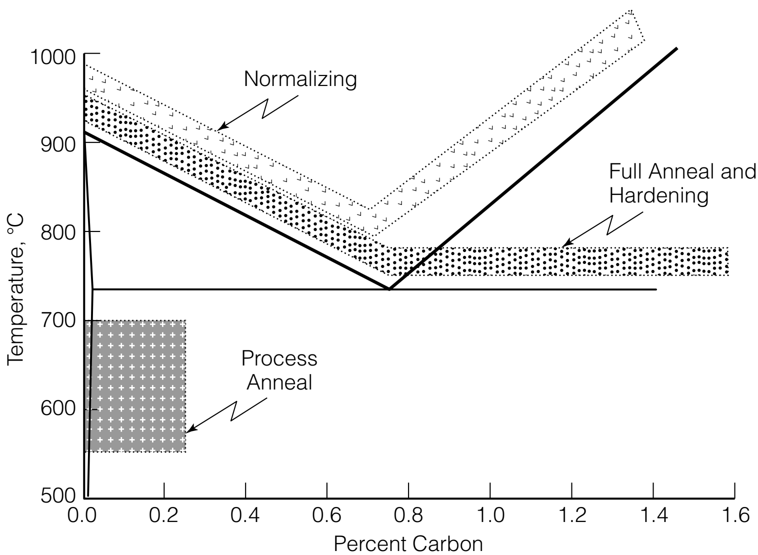

FIGURE 3.7 Heat treatment temperatures.

electrical and magnetic properties. Four types of annealing can be performed, depending on the desired results of the heat treatment:

Full annealing requires heating the steel to about 50°C above the austenitic temperature line and holding the temperature until all the steel transforms into either austenite or austenite–cementite, depending on the carbon content. The steel is then cooled at a rate of about 20°C per hour in a furnace to a temperature of about 680°C, followed by natural convection cooling to room temperature. Due to the slow cooling rate, the grain structure is a coarse pearlite with ferrite or cementite, depending on the carbon content. The slow cooling rate ensures uniform properties of the treated steel. The steel is soft and ductile.

Process annealing is used to treat work-hardened parts made with low carbon steel (i.e., less than 0.25 percent carbon). 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, as occurs during full annealing. Hence, the only change that occurs is refinement of the size, shape, and distribution of the grain structure.

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

Spheroidization is an annealing process used to improve the ability of high carbon (i.e., more than 0.6 percent carbon) steel to be machined or cold worked. It also improves abrasion resistance. The cementite is formed into globules (spheroids) dispersed throughout the ferrite matrix.

3.3.2 Normalizing

Normalizing is similar to annealing, with a slight difference in the temperature and the rate of cooling. Steel is normalized by heating to about 60°C (110°F) above the austenite line and then cooling under natural convection. The material is then air cooled. Normalizing produces a uniform, fine-grained microstructure. However, since the rate of cooling is faster than that used for full annealing, the rate of cooling of shapes with varying thicknesses results in the normalized parts having less uniformity than could be achieved with annealing. Since structural plate has a uniform thickness, normalizing is an effective process and results in high fracture toughness of the material.

3.3.3 Hardening

Steel is hardened by heating it to a temperature above the transformation range and holding it until austenite is formed. The steel is then quenched (cooled rapidly) by plunging it into, or spraying it with, water, brine, or oil. The rapid cooling "locks" the iron into a BCC structure, *martensite*, rather than allowing the transformation to the ferrite FCC structure. Martensite has a very hard and brittle structure. Since the cooling occurs more rapidly at the surface of the material being hardened, the surface of the material is harder and more brittle than the interior of the element, creating nonhomogenous characteristics. Due to the rapid cooling, hardening puts the steel in a state of strain. This strain sometimes causes steel pieces with sharp angles or grooves to crack immediately after hardening. Thus, hardening must be followed by tempering.

3.3.4 Tempering

The predominance of martensite in quench-hardened steel results in an undesirable brittleness. Tempering is performed to improve ductility and toughness. Martensite is a somewhat instable structure. Heating causes carbon atoms to diffuse from martensite to produce a carbide precipitate and formation of ferrite and cementite. After quenching, the steel is cooled to about 40°C then reheated by immersion in either oil or nitrate salts. The steel is maintained at the elevated temperature for about two hours and then cooled in still air.

3.3.5 Example of Heat Treatment

In the quest to economically produce high-strength low-alloy steels, the industry has developed specifications for several new steel products, such as A913. This steel is available with yield stresses ranging from 50,000 to 75,000 psi. The superior properties of A913 steel are obtained by a quench-self-tempering process. Following the last hot rolling pass for shaping, for which the temperature is typically 850°C (1600°F), an intense water-cooling spray is applied to the surface of the beam to quench (rapidly cool) the skin. Cooling is interrupted before the core on the material is affected. The outer layers are then tempered as the internal heat of the beam flows to the surface. After the short cooling phase, the self-tempering temperature is 600°C (1100°F) (Bouchard and Axmann, 2000).

3.4 Steel Alloys

Alloy metals can be used to alter the characteristics of steel. By some counts, there are as many as 250,000 different alloys of steel produced. Of these, as many as 200 may be used for civil engineering applications. Rather than go into the specific characteristics of selected alloys, the general effect of different alloying agents will be presented. Alloy agents are added to improve one or more of the following properties:

1. hardenability
2. corrosion resistance
3. machineability
4. ductility
5. strength

TABLE 3.1 Common Steel Alloying Agents (Budinski, 1996) (Reprinted with permission of Prentice-Hall, Inc.)

	Typical Ranges in Alloy Steels (%)	Principal Effects
Aluminum	<2	Aids nitriding Restricts grain froth Removes oxygen in steel melting
Sulfur	<0.5	Adds machinability Reduces weldability and ductility
Chromium	0.3 to 0.4	Increases resistance to corrosion and oxidation Increases hardenability Increases high-temperature strength Can combine with carbon to form hard, wear-resistant microconstituents
Nickel	0.3 to 5	Promotes an austenitic structure Increases hardenability Increases toughness
Copper	0.2 to 0.5	Promotes tenacious oxide film to aid atmospheric corrosion resistance
Manganese	0.3 to 2	Increases hardenability Promotes an austenitic structure Combines with sulfur to reduce its adverse effects
Silicon	0.2 to 2.5	Removes oxygen in steel making Improves toughness Increases hardenability
Molybdenum	0.1 to 0.5	Promotes grain refinement Increases hardenability Improves high-temperature strength
Vanadium	0.1 to 0.3	Promotes grain refinement Increases hardenability Will combine with carbon to form wear-resistant microconstituents

Common alloy agents, their typical percentage range, and their effects are summarized in Table 3.1.

By altering the carbon and alloy content and by using different heat treatments, steel can be produced with a wide variety of characteristics.

These are classified as follows:

1. Low alloy
   - Low carbon
   - Plain
   - High strength–low alloy
   - Medium carbon
   - Plain
   - Heat treatable
   - High carbon
   - Plain
   - Tool
2. High Alloy
   - Tool
   - Stainless

Steels used for construction projects are predominantly low- and medium-carbon plain steels. Stainless steel has been used in some highly corrosive applications, such as dowel bars in concrete pavements and steel components in swimming pools and drainage lines. The Specialty Steel Industry of North America, SSINA, promotes the use of stainless steel for structural members where corrosion resistance is an important design consideration (SSINA, 1999).

The use and control of alloying agents is one of the most significant factors in the development of steels with better performance characteristics. The earliest specification for steel used in building and bridge construction, published in 1900, did not contain any chemical requirements. In 1991 ASTM published the specification which controls content of 10 alloying elements in addition to carbon (Hassett, 2003).

3.5 Structural Steel

Structural steel is used in hot-rolled structural shapes, plates, and bars. Structural steel is used for various types of structural members, such as columns, beams, bracings, frames, trusses, bridge girders, and other structural applications (see Figure 3.8).

3.5.1 Structural Steel Grades

Due to the widespread use of steel in many applications, there are a wide variety of systems for identifying or designating steel, based on grade, type and class. Virtually every country with an industrial capacity has specifications for steel. In the United States, there are several associations that write specifications for steel, such as the Society of Automotive Engineers, SAE, the American Iron and Steel Institute, AISI, and the American Society for Testing and Materials, ASTM. The most widely used designation system was developed cooperatively by SAE and AISI based on chemical composition (Key-to-Steel, 2005). However, the materials and products used in building design and construction in the United States are almost exclusively designated by ASTM specifications (Carter, 2004). ASTM specification names consist of a letter,

FIGURE 3.8 Structural steel used to make columns, beams, and floors for the structural support of a building.

generally an A for ferrous materials, followed by an arbitrary serially assigned number. For example, ASTM A7 was a specification for structural steel written in 1900 and ASTM A992 was published in 1999 (Carter, 2004). The designation or specification number does not contain any meaningful information other than to serve as a reference. Within ASTM specifications, the terms *grade, type*, and *class* are used in an inconsistent manner. In some ASTM steel specifications, the term grade identifies the yield strength, while in other specifications, the term grade can indicate requirements for both chemical compositions and mechanical properties. ASTM and SAE have developed the Unified Numbering System, UNS (ASTM E527), based on chemical composition. This system uses a letter to identify the broad class of alloys, and a five-digit number to define specific alloys within the class.

Several grades of structural steel are produced in the United States. Table 3.2 is a summary of selected information from various sources. The American Institute of Steel Construction, AISC, Manual for Steel Construction is an excellent reference on the types of steel used for structural applications. However, the best sources of information for structural steels are the various ASTM specifications. Of particular note is the fact that additional requirements are frequently included, dependent on the geometry of the product made with a particular steel.

Historically, dating back to 1900, only two types of structural steel were used in the United States: A7 for bridges and A9 for buildings. The specifications for these materials were very similar and in 1938, they were combined

TABLE 3.2 Designations, Properties, and Composition of ASTM Structural Steel

Steel Type	ASTM designation		F_y (psi)	F_u[1] (psi)	Elongation[2]	Typical Chemical Composition[1] C	Cu[4]	Mn	P	S	Ni	Cr	Si	Mo	V
Carbon	A36		36	58–80	23	0.26	0.2	0.75	0.04	0.05					
	A53 Gr. B		35	60		0.25	0.4	0.95	0.05	0.045	0.4	0.4		0.15	0.08
	A500	Gr. B	42	58	23	0.3	0.18		0.05	0.63					
			46	58											
		Gr. C	46	62	21	0.27	0.18	1.4	0.05	0.063					
			50	62											
	A501		36	58	23	0.3	0.18		0.15	0.63					
	A529	Gr.50	50	65–100	19	0.27	0.2	1.35	0.04	0.05					
		Gr.55	55	70–100											
High-strength Low-alloy	A572	Gr. 42	42	60	24	0.21	-	1.35	0.04	0.05					
		Gr. 50	50	65	21	0.23	-	1.35	0.04	0.05					
		Gr. 55	55	70		0.25	-	1.35	0.04	0.05					
		Gr. 60	60	75	18	0.26	-	1.35	0.04	0.05					
		Gr. 65	65	80	17	0.26	-	1.35	0.04	0.05					
	A618	Gr. I&II	50	70	22	0.2	0.2	1.35	0.04	0.05					
		Gr. III	50	65	22	.023	-	1.35	0.04	0.05			0.3		
	A913	50	50	60	21	0.12	0.45	1.60	0.04	0.03	0.25	0.25	0.4	0.07	0.06
		65	65	80	17	0.35	0.35	1.60	0.04	0.03	0.25	0.25	0.4	0.07	0.06
	A992[3]		50–65	65	18	0.232	0.60	0.5–0.15	0.35	0.45	0.45			0.15	0.11
Corrosion resistant, High-strength low-alloy	A242	50	50	70	18	0.15	0.2	1.0	0.15	0.05					
	A588		50	70	21	0.19	0.2–0.4	0.25–1.35	0.04	0.05	0.04	0.4–0.7			0.02–0.1

[1] Minimum unless range or other control noted.
[2] Two-inch gauge length.
[3] A maximum-yield-to–tensile-strength ratio of 0.85 and carbon equivalent formula are included as mandatory in ASTM 992.
[4] Several steel specifications can include a minimum copper content to provide weather resistance.

into a single specification, A7. The specification for A7 and A9 were limited to requirements for the tensile strength and yield point only; there were no chemical specifications. The chemical composition, particularly carbon content, became an issue during the 1950s, as welding gained favor for making structural connections. By 1964, AISC adopted five grades of steel for structural applications. The 1999 AISC Load and Resistance Factor Design Specification for Structural Steel Buildings, 1999, identifies 15 different ASTM steel designations for structural applications.

3.5.2 Sectional Shapes

Figure 3.9 illustrates structural cross-sectional shapes commonly used in structural applications. These shapes are produced in different sizes and are designated with the letters W, HP, M, S, C, MC, and L. W shapes are doubly symmetric wide-flange shapes whose flanges are substantially parallel. HP shapes are also wide-flange shapes whose flanges and webs are of the same nominal thickness and whose depth and width are essentially the same. The S shapes are doubly symmetric shapes whose inside flange surfaces have approximately 16.67% slope. The M shapes are doubly symmetric shapes that cannot be classified as W, S, or HP shapes. C shapes are channels with inside flange surfaces having a slope of approximately 16.67%. MC shapes are channels that cannot be classified as C shapes. L shapes are angle shapes with either equal or unequal legs. In addition to these shapes, other structural sections are available, such as tee, sheet piling, and rail, as shown in Figure 3.9.

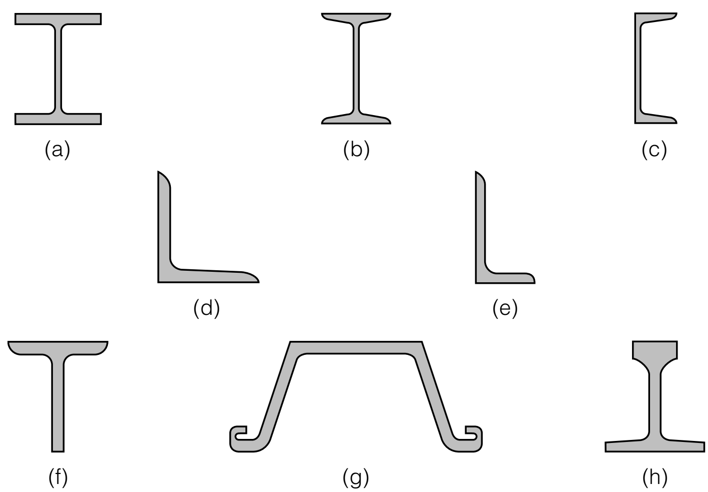

FIGURE 3.9 Shapes commonly used in structural applications: (a) wide-flange (W, HP, and M shapes), (b) I-beam (S shape), (c) channel (C and MC shapes), (d) equal-legs angle (L shape), (e) unequal-legs angle (L shape), (f) tee, (g) sheet piling, and (h) rail.

The W, M, S, HP, C, and MC shapes are designated by a letter, followed by two numbers separated by an ×. The letter indicates the shape, while the two numbers indicate the nominal depth and the weight per linear unit length. For example, W 44 × 335 means W shape with a nominal depth of 44 in. and a weight of 335 lb/linear foot. An angle is designated with the letter L, followed by three numbers that indicate the leg dimensions and thickness in inches, such as L 4 × 4 × 1/2. Dimensions of these structural shapes are controlled by ASTM A6/A6M.

W shapes are commonly used as beams and columns, HP shapes are used as bearing piles, and S shapes are used as beams or girders. Composite sections can also be formed by welding different shapes to use in various structural applications. Sheet piling sections are connected to each other and are used as retaining walls.

Tables 3.3 and 3.4 summarize the applicable ASTM specifications/designations for structural steels, and plates and bars, respectively (Carter, 2004). These tables are guides only; specific information should be sought from the applicable specifications for each material and application. In particular, the dimension and application of a member can affect some finer points about material selection, which are not covered in these tables. In general, the materials identified as "preferred" in the tables are generally available in the market place. Those identified as "other applicable materials" may or may not be readily available.

3.5.3 Specialty Steels in Structural Applications

As the ability to refine steels improves, it is possible to produce special products with sufficient economy to permit their use in construction projects. The Federal Highway Administration, US Navy, and AISI have taken a leading role in the development and application of high-performance steels. These are defined as materials that possess the optimum combination of properties required to build cost-effective structures that will be safe and durable throughout their service life (Lane et. al, 1998). One of the products developed through this effort is high-performance steels, HPS. Currently, two products are available: HPS 50W and HPS 70W. These are weathering steels that form a corrosion barrier on the surface of the steel when first exposed to the environment. This surface resists further corrosion, and hence reduces the need for maintenance. HPS 70W has stronger tensile properties than steel traditionally used for bridge construction, and hence bridges can be designed with a reduced quantity of material. These savings are somewhat offset by the cost of the material, but there is still a net reduction in construction costs. The tensile requirements of HPS 70W are yield strength 70,000 psi, tensile strength of 85,000 to 110,000 psi, and an elongation of 19% (2″ gauge length). In addition, HPS must pass impact tests. HPS 70W is manufactured to tight and extensive alloy content requirements, as shown in Table 3.5 (ISG Plate, 2003).

Comparing the chemical requirements in Table 3.5 with those in Table 3.2 demonstrates that HPS 70W has more extensive chemical requirements,

TABLE 3.3 Applicable ASTM Structural Shapes

Steel Type	ASTM designation		W	M	S	HP	C	MC	L	HSS Rect	HSS Round	Steel Pipe
Carbon	A36		▒	■	■	■	■	■	■			
	A53 Gr. B											■
	A500	Gr. B-42									■	
		Gr. B-46								■		
		Gr. C-46									▒	
		Gr. C-50								▒		
	A501									▒	▒	
	A529	Gr. 50	▒	▒	▒	▒	▒	▒	▒			
		Gr. 55	▒	▒	▒	▒	▒	▒	▒			
High-strength Low-alloy	A572	Gr. 42	▒	▒	▒	▒	▒	▒	▒			
		Gr. 50	▒	▒	▒	▒	▒	▒	▒			
		Gr. 55	▒	▒	▒	▒	▒	▒	▒			
		Gr. 60	▒	▒	▒	▒	▒	▒	▒			
		Gr. 65	▒	▒	▒	▒	▒	▒	▒			
	A618	Gr. I&II								▒	▒	
		Gr. III								▒	▒	
	A913	50	▒	▒	▒	▒	▒	▒	▒			
		65	▒	▒	▒	▒	▒	▒	▒			
	A992		■									
Corrosion resistant, High-strength low-alloy	A242	50	▒	▒	▒	▒	▒	▒	▒			
	A588		▒	▒	▒	▒	▒	▒	▒			
	A847									▒	▒	

■ = Preferred material specification
▒ = Other applicable material specification, the availability of which should be confirmed prior to specification
(blank) = Material specification does not apply
HSS = hollow structural shape

lower carbon content, and tighter controls on phosphorus and sulfur, which are detrimental alloy elements. The lower carbon content improves the weldability of the steel.

The industry has recognized the advantages of designing with the high performance steels. The first HPS bridge went into service in 1997. As of

TABLE 3.4 Applicable ASTM Specifications for Plates and Bars

Steel Types	ASTM designations	f_y or Grade	Thickness ranges									
			≤0.75	>0.75–1.25	1.25–1.5	1.5–2	2–2.5	2.5–4	4–5	5–6	6–8	>8
Carbon	A36	32										
		36										
	A529	Gr. 50		b	b	b	b					
		Gr. 55		b	b							
High-Strength Low-alloy	A572	Gr. 42										
		Gr. 50										
		Gr. 55										
		Gr. 60										
		Gr. 65										
Corrosion Resistant, High-Strength Low-Alloy	A242	42										
		46										
		50										
	A588	42										
		46										
		50										
Quenched and Tempered Alloy	A514[a]	90										
		100										
Quenched and Tempered Low-Alloy	A852	70										

■ = Preferred material specification
▒ = Other applicable material specification, the availability of which should be confirmed prior to specification
□ = Material specification does not apply
a = Available as plates only
b = Applicable to bars only above 1 in. thickness

TABLE 3.5 Chemical Requirements of HPS 70W

Element	Composition (% by weight)
Carbon	0.11 max
Manganese	1.10–1.35
Phosphorus	0.020 max
Sulfur*	0.006 max
Silicon	0.30–0.50
Copper	0.25–0.40
Nickel	0.25–0.40
Chromium	0.45–0.70
Molybdenum	0.02–0.08
Vanadium	0.04–0.08
Aluminum	0.01–0.04
Nitrogen	0.015 max

*All HPS 70 must be calcium treated for sulfide shape control

April 2002, more than 150 bridges with HPS have either been constructed or were in the design and construction stage (FHWA, 2002).

The desire to improve the appearance and durability of steel structures has produced an interest in designing structural members with stainless steel. The durability of stainless steel has long been recognized, but the cost of the material was prohibitive. The ability of stainless steel to resist corrosion rests in the high chromium content. Whereas common structural steels have 0.3 to 0.4 percent chromium, stainless steel has in excess of 10 percent, by definition. Five AISI grades of stainless steel are used for structural applications (SSINA, 1999):

- 304: the most readily available stainless steel, containing 18% chromium and 8% nickel. Excellent corrosion resistance and formability,
- 316: similar to 304, but with the addition of 3–4 percent molybdenum for greater corrosion resistance. Generally specified for highly corrosive environments such as industrial, chemical, and seacoast atmospheres
- 409: a straight chrome alloy, 11 to 12 percent chromium. Primarily used for interior applications.
- 410–3: a dual phase alloy with micro alloy element control that permits welding in up to 1.25 inches.
- 2205: a duplex structure with about equal parts of austenite and ferrite. Excellent corrosion resistance and about twice the yield strength of conventional grades.

The chemical and tensile properties of these grades are summarized in Table 3.6.

TABLE 3.6 Properties of Stainless Steels Used for Structural Applications

AISI Type	F_y (ksi)	F_u (ksi)	Percent Elong*	Components (typically maximum percent by weight)									
				C	Cr	Mn	Mo	N	Ni	P	S	Si	Ti
304	31.2	73.2	70	0.08	18–20	2			8–10.5	0.045	0.03	1	
316	29.7	74.7	40	0.08	16–18	2				0.045	0.03	0.75	
409	34.8	65.3	25	0.08	11.13	1				0.045	0.045	1	0.75
410	178	221	45	0.15	12.5	1				0.04	0.03		
2205	74.7	110	35	0.02	22.4	0.7	3.3	0.16	5.8	0.25	0.001	0.4	

* Percent elongation is the percentage of plastic strain at fracture (2″ gauge length)

3.6 Fastening Products

Fastening products include (Carter, 2004)

- Conventional bolts
- Twist-off-type tension control bolt assemblies
- Nuts
- Washers
- Compressible-washer-type direct tension indicators
- Anchor rods
- Threaded rods
- Forged steel structural hardware

Table 3.7 summarizes the applicable ASTM specifications for each type of fastener (Carter, 2004). High-strength bolts have a tensile strength in excess of 100,000 psi. Common bolts have a tensile strength of 60,000 psi. The preferred material for anchor rods, F1554 Grade 36, has a yield stress of 36,000 psi and an ultimate strength in the range of 58,000 to 80,000 psi. A36, with a yield stress of 36,000 psi, is preferred for threaded rods. Nuts, washers, and direct tension indicators are made with materials that do not have a minimum required strength.

Structural connections are made by riveting, bolting, or welding. Rivet connections were used extensively in the past, but modern bolt technology has made riveting obsolete. Bolted connections may be snug tightened, pretensioned, or slip critical (Miller, 2001). Snug-tightened joints are accomplished by either a few impacts of an impact wrench or the full effort of an ironworker using an ordinary spud wrench to bring the members into firm contact. Pretensioned joints require tightening the bolt to a significant tensile stress with a corresponding compressive stress in the attached members. Four methods are used to ensure that the bolt is tightened to a sufficient stress level: turn-of-nut, calibrated wrench, twist-off-type tension-control bolts, and direct tension indicators. Bolts in slip-critical joints are also installed to pretensioned requirements, but these joints have “faying surfaces that have been prepared to provide a calculable resistance against slip.” When the joint is placed under load, the stresses may be transmitted through the joint by the friction between the members. However, if slip occurs, the bolts will be placed in shear, in addition to the tension stresses from the installation—hence the need for high-strength bolts.

3.7 Reinforcing Steel

Since concrete has negligible tensile strength, structural concrete members subjected to tensile and flexural stresses must be reinforced. Either conventional or prestressed reinforcing can be used, depending on the design

TABLE 3.7 Applicable ASTM Specifications for Structural Fasteners

ASTM Designation		F_y Yield Stress (ksi)	F_u Tensile Stress[a] (ksi)	Diameter Range (in)	High-strength Bolts	Common Bolts	Nuts	Washers	Direct Tension Indicators	Threaded Rods	Anchor Rods: Hooked	Anchor Rods: Headed	Anchor Rods: Threaded & Nutted
A325		-	105	>1–1.5	■								
		-	120	0.5–1.5	■								
A490		-	150	0.5–1.5	■								
F1852		-	105	1.125	■								
		-	120	0.5–1	■								
A194 Gr. 2H		-	-	0.25–4		▒							
A563		-	-	0.25–4		■							
F436[b]		-	-	0.25–4			■						
F959		-	-	0.5–1.5				■					
A36		36	58–80	<10					■				
A193 Gr. B7		-	100	>4–7						■	▒		▒
		-	115	>2.5–4						▒	▒		▒
		-	125	≤2.5						▒	▒		▒
A307	Gr. A	-	60	0.25–4			■					▒	
	Gr. C	-	58–80	0.25–4						▒	▒		▒
A354 Gr. BD		-	140	2.5–4						▒	▒	▒	▒
			150	0.25–2.5						▒	▒	▒	▒
A449		-	90	1.5–3	c					▒	▒	▒	▒
			105	1.125–1.5	c					▒	▒	▒	▒
			120	0.25–1	c					▒	▒	▒	▒
A572	Gr. 42	42	60	<6						▒	▒		▒
	Gr. 50	50	65	<4						▒	▒		▒
	Gr. 55	55	70	<2						▒	▒		▒
	Gr. 60	60	75	<1.25						▒	▒		▒
	Gr. 65	65	80	<1.25						▒	▒		▒
A588		42	63	>5–8						▒	▒		▒
		46	67	>4–5						▒	▒		▒
		50	70	<4						▒	▒		▒
A687		105	150 max	0.625–3						▒	▒		▒
F1554	Gr. 36	36	58–80	0.25–4							■	■	■
	Gr. 55	55	75–95	0.25–4							▒	▒	▒
	Gr. 105	105	125–150	0.25–3							▒	▒	▒

■ = Preferred material specification

▒ = Other applicable material specification, the availability of which should be confirmed before specifying

(blank) = Material specification does not apply

- indicates that a value is not specified in the material specification

[a] Minimum values unless range or max. is indicated

[b] Special washer requirements apply for some steel-to-steel bolting, check design documents

[c] LRFD has limitations on use of ASTM A449 bolts

situation. In conventional reinforcing, the stresses fluctuate with loads on the structure. This does not place any special requirements on the steel. On the other hand, in prestressed reinforcement, the steel is under continuous tension. Any stress relaxation will reduce the effectiveness of the reinforcement. Hence, special steels are required.

Reinforcing steel (rebar) is manufactured in three forms: *plain bars, deformed bars,* and *plain and deformed wire fabrics.* Plain bars are round, without surface deformations. Plain bars provide only limited bond with the concrete and, therefore, are not typically used in sections subjected to tension or bending. Deformed bars have protrusions (deformations) at the surface, as shown Figure 3.10; thus, they ensure a good bond between the bar and the concrete. The deformed surface of the bar prevents slipping, allowing the concrete and steel to work as one unit. Wire fabrics are flat sheets in which wires pass each other at right angles, and one set of elements is parallel to the fabric axis. Plain wire fabrics develop the anchorage in concrete at the welded intersections, while deformed wire fabrics develop anchorage through deformations and at the welded intersections.

Deformed bars are used in concrete beams, slabs, columns, walls, footings, pavements, and other concrete structures, as well as in masonry construction. Welded wire fabrics are used in some concrete slabs and pavements, mostly to resist temperature and shrinkage stresses. Welded wire fabrics can be more economical to place, and thus allow for closer spacing of bars than is practical with individual bars.

FIGURE 3.10 Steel rebars used to reinforce PCC columns.

Reinforcing steel is produced in the standard sizes shown in Table 3.8. Bars are made of four types of steel: A615 (billet), A616 (rail), A617 (axle), and A706 (low-alloy), as shown in Table 3.9. Billet steel is the most widely used. A706 steel is often used when the rebar must be welded to structural steel. Reinforcing steel is produced in four grades: 40, 50, 60, and 75, with yield stresses of 276 MPa, 345 MPa, 414 MPa, and 517 MPa (40 ksi, 50 ksi, 60 ksi, and 75 ksi), respectively.

Prestressed concrete requires special wires, strands, cables, and bars. Steel for prestressed concrete reinforcement must have high strength and low relaxation properties. High-carbon steels and high-strength alloy steels are used for this purpose. Properties of prestressed concrete reinforcement are presented in ASTM specification A416 and AASHTO specification M203. These specifications define the requirements for a seven-wire uncoated steel strand. The specifications allow two types of steel: stress-relieved (normal-relaxation) and low-relaxation. Relaxation refers to the percent of stress reduction that occurs when a constant amount of strain is applied over an extended time period. Both stress-relieved and low-relaxation steels can be specified as Grade 250 or Grade 270, with ultimate strengths of 1725 MPa (250 ksi) and 1860 MPa (270 ksi), respectively. The specifications for this application are based on mechanical properties only; the chemistry of wires is not pertinent to this application. After stranding, low-relaxation strands are subjected to a continuous thermal–mechanical treatment to produce the required mechanical properties. Table 3.10 shows the required properties for seven-wire strand.

3.8 Mechanical Testing of Steel

Many tests are available to evaluate the mechanical properties of steel. This section summarizes some laboratory tests commonly used to determine properties required in product specifications. Test specimens can take several shapes, such as bar, tube, wire, flat section, and notched bar, depending on the test purpose and the application.

Certain methods of fabrication, such as bending, forming, and welding, or operations involving heating, may affect the properties of the material being tested. Therefore, the product specifications cover the stage of manufacture at which mechanical testing is performed. The properties shown by testing before the material is fabricated may not necessarily be representative of the product after it has been completely fabricated. In addition, flaws in the specimen or improper machining or preparation of the test specimen will give erroneous results (ASTM A370).

3.8.1 Tension Test

The tension test (ASTM E8) on steel is performed to determine the yield strength, yield point, ultimate (tensile) strength, elongation, and reduction

TABLE 3.8 Standard-Size Reinforcing Bars According to ASTM A615*

		Nominal Dimensions***			Deformation Requirements (mm)****		
Bar Designation Number**	Nominal Mass (kg/m)	Diameter (mm)	Cross-Sectional Area (mm^2)	Perimeter (mm)	Maximum Average Spacing	Minimum Average Height	Maximum Gap*****
10 [3]	0.560	9.5	71	29.9	6.7	0.38	3.6
13 [4]	0.994	12.7	129	39.9	8.9	0.51	4.9
16 [5]	1.552	15.9	199	49.9	11.1	0.71	6.1
19 [6]	2.235	19.1	284	59.8	13.3	0.97	7.3
22 [7]	3.042	22.2	387	69.8	15.5	1.12	8.5
25 [8]	3.973	25.4	510	79.8	17.8	1.27	9.7
29 [9]	5.059	28.7	645	90.0	20.1	1.42	10.9
32 [10]	6.404	32.3	819	101.3	22.6	1.63	12.4
36 [11]	7.907	35.8	1006	112.5	25.1	1.80	13.7
43 [14]	11.38	43.0	1452	135.1	30.1	2.16	16.5
57 [18]	20.24	57.3	2581	180.1	40.1	2.59	21.9

**Bar numbers approximate the number of millimeters of the nominal diameter of the bars. [Bar numbers are based on the number of eighths of an inch of the nominal diameter of the bars.]

***The nominal dimensions of a deformed bar are equivalent to those of a plain round bar having the same weight per meter as the deformed bar.

****Requirements for protrusions on the surface of the bar.

*****Chord 12.5% of Nominal Perimeter

TABLE 3.9 Types and Properties of Reinforcing Bars According to ASTM (Somayaji, 2001) (Reprinted by permission of Pearson Education, Inc.)

ASTM Designation	Type	Grade	Tensile strength min., MPa (ksi)	Yield strength* Min., MPa (ksi)	Size availability (No.)
A615	Billet steel bars (plain and deformed)	40 60 75	483 (70) 620 (90) 689 (100)	276 (40) 414 (60) 517 (75)	3–6 3–18 11–18
A616	Rail steel (plain and deformed)	50 60	552 (80) 620 (90)	345 (50) 474 (60)	3–11 3–11
A617	Axle steel (plain and deformed)	40 60	483 (70) 620 (90)	276 (40) 414 (60)	3–11 3–11
A706	Low-alloy steel deformed bars	60	552 (80)	414–538 (60–78)	3–18

*When the steel does not have a well-defined yield point, yield strength is the stress corresponding to a strain of 0.005 m/m (0.5% extension) for grades 40, 50, and 60, and a strain of 0.0035 m/m (0.35% extension) for grade 75 of A615, A616, and A617 steels. For A706 steel, grade point is determined at a strain of 0.0035 m/m.

TABLE 3.10 Required Properties for Seven-Wire Strand

Property	Stress-relieved		Low-relaxation	
	Grade 250	Grade 270	Grade 250	Grade 270
Breaking strength,* MPa (ksi)	1725 (250)	1860 (270)	1725 (250)	1860 (270)
Yield strength (1% extension)	85% of breaking strength		90% of breaking strength	
Elongation (min. percent)	3.5		3.5	
Relaxation** (max. percent)				
Load = 70% min. breaking strength	—		2.5	
Load = 80% min. breaking strength	—		3.5	

*Breaking strength is the maximum load required to break one or more wires.

**Relaxation is the reduction in stress that occurs when a constant strain is applied over an extended time period. The specification is for a load duration of 1000 hours at a test temperature of 20 ± 2°C (68 ± 3°F).

of area. Typically, the test is performed at temperatures between 10°C and 35°C (50°F to 95°F).

The test specimen can be either full sized or machined into a shape, as prescribed in the product specifications for the material being tested. It is desirable to use a small cross-sectional area at the center portion of the specimen to ensure fracture within the gauge length. Several cross-sectional shapes are permitted, such as round and rectangular, as shown in Figure 3.11. Plate, sheet, round rod, wire, and tube specimens may be used. A 12.5 (1/2 in.) diameter round specimen is used in many cases. The gauge length over which the elongation is measured typically is four times the diameter for most round-rod specimens.

Various types of gripping devices may be used to hold the specimen, depending on its shape. In all cases, the axis of the test specimen should be placed at the center of the testing machine head to ensure axial tensile stresses within the gauge length without bending. An extensometer with a dial gauge (Figure 1.25) or an LVDT (Figure 1.29) is used to measure the deformation of the entire gauge length. The test is performed by applying an axial load to the specimen at a specified rate. Figure 3.12 shows a tensile test being performed on a round steel specimen using an LVDT extensometer to measure the deformation.

As discussed in Chapter 1, mild steel has a unique stress–strain relation (Figure 3.13). Here, a linear elastic response is displayed up to the proportion limit. As the stress is increased beyond the proportion limit, the steel will yield, at which time the strain will increase without an increase in stress (actually the stress will slightly decrease). As tension increases past the yield point, strain increases following a nonlinear relation up to the point of failure.

Note that the decrease in stress after the peak does not mean a decrease in strength. In fact, the actual stress continues to increase until failure. The reason for the apparent decrease is that a neck is formed in the steel specimen, causing an appreciable decrease in the cross-sectional area. The traditional, or engineering, way of calculating the stress and strain uses the original

FIGURE 3.11 Tension test specimens with round and rectangular cross-sections.

FIGURE 3.12 Tension test on a round steel specimen showing grips and an extensometer with an LVDT.

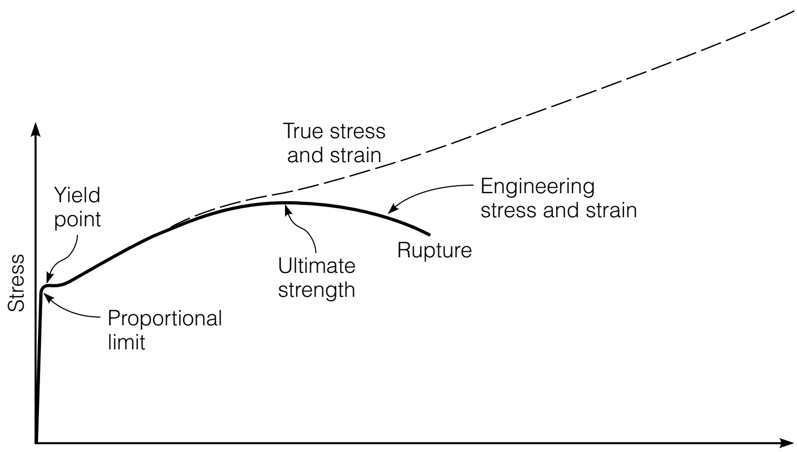

FIGURE 3.13 Typical stress-strain behavior of mild steel.

cross-sectional area and gauge length. If the stress and stains are calculated based on the instantaneous cross-sectional area and gauge length, a *true stress–strain curve* is obtained, which is different than the *engineering stress–strain curve* (Figure 3.13).

As shown in Figure 3.13, the true stress is larger than the engineering stress, because of the reduced cross-sectional area at the neck. Also, the true strain is larger than the engineering strain, since the increase in length at the vicinity of the neck is much larger than the increase in length outside of the neck. The specimen experiences the largest deformation (contraction of the cross-sectional area and increase in length) at the regions closest to the neck, due to the nonuniform distribution of the deformation.

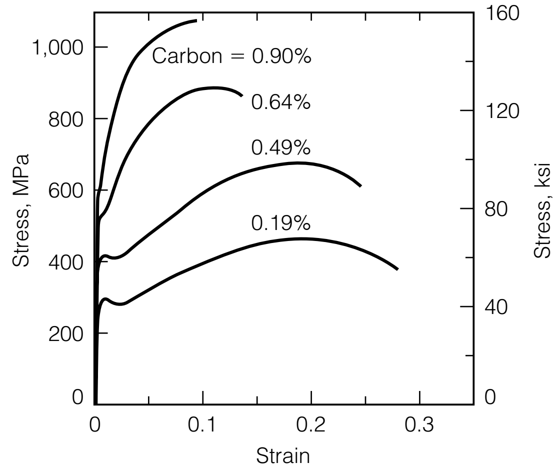

FIGURE 3.14 Tensile stress-strain diagrams of hot-rolled steel bars with different carbon contents.

The large increase in length at the neck increases the true strain to a large extent because the definition of true strain utilizes a ratio of the change in length in an infinitesimal gauge length. By decreasing the gauge length toward an infinitesimal size and increasing the length due to localization in the neck, the numerator of an expression is increased while the denominator stays small, resulting in a significant increase in the ratio of the two numbers. Note that when calculating the true strain, a small gauge length should be used at the neck, since the properties of the material (such as the cross section) at the neck represent the true material properties. For various practical applications, however, the engineering stresses and strains are used, rather than the true stresses and strains.

Different carbon-content steels have different stress–strain relations. Increasing the carbon content in the steel increases the yield stress and reduces the ductility. Figure 3.14 shows the tension stress–strain diagram for hot-rolled steel bars containing carbons from 0.19% to 0.90%. Increasing the carbon content from 0.19% to 0.90% increases the yield stress from 280 MPa to 620 MPa (40 ksi to 90 ksi). Also, this increase in carbon content decreases the fracture strain from about 0.27 m/m to 0.09 m/m. Note that the increase in carbon content does not change the modulus of elasticity.

Sample Problem 3.2

A steel alloy bar 100 mm long with a rectangular cross section of 10 mm × 40 mm is subjected to tension with a load of 89 kN and experiences an increase in length of 0.1 mm. If the increase in length is entirely elastic, calculate the modulus of elasticity of the steel alloy.

Solution

$$\sigma = \frac{89000}{0.01 \times 0.04} = 0.225 \times 10^9 \text{ Pa} = 0.2225 \text{ GPa}$$

$$\varepsilon = \frac{0.1}{100} = 0.001 \text{ mm/mm}$$

$$E = \frac{\sigma}{\varepsilon} = \frac{0.2225}{0.001} = 222.5 \text{ GPa}$$

Sample Problem 3.3

A steel specimen is tested in tension. The specimen is 1 in. wide by 0.5 in. thick in the test region. By monitoring the load dial of the testing machine, it was found that the specimen yielded at a load of 36 kips and fractured at 48 kips.

a. Determine the tensile stresses at yield and at fracture.
b. If the original gauge length was 4 in., estimate the gauge length when the specimen is stressed to 1/2 the yield stress.

Solution

a. Yield stress $(\sigma_y) = 36/(1 \times 0.5) = 72$ ksi

   Fracture stress $(\sigma_f) = 48/(1 \times 0.5) = 96$ ksi

b. Assume $E = 30 \times 10^6$ psi

   $$\varepsilon = \left(\tfrac{1}{2}\right)\sigma_y/E = (1/2) \times 72 \times 10^3/(30 \times 10^6) = 0.0012 \text{ in./in.}$$

   $$\Delta L = L\varepsilon = 4 \times 0.0012 = 0.0048 \text{ in.}$$

   Final gauge length $= 4 + 0.0048 = 4.0048$ in.

Steel is generally assumed to be a homogenous and isotropic material. However, in the production of structural members, the final shape may be obtained by cold rolling. This essentially causes the steel to undergo plastic deformations, with the degree of deformation varying throughout the member. As discussed in Chapter 1, plastic deformation causes an increase in yield strength and a reduction in ductility. Figure 3.15 demonstrates that the measured properties vary, depending on the orientation of the sample relative to the axis of rolling (Hassett, 2003). Thus, it is necessary to specify how the sample is collected when evaluating the mechanical properties of steel.

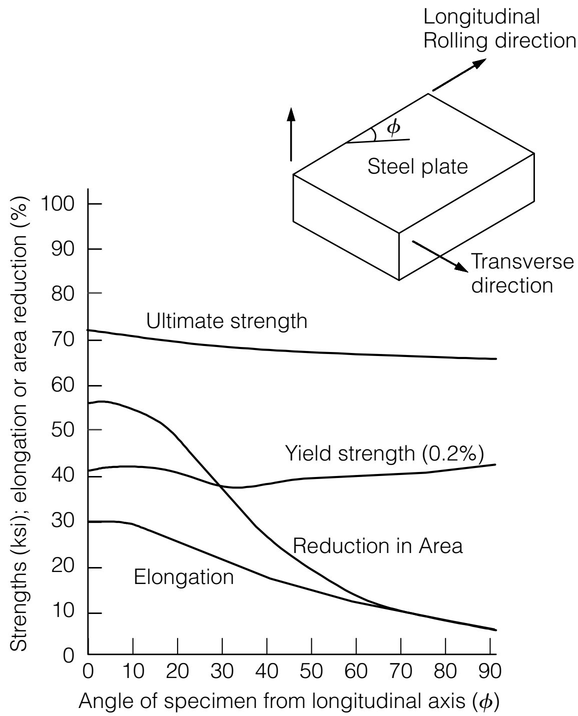

FIGURE 3.15 Example of effect of specimen orientation on measured tensile properties of steel.

3.8.2 Torsion Test

The torsion test (ASTM E143) is used to determine the shear modulus of structural materials. The shear modulus is used in the design of members subjected to torsion, such as rotating shafts and helical compression springs. In this test a cylindrical, or tubular, specimen is loaded either incrementally or continually by applying an external torque to cause a uniform twist within the gauge length (Figure 3.16). The amount of applied torque and the corresponding angle of twist are measured throughout the test. Figure 3.17 shows the shear stress–strain curve. The shear modulus is the ratio of maximum shear stress to the corresponding shear strain below the proportional limit of the material, which is the slope of the straight line between R (a pre-torque stress) and P (the proportional limit). For a circular cross section, the maximum shear stress (τ_{max}), shear strain (γ), and the shear modulus (G) are determined by the equations

$$\tau_{max} = \frac{Tr}{J} \tag{3.1}$$

$$\gamma = \frac{\theta r}{L} \tag{3.2}$$

$$G = \frac{\tau_{max}}{\gamma} = \frac{TL}{J\theta} \tag{3.3}$$

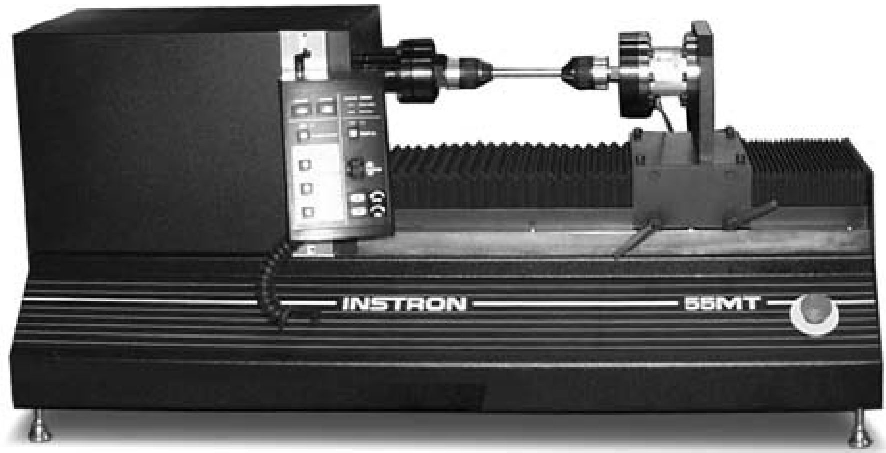

FIGURE 3.16 Torsion test apparatus.

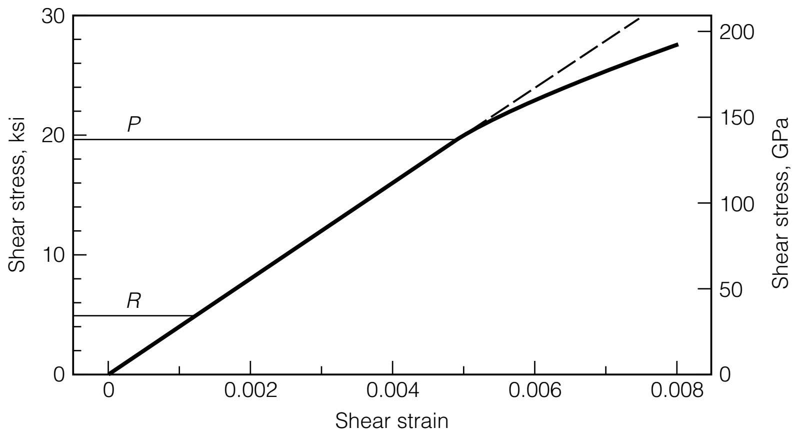

FIGURE 3.17 Typical shear stress-strain diagram of steel (ASTM E143). Copyright ASTM. Reprinted with permission.

where

T = torque
r = radius
J = polar moment of inertia of the specimen about its center, $\pi r^4/2$ for a solid circular cross section.
θ = angle of twist in radians
L = gauge length

The test method is limited to materials and stresses at which creep is negligible compared with the strain produced immediately upon loading. The test specimen should be sound, without imperfections near the surface. Also, the specimen should be straight and of uniform diameter for a length equal to the gauge length plus two to four diameters. The gauge length should be at least four diameters. During the test, torque is read from a dial gauge or a readout device attached to the testing machine, while the angle of twist may be measured using a torsiometer fastened to the specimen at the two ends of the gauge length. A curve-fitting procedure can be used to estimate the straight-line portion of the shear stress–strain relation of Figure 3.17 (ASTM E143).

Sample Problem 3.4

A rod with a length of 1 m and a radius of 20 mm is made of high-strength steel. The rod is subjected to a torque *T*, which produces a shear stress below the proportional limit. If the cross section at one end is rotated 45 degrees in relation to the other end, and the shear modulus *G* of the material is 90 GPa, what is the amount of applied torque?

Solution

$$J = \pi r^4/2 = \pi(0.02)^4/2 = 0.2513 \times 10^{-6}\ \text{m}^4$$

$$\theta = 45(\pi/180) = \pi/4$$

$$T = GJ\theta/L = (90 \times 10^9) \times (0.2513 \times 10^{-6}) \times (\pi/4)/1$$

$$= 17.8 \times 10^3\ \text{N.m} = 17.8\ \text{kN.m}$$

3.8.3 Charpy V Notch Impact Test

The Charpy V Notch impact test (ASTM E23) is used to measure the toughness of the material or the energy required to fracture a V-notched simply supported specimen. The test is used for structural steels in tension members.

The standard specimen is 55 × 10 × 10 mm (2.165 × 0.394 × 0.394 in.) with a V notch at the center, as shown in Figure 3.18. Before testing, the specimen is brought to the specified temperature for a minimum of 5 min in a liquid bath or 30 min in a gas medium. The specimen is inserted into the Charpy V notch impact-testing machine (Figure 3.19) using centering tongs. The swinging arm of the machine has a striking tip that impacts the specimen on the side opposite the V notch. The striking head is released from the pretest position, striking and fracturing the specimen. By fracturing the test specimen, some of the kinetic energy of the striking head is absorbed, thereby reducing the ultimate height the strike head attains. By measuring the height the strike head attains after striking the specimen,

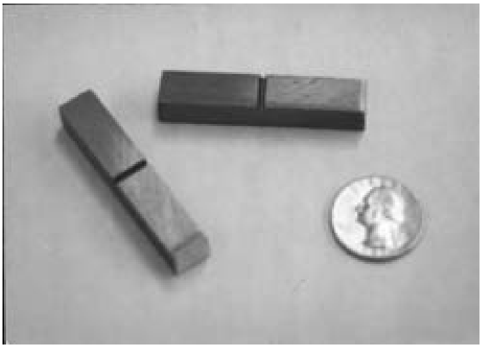

FIGURE 3.18 Charpy V notch specimens.

FIGURE 3.19 Charpy V notch impact testing machine.

the energy required to fracture the specimen is computed. This energy is measured in m·N (ft·lb) as indicated on a gauge attached to the machine.

The lateral expansion of the specimen is typically measured after the test using a dial gauge device. The lateral expansion is a measure of the plastic deformation during the test. The higher the toughness of the steel, the larger the lateral expansion.

Figure 1.13, in Chapter 1, shows the typical energy (toughness) required to fracture structural steel specimens at different temperatures. The figure

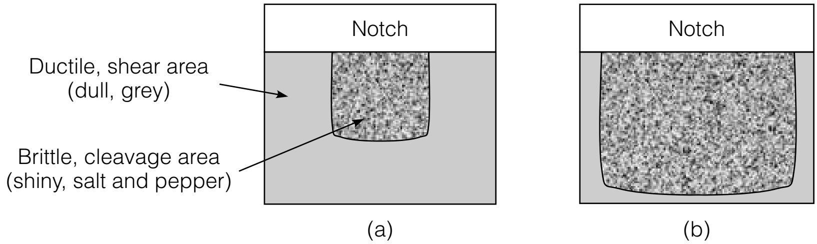

FIGURE 3.20 Fracture surface of Charpy V notch specimen: (a) at high temperature and (b) at low temperature.

shows that the required energy is high at high temperatures and low at low temperatures. This indicates that the material changes from ductile to brittle as the temperature decreases.

The fracture surface typically consists of a dull shear area (ductile) at the edges and a shiny cleavage area (brittle) at the center, as depicted in Figure 3.20. As the toughness of the steel decreases, due to lowering the temperature, for example, the shear area decreases while the cleavage area increases.

Sample Problem 3.5

A Charpy V Notch (CVN) test was performed on a steel specimen and produced the following readings:

Temperature (°F)	Toughness (ft.lb)
−40	5
30	7
100	28
170	66
240	79
310	80

Plot the toughness-versus-temperature relation, and determine the temperature transition zone between ductile and brittle behavior.

Solution

The toughness-versus-temperature relation is as shown in Figure SP3.5. From the figure, the temperature transition zone between ductile and brittle behavior can be seen to be 30 to 240°F.

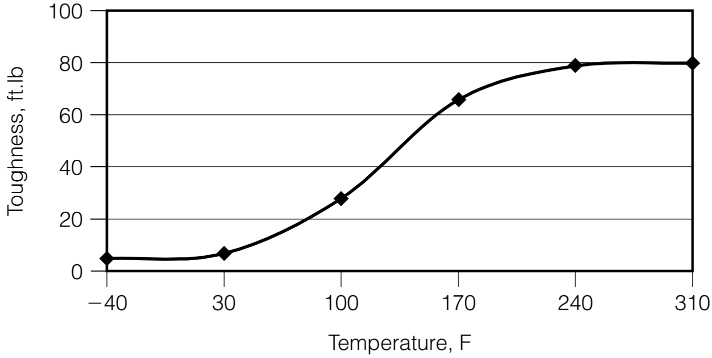

FIGURE SP3.5

3.8.4 Bend Test

In many engineering applications, steel is bent to a desired shape, especially in the case of reinforcing steel. The ductility to accommodate bending is checked by performing the semiguided bend test (ASTM E290). The test evaluates the ability of steel, or a weld, to resist cracking during bending. The test is conducted by bending the specimen through a specified angle and to a specified inside radius of curvature. When complete fracture does not occur, the criterion for failure is the number and size of cracks found on the tension surface of the specimen after bending.

The bend test is made by applying a transverse force to the specimen in the portion that is being bent, usually at midlength. Three arrangements can be used, as illustrated in Figure 3.21. In the first arrangement, the specimen is fixed at one end and bent around a reaction pin or mandrel by applying a force near the free end, as shown in Figure 3.21(a). In the second arrangement, the specimen is held at one end and a rotating device is used to bend the specimen around the pin or mandrel, as shown in Figure 3.21(b). In the third arrangement, a force is applied in the middle of a specimen simply supported at both ends, Figure 3.21(c).

3.8.5 Hardness Test

Hardness is a measure of a material's resistance to localized plastic deformation, such as a small dent or scratch on the surface of the material. A certain hardness is required for many machine parts and tools. Several tests are available to evaluate the hardness of materials. In these tests an indenter (penetrator) is forced into the surface of the material with a specified load

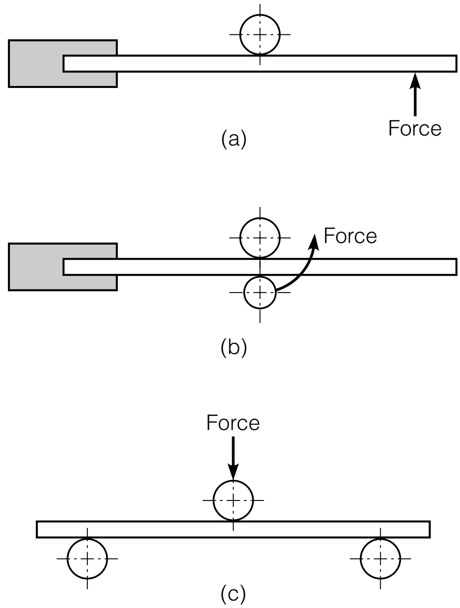

FIGURE 3.21 Schematic fixtures for semi-guided bend test (ASTM E290). Copyright ASTM. Reprinted with permission.

magnitude and rate of application. The depth, or the size, of the indentation is measured and related to a hardness index number. Hard materials result in small impressions, corresponding to high hardness numbers. Hardness measurements depend on test conditions and are, therefore, relative. Correlations and tables are available to convert the hardness measurements from one test to another and to approximate the tensile strength of the material (ASTM A370).

One of the methods commonly used to measure hardness of steel and other metals is the *Rockwell hardness test* (ASTM E18). In this test the depth of penetration of a diamond cone, or a steel ball, into the specimen is determined under fixed conditions (Figure 3.22). A preliminary load of 10 kg is applied first, followed by an additional load. The Rockwell number, which is proportional to the difference in penetration between the preliminary and total loads, is read from the machine by means of a dial, digital display, pointer, or other device. Two scales are frequently used, namely, B and C. Scale B uses a 1.588 mm (1/16 in.) steel ball indenter and a total load of 100 kg, while scale C uses a diamond spheroconical indenter with a 120° angle and a total load of 150 kg.

To test very thin steel or thin surface layers, the *Rockwell superficial hardness test* is used. The procedure is the same as the Rockwell hardness test except that smaller preliminary and total loads are used. The Rockwell hardness number is reported as a number, followed by the symbol HR, and another symbol representing the indenter and forces used. For example, 68 HRC indicates a Rockwell hardness number of 68 on Rockwell C scale.

FIGURE 3.22 Rockwell hardness test machine.

Hardness tests are simple, inexpensive, nondestructive, and do not require special specimens. In addition, other mechanical properties, such as the tensile strength, can be estimated from the hardness numbers. Therefore, hardness tests are very common and are typically performed more frequently than other mechanical tests.

3.8.6 Ultrasonic Testing

Ultrasonic testing is a nondestructive method for detecting flaws in materials. It is particularly useful for the evaluation of welds. During the test, a sound wave is directed toward the weld joint and reflected back from a discontinuity, as shown on Figure 3.23. A sensor captures the energy of the reflected wave and the results are displayed on an oscilloscope. This method is highly sensitive in detecting planar defects, such as incomplete weld fusion, delamination, or cracks (Hassett, 2003).

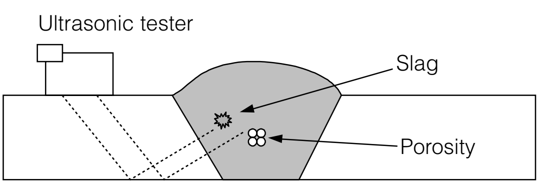

FIGURE 3.23 Ultrasonic test of welds.

3.9 Welding

Many civil engineering structures, such as steel bridges, frames, and trusses require welding during construction and repair. Welding is a technique for joining two metal pieces by applying heat to fuse the pieces together. A filler metal may be used to facilitate the process. The chemical properties of the welding material must be carefully selected to be compatible with the materials being welded. A variety of welding methods are available, but the common types are arc welding and gas welding. Other types of welding include flux-cored arc welding, self-shielded flux arc welding, and electroslag welding (Frank and Smith 1990).

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. The resulting deposited weld metal is a cast structure with a composition dependent upon the base metal, electrode, and flux chemistry. *Shielded metal arc welding (stick welding)* is the most common form of arc welding. It is limited to short welds in bridge construction. A consumable electrode, which is covered with flux, is used. The flux produces a shielding atmosphere at the arc to prevent oxidation of the molten metal. The flux is also used to trap impurities in the molten weld pool. The solidified flux forms a slag that covers the solidified weld, as shown in Figure 3.24. *Submerged arc welding* is a semiautomatic or automatic arc welding process. In this process, a bare wire electrode is automatically fed by the welding machine while a granular flux is fed into the joint ahead of the electrode. The arc takes place in the molten flux, which completely shields the weld pool from the atmosphere. The molten flux concentrates the arc heat, resulting in deep penetration into the base metal.

Gas welding (mig welding) is another type of welding in which no flux is used. An external shielding gas is used, which shields the molten weld

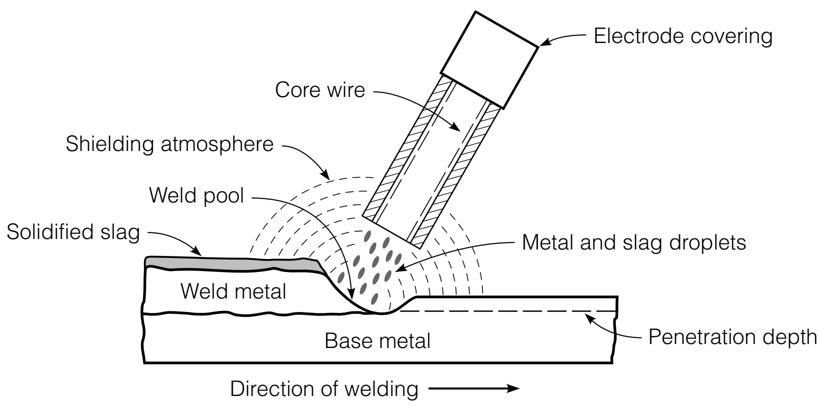

FIGURE 3.24 Schematic drawing of arc welding.

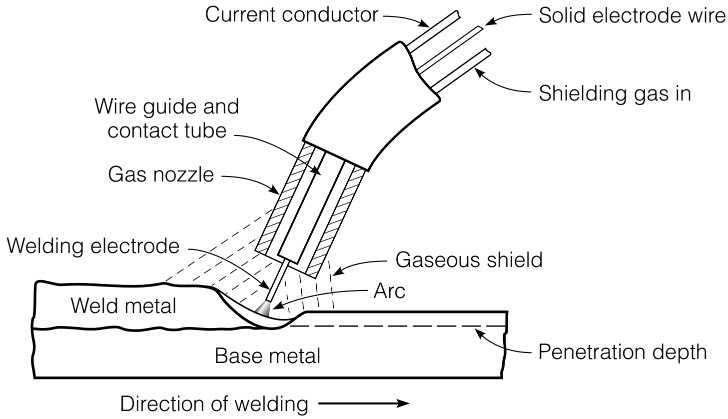

FIGURE 3.25 Schematic drawing of gas welding.

pool and provides the desired arc characteristics (Figure 3.25). This welding process is normally used for small welds due to the lack of slag formation.

Care must be taken during welding to consider the distortion that is the result of the nonuniform heating of the welding process. When the molten weld metal cools, it shrinks, causing deformation of the material and introducing residual stresses into the structure. Frequently, these residual stresses cause cracks outside the weld area. The distortion produced by welding can be controlled by proper sequencing of the welds and predeforming the components prior to welding. Finally, care must be taken by the welder and the inspector to protect their eyes and skin from the intensive ultraviolet radiation produced during welding (Frank and Smith 1990).

The relative ease with which steel can be welded is related to the hardness of the steel. In general, harder steels are more difficult to weld. Winterton developed the concept of using a carbon equivalent formula for estimating the carbon equivalent of steels and an associated zone chart for determining the need to preheat steel to control the development of hydrogen in the welded steel. There are several different carbon equivalent formulas. The one used for structural steels is

$$CE = C + \frac{(Mn + Si)}{6} + \frac{(Cr + Mo + V)}{5} + \frac{(Ni + Cu)}{15} \qquad (3.4)$$

Figure 3.26 shows the zones associated with the different combinations of carbon and carbon equivalent. The zones are used as a guide to determining the method used to determine preheat requirements (Hassett, 2003):

- Zone I—Cracking is unlikely, but may occur with high hydrogen or high restraint. Use hydrogen control method to determine preheat.
- Zone II—The hardness control method and selected hardness shall be used to determine minimum energy input for single-pass fillet welds without preheat.
- Zone III—The hydrogen control method shall be used.

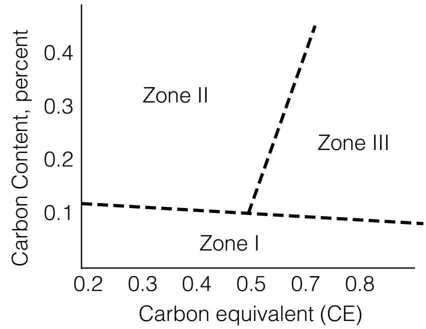

FIGURE 3.26 Welding zone classification of steel.

The hardness and hydrogen control methods are means of determining the level of energy used to preheat the weld area before the weld is performed. Preheating of the metal and the use of low hydrogen electrodes are the best means of avoiding hydrogen embrittlement. This occurs when steel is melted during welding, which may allow hydrogen to dissolve in the molten metal and diffuse into the base metal adjacent to the weld.

Whenever metal is welded, the base material adjacent to the weld is heated to a temperature that may be sufficient to affect its metallurgy. The material affected in this manner is termed the heat-affected zone, HAZ (Figure 3.27). The material in the HAZ is a high-risk area for failure, especially if proper preheating and cooling procedures are not followed.

3.10 Steel Corrosion

Corrosion is defined as the destruction of a material by electrochemical reaction to the environment. For simplicity, corrosion of steel can be defined as the destruction that can be detected by rust formation. Corrosion of steel

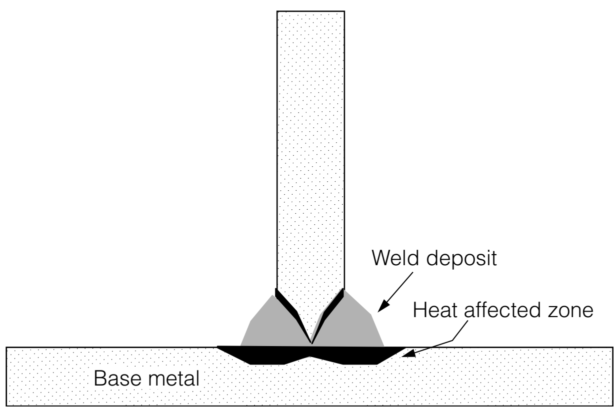

FIGURE 3.27 Heat affected zone poduced during welding.

structures can cause serious problems and embarrassing and/or dangerous failures. For example, corrosion of steel bridges, if left unchecked, may result in lowering weight limits, costly steel replacement, or collapse of the structure. Other examples include corrosion of steel pipes, trusses, frames, and other structures. It is estimated that the cost of corrosion in the United States alone is $8 billion each year (Frank and Smith 1990).

Corrosion is an electrochemical process; that is, it is a chemical reaction in which there is transfer of electrons from one chemical species to another. In the case of steel, the transfer is between iron and oxygen, a process called *oxidation reduction*. Corrosion requires the following four elements (without any of them corrosion will not occur):

1. an *anode*—the electrode where corrosion occurs
2. a *cathode*—the other electrode needed to form a corrosion cell
3. a *conductor*—a metallic pathway for electrons to flow
4. an *electrolyte*—a liquid that can support the flow of electrons

Steel, being a heterogeneous material, contains anodes and cathodes. Steel is also an electrical conductor. Therefore, steel contains three of the four elements needed for corrosion, while moisture is usually the fourth element (electrolyte).

The actual electrochemical reactions that occur when steel corrodes are very complex. However, the basic reactions for atmospherically exposed steel in a chemically neutral environment are dissolution of the metal at the anode and reduction of oxygen at the cathode.

Contaminants deposited on the steel surface affect the corrosion reactions and the rate of corrosion. Salt, from deicing or a marine environment, is a common contaminant that accelerates corrosion of steel bridges and reinforcing steel in concrete.

The environment plays an important role in determining corrosion rates. Since an electrolyte is needed in the corrosion reaction, the amount of time the steel stays wet will affect the rate of corrosion. Also, contaminants in the air, such as oxides or sulfur, accelerate corrosion. Thus, areas with acid rain, coal-burning power plants, and other chemical plants may accelerate corrosion.

3.10.1 Methods for Corrosion Resistance

Since steel contains three of the four elements needed for corrosion, protective coatings can be used to isolate the steel from moisture, the fourth element. There are three mechanisms by which coatings provide corrosion protection (Hare 1987):

1. *Barrier coatings* work solely by isolating the steel from the moisture. These coatings have low water and oxygen permeability.
2. *Inhabitive primer coatings* contain passivating pigments. They are low-solubility pigments that migrate to the steel surface when moisture passes through the film to passivate the steel surface.

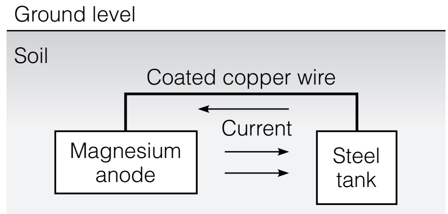

FIGURE 3.28 Cathodic protection of an underground pipeline using a magnesium sacrificial anode.

3. *Sacrificial primers (cathodic protection)* contain pigments such as elemental zinc. Since zinc is higher than iron in the galvanic series, when corrosion conditions exist the zinc gives up electrons to the steel, becomes the anode, and corrodes to protect the steel. There should be close contact between the steel and the sacrificial primer in order to have an effective corrosion protection.

Cathodic protection can take forms other than coating. For example, steel structures such as water heaters, underground tanks and pipes, and marine equipment, can be electrically connected to another metal that is more reactive in the particular environment, such as magnesium or zinc. Such reactive metal (sacrificial anode) experiences oxidation and gives up electrons to the steel, protecting the steel from corrosion. Figure 3.28 illustrates an underground steel tank that is electrically connected to a magnesium sacrificial anode (Fontana and Green 1978).

SUMMARY

The history of civil engineering is closely tied to that of steel, and this will continue into the foreseeable future. With the development of modern production facilities, the availability of a wide variety of economical steel products is virtually assured. High strength, ductility, the ability to carry tensile as well as compressive loads, and the ability to join members either with welding or mechanical fastening are the primary positive attributes of steel as a structural material. The properties of steel can be tailored to meet the needs of specific applications through alloying and heat treatments. The primary shortcoming of steel is its tendency to corrode. When using steel in structures, the engineer should consider the means for protecting the steel from corrosion over the life of the structure.

QUESTIONS AND PROBLEMS

3.1 What is the chemical composition of steel? What is the effect of carbon on the mechanical properties of steel?

3.2 Why does the iron–carbon phase diagram go only to 6.7% carbon?

3.3 Draw a simple iron–carbon phase diagram showing the liquid, liquid–solid, and solid phases.

3.4 What is the typical maximum percent of carbon in steel used for structures?

3.5 Calculate the amounts and compositions of phases and constituents of steel composed of iron and 0.10% carbon just above and below the eutectoid isotherm.

3.6 Briefly discuss four heat treatment methods to enhance the properties of steel. What are the advantages of each treatment?

3.7 Define alloy steels. Explain why alloys are added to steel.

3.8 Name three alloying agents and their principal effects.

3.9 Specifically state the shape and size of the structural steel section: W 36 × 182.

3.10 What are the typical uses of structural steel?

3.11 Why is reinforcing steel used in concrete? Discuss the typical properties of reinforcing steel.

3.12 What is high performance steel? State two HPS products that are currently being used in structural applications and show their properties.

3.13 Name three mechanical tests used to measure properties of steel.

3.14 The following laboratory tests are performed on steel specimens:

a. Tension test

b. Charpy V notch test

c. Bend test

What are the significance and use of these tests?

3.15 Sketch the stress–strain behavior of steel, and identify different levels of strength. What is the effect of increasing the carbon content in steel? What is a typical value for yield strength of mild steel?

3.16 Draw a typical stress–strain relationship for steel subjected to tension. On the graph, show the modulus of elasticity, the yield strength, the ultimate stress, and the rupture stress.

3.17 A steel specimen is tested in tension. The specimen is 1.5 in. wide by 0.5 in. thick in the test region. By monitoring the load dial of the testing machine, it was found that the specimen yielded at a load of 37.5 kips and fractured at 52.5 kips.

a. Determine the tensile stresses at yield and at fracture.
b. Estimate how much increase in length would occur at 60% of the yield stress in a 2-in. gauge length.

3.18 A round steel alloy bar with a diameter of 0.5 in. and a gauge length of 3.2 in. was subjected to tension, with the results shown in the accompanying table. Using a computer spreadsheet program, plot the stress–strain relationship. From the graph, determine the Young's modulus of the steel alloy and the deformation corresponding to a 8225-lb load.

Load, lb	Deformation, 10^{-4} in.
2,000	11.28
4,000	22.54
6,000	33.80
8,000	45.08
10,000	56.36
12,000	67.66

3.19 Testing a round steel alloy bar with a diameter of 15 mm and a gauge length of 250 mm produced the stress–strain relation shown in Figure P3.19.

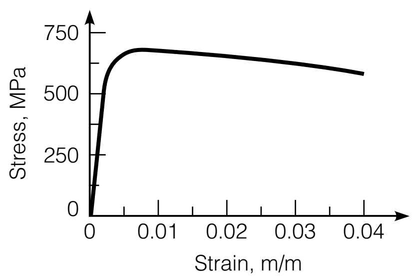

FIGURE P3.19

Determine

a. the elastic modulus
b. the proportional limit
c. the yield strength at a strain offset of 0.002
d. the tensile strength
e. the magnitude of the load required to produce an increase in length of 0.38 mm
f. the final deformation, if the specimen is unloaded after being strained by the amount specified in (e)

In designing a typical structure made of this material, would you expect the stress applied in (e) reasonable? Why?

3.20 During the tension test on a steel rod within the elastic region the following data were measured:

Applied load = 102 kN
Original diameter = 25 mm
Current diameter = 24.99325 mm
Original gauge length = 100 mm
Current gauge length = 100.1 mm

Calculate the Young's modulus and Poisson's ratio.

3.21 A grade 36 round steel bar with a diameter of 0.5 inches and a gauge length of 2 inches was subjected to tension to rupture following ASTM E-8 test procedure. The load and deformation data were as shown in the following table:

Load (kips)	Displacement (in.)	Load (kips)	Displacement (in.)
0	0	8.56	0.08301
2.75	0.00096	8.79	0.09557
4.07	0.00141	8.98	0.10878
7.12	0.00242	9.15	0.12207
7.14	0.01691	9.25	0.13372
7.34	0.04196	9.35	0.14741
7.53	0.04599	9.44	0.18199
7.91	0.05847	7.87	0.29814
8.28	0.07117		

Using a spreadsheet program obtain the following:

a. A plot of the stress–strain relationship. Label the axes and show units.
b. A plot of the linear portion of the stress–strain relationship. Determine modulus of elasticity using the best fit approach.
c. Proportional limit.
d. Yield stress.
e. Ultimate strength.
f. When the applied load was 4.07 kips, the diameter was measured as 0.499905 inches. Determine Poisson's ratio.
g. After the rod was broken, the two parts were put together and the diameter at the neck was measured as 0.416012 in. What is the true stress value at fracture? Is the true stress at fracture larger or smaller than the engineering stress at fracture? Why?
h. Do you expect the true strain at fracture to be larger or smaller than the engineering strain at fracture? Why?

3.22 A high-yield-strength alloy steel bar with a rectangular cross section that has a width of 37.5 mm, a thickness of 6.25 mm, and a gauge length of 203 mm was tested in tension to rupture, according to ASTM E-8 method. The load and deformation data were as shown in Table P3.22.

Table P3.22

Load (kN)	Displacement (mm)	Load (kN)	Displacement (mm)
0	0	159.4	8.560
18.5	0.102	161.2	9.856
84.3	0.379	162.8	11.217
147.4	0.623	164.2	12.588
147.6	1.744	165.0	13.789
149.2	4.327	165.8	15.201
150.8	4.742	166.6	18.767
153.9	6.030	153.6	30.746
157.0	7.339		

Using a spreadsheet program, obtain the following:

a. A plot of the stress–strain relationship. Label the axes and show units.
b. A plot of the linear portion of the stress–strain relationship. Determine modulus of elasticity using the best-fit approach.
c. Proportional limit.
d. Yield stress.
e. Ultimate strength.
f. If the specimen is loaded to 155 kN only and then unloaded, what is the permanent deformation?
g. In designing a typical structure made of this material, would you expect the stress applied in (f) safe? Why?

3.23 An ASTM A615 grade 60 number 10 rebar with a gauge length of 8 inches was subjected to tension to fracture according to ASTM E-8 method. The load and deformation data were as shown Table P3.23.

Table P3.23

Load (kips)	Displacement (in.)	Load (kips)	Displacement (in.)
0	0	106.27	0.3320
13.97	0.0036	109.46	0.3823
42.46	0.0094	111.55	0.4351
74.11	0.0163	113.64	0.4883
86.15	0.0676	115.23	0.5392
95.72	0.1592	117.44	0.6032
100.51	0.2339	119.65	0.7279
103.94	0.2847	118.18	0.8832

Using a spreadsheet program obtain the following:

a. A plot of the stress–strain relationship. Label the axes and show units.
b. A plot of the linear portion of the stress–strain relationship. Determine modulus of elasticity using the best-fit approach.
c. Proportional limit.
d. Yield stress.
e. Ultimate strength.
f. If the rebar is loaded to 88,000 lb only and then unloaded, what is the permanent change in length?

3.24 A steel pipe having a length of 1 m, an outside diameter of 0.2 m, and a wall thickness of 10 mm, is subjected to an axial compression of 200 kN. Assuming a modulus of elasticity of 200 GPa and a Poisson's ratio of 0.3, find

a. the shortening of the pipe,
b. the increase in the outside diameter, and
c. the increase in the wall thickness.

3.25 A drill rod with a diameter of 12 mm is made of high-strength steel alloy with a shear modulus of 80 GPa. The rod is to be subjected to a torque *T*. What is the minimum required length *L* of the rod so that the cross section at one end can be rotated 90° with respect to the other end without exceeding an allowable shear stress of 300 MPa?

3.26 What is the shear modulus of the material whose shear stress–strain relation is shown in Figure 3.17? Solve the problem using

a. SI units
b. U.S. customary units

3.27 An engineering technician performed a tension test on an A36 mild steel specimen to fracture. The original diameter of the specimen is 0.5 in. and the gauge length is 2.0 in. The information obtained from this experiment consists of applied tensile load (*P*) and increase in length (ΔL). The results are tabulated in Table P3.27. Using a spreadsheet program, complete the table by calculating the engineering stress (σ) and the engineering strain (ε). Determine the toughness of the material (u_t) by calculating the area under the stress–strain curve, namely,

$$u_t = \int_0^{\varepsilon_f} \sigma \, d\varepsilon$$

where ε_f is the strain at fracture. The preceding integral can be approximated numerically using a trapezoidal integration technique:

$$u_t = \sum_{i=1}^{n} u_i = \sum_{i=1}^{n} \frac{1}{2}(\sigma_i + \sigma_{i-1})(\varepsilon_i - \varepsilon_{i-1})$$

3.28 A Charpy V Notch (CVN) test was performed on a steel specimen and produced the readings shown in Table P3.28. Plot the toughness-versus-temperature relation and determine the temperature transition zone between ductile and brittle behavior.

Table P3.27

Observation No.	*P* (lb)	ΔL (in.)	σ (psi)	ε (in./in.)	u_i (psi)
0	0	0.0000			N/A
1	1000	0.0005			
2	2730	0.0010			
3	4180	0.0015			
4	6360	0.0020			
5	8220	0.0025			
6	9310	0.0030			
7	9310	0.0035			
8	9310	0.0040			
9	9320	0.0045			
10	9330	0.0050			
11	9420	0.0100			
12	9450	0.0150			
13	9460	0.0200			
14	9510	0.0250			
15	9690	0.0300			
16	9560	0.0350			
17	9540	0.0400			
18	9650	0.0450			
19	10,060	0.0500			
20	11,870	0.1000			
21	12,830	0.1500			
22	13,360	0.2000			
23	13,670	0.2500			
24	13,850	0.3000			
25	13,920	0.3500			
26	13,960	0.4000			
27	13,800	0.5000			
28	13,600	0.5500			
29	13,150	0.6000			
30	12,510	0.6500			
31	11,690	0.7000			
					$u_t =$

Table P3.28

Temperature, C	Toughness, Joule (N.m)
−40	7
0	15
50	54
100	109
150	120
200	122

3.29 A Charpy V Notch test was conducted for an ASTM A572 Grade 50 bridge steel. The average values of the test results at four different test temperatures were found to be

10 ft.lb at −50°F
15 ft.lb at 0°F
40 ft.lb at 40°F
60 ft.lb at 100°F

The bridge will be located in a region where specifications require a minimum of 25 ft.lb fracture toughness at 30°F for welded fracture-critical members. If the bridge contains a welded flange in a fracture-critical member, does the steel have adequate Charpy V notch fracture toughness? Show your supporting calculations.

3.30 How can the flaws in steel and welds be detected? Discuss the concept of a nondestructive test used for this purpose.

3.31 Determine the welding zone classification of A36 and A922 steel.

3.32 Briefly define steel corrosion. What are the four elements necessary for corrosion to occur?

3.33 Discuss the main methods used to protect steel from corrosion.

3.11 References

Bouchard, S., and G. Axmann. ASTM A913 Grades 50 and 65: Steels for Seismic Applications. *STESSA Conference Proceedings,* 2000.

Budinski, K. G. *Engineering Materials, Properties and Selection.* 5th ed. Upper Saddle River, NJ: Prentice Hall, 1996.

Callister, W. D., Jr. *Materials Science and Engineering—an Introduction.* 6th ed. New York: John Wiley and Sons, 2003.

Carter, C. J., Are You Properly Specifying Materials? *Modern Steel Construction*, January edition, 2004.

Cordon, W. A. *Properties, Evaluation, and Control of Engineering Materials.* New York: McGraw-Hill, 1979.

Federal Highway Administration. A High Performance Steel Scorecard, Focus, http://www.tfhrc.gov/focus/apr02/steel.htm, 2002.

Fontana, M. G. and N. D. Greene. *Corrosion Engineering.* 2d ed. New York: McGraw-Hill, 1978.

Frank, K. H. and L. M. Smith. *Highway Materials Engineering: Steel, Welding and Coatings*. Publication No. FHWA-HI-90-006. Washington, DC: Federal Highway Administration, 1990.

Hare, C. H. *Protective Coatings for Bridge Steel*. National Cooperative Highway Research Program, Synthesis of Highway Practice No. 136. Washington, DC: Transportation Research Board, 1987.

Hassett, P.M. *Steel Construction in the New Millennium*. Hassett Engineering, Inc., Castro Valley, CA, 2003.

ISG Plate. *High Performance Steel for Bridges*. Coatsville, PA, 2003.

Key-to-Steel. Designation of Carbon and Low-Alloy Steels, http://www.key-to-steel.com, 2005.

Lane, S., E. Mulley, B. Wright, M. Simon, and J.D. Cooper. Focus on high-performance, *Better Roads*, May, 1998.

Miller, D. Mixing Welds and Bolts, Part 1. *Welding Innovations*. Vol. XVIII, No. 2, 2001.

Somayaji, S. *Civil Engineering Materials.* Upper Saddle River, NJ: Prentice Hall, 2001.

Specialty Steel Industry of North America. *Stainless Steel for Structural Applications, Designer Handbook*. Washington, DC, 1999.