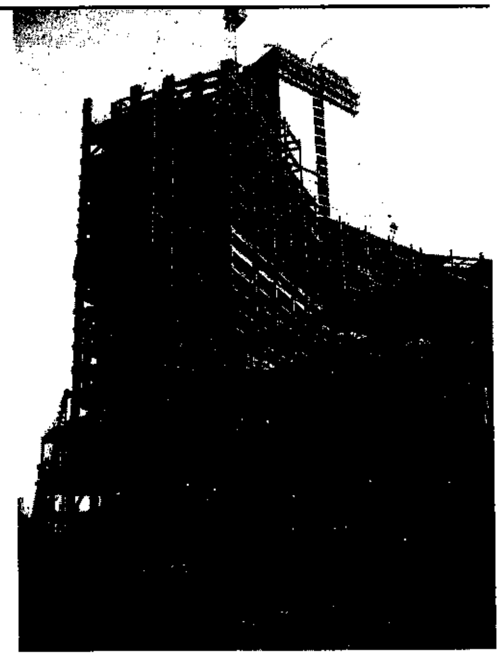
Chapter 3



The Palazzo, Las Vegas.
Photo courtesy Walter P Moore.

Steel Building Materials

3.1 INTRODUCTION

Steel has been produced in the United States since the 1800s. Its first use in a bridge was a railroad bridge across the Mississippi River in St. Louis, built in 1874 by James B. Eads. The bridge, known as the Eads Bridge, is still an inspiring steel structure crossing the river in the shadow of the St. Louis Gateway Arch. The first skyscraper is generally considered to be the Home Insurance Building, designed by William LeBaron Jenney and erected at 135 South La Salle Street, Chicago. The building was started on May 1, 1884 and completed in the fall of 1885. It was originally a 10-story building but later had 2 additional stories added. The original structural design called for wrought iron beams bolted through angle-iron brackets to cast iron columns. As the framework reached the 6th floor, the Carnegie-Phipps Steel Company of Pittsburgh, Pennsylvania indicated that they were now rolling "Bessemer Steel" and requested permission to substitute steel members for the wrought iron beams on all remaining floors. Thus, this was the first use of steel beams in a building. The Home Insurance Building was demolished in 1929.

The first all-steel skyscraper was the Rand-McNally Building at 165 West Adams Street in Chicago designed by Daniel Burnham and John Root. This 10-story building was built from 1888–1890 and was constructed of built-up members made from standard rolled steel bridge shapes that were riveted together. It began a continuous evolution in steel building structures that continues today as new ideas are brought into play by architects and engineers who continue to build with steel.

This evolution in steel buildings has occurred in the materials used, the applications of innovative designers, and the specifications that direct their designs.

3.2 APPLICABILITY OF THE AISC SPECIFICATION

The specification that guides the design of our modern steel buildings was first published by AISC in 1923. At that time its purpose was to promote uniform practice in the design of steel buildings. Up to then, numerous approaches were being used across the industry. Steel producers each had their own standard for design whereas the larger cities also required that their own standards be used. This multiplicity of standards was no standard at all. It lead to a confusion of approaches whereby designers were continually called upon to change how they designed, depending on where their current building project was to be located.

The 1923 specification defined "the practice adopted by the American Institute of Steel Construction for the design, fabrication, and erection of structural steel buildings." It went on to provide direction on how to obtain a satisfactory structure. The following requirements were to be fulfilled:

1. The material used must be suitable, of uniform quality, and without defects affecting the strength or service of the structure.
2. Proper loads and conditions must be assumed in the design.
3. The unit stresses must be suitable for the material used.
4. The workmanship must be good, so that defects or injuries are not produced in the manufacture.
5. The computations and design must be properly made so that the unit stresses specified shall not be exceeded, and the structure and its details shall possess the requisite strength and rigidity.

The specification also provided guidance on the material to be used, stating "Structural steel shall conform to the Standard Specifications of the American Society for Testing Materials for Structural Steel for Buildings, Serial Designation A 9-21, as amended to date." These principles from 1923 are still important to steel construction almost a century later.

The 2005 AISC Specification for Structural Steel Buildings supersedes all previous AISC Specifications and thus brings together, into one document, the necessary provisions for the design of steel building structures. Over the years, the specification has lost the terms fabrication and erection from its scope, because the development of standard practice of building design and construction has changed responsibilities of the various parties. In addition, the AISC Specification has regularly been used to guide the design of structures other than building structures. In recognition of this practice, and to ensure that the specification is properly applied, the scope of this edition has been revised to state "This specification sets forth criteria for the design of structural steel buildings and other structures, where other structures are defined as those structures designed, fabricated, and erected in a manner similar to buildings, with building-like vertical and lateral load-resisting-elements."

Additionally, the specification indicates that it "shall apply to the design of the structural steel system, where the steel elements are defined in the AISC Code of Standard Practice for Steel Buildings and Bridges Section 2.1. In that document, structural steel is defined as those elements of the structural frame that are shown and sized in the structural Design Drawings, essential to support the design loads . . ." and are given here in Table 3.1. Examples of many

Table 3.1 Definitions of Structural Steel[a]

Anchor rods that will receive structural steel.
Base plates.
Beams, including built-up beams, if made from standard structural shapes and/or plates.
Bearing plates.
Bearings of steel for girders, trusses, or bridges.
Bracing, if permanent.
Canopy framing, if made from standard structural shapes and/or plates.
Columns, including built-up columns, if made from standard structural shapes and/or plates.
Connection materials for framing structural steel to structural steel.
Crane stops, if made from standard structural shapes and/or plates.
Door frames, if made from standard structural shapes and/or plates and if part of the structural steel frame.
Edge angles and plates, if attached to the structural steel frame or steel (open-web) joists.
Embedded structural steel parts, other than bearing plates, that will receive structural steel.
Expansion joints, if attached to the structural steel frame.
Fasteners for connecting structural steel items: permanent shop bolts, nuts, and washers; shop bolts, nuts, and washers for shipment; field bolts, nuts, and washers for permanent connections; and permanent pins.
Floor-opening frames, if made from standard structural shapes and/or plates and attached to the structural steel frame or steel (open-web) joists.
Floor plates (checkered or plain), if attached to the structural steel frame.
Girders, including built-up girders, if made from standard structural shapes and/or plates.
Girts, if made from standard structural shapes.
Grillage beams and girders.
Hangers, if made from standard structural shapes, plates, and/or rods and framing structural steel to structural steel.
Leveling nuts and washers.
Leveling plates.
Leveling screws.
Lintels, if attached to the structural steel frame.
Machinery supports, if made from standard structural shapes and/or plates and attached to the structural steel frame.
Marquee framing, if made from standard structural shapes and/or plates.
Monorail elements, if made from standard structural shapes and/or plates and attached to the structural steel frame.
Posts, if part of the structural steel frame.
Purlins, if made from standard structural shapes.
Relieving angles, if attached to the structural steel frame.
Roof-opening frames, if made from standard structural shapes and/or plates and attached to the structural steel frame or steel (open-web) joists.
Roof-screen support frames, if made from standard structural shapes.
Sag rods, if part of the structural steel frame and connecting structural steel to structural steel.
Shear stud connectors, if specified to be shop attached.
Shims, if permanent.
Struts, if permanent and part of the structural steel frame.
Tie rods, if part of the structural steel frame.
Trusses, if made from standard structural shapes and/or built-up members.
Wall-opening frames, if made from standard structural shapes and/or plates and attached to the structural steel frame.
Wedges, if permanent.

[a]From Code of Standard Practice for Steel Buildings and Bridges, AISC 2005.

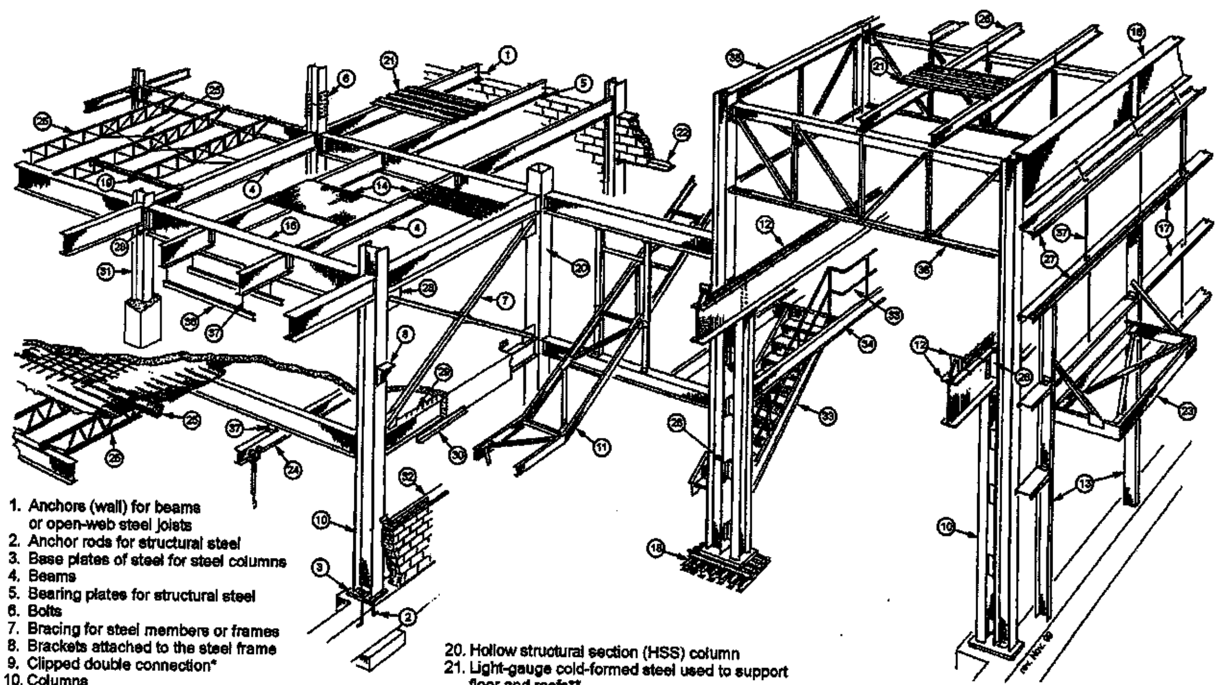


Figure 3.1 Steel Elements. Copyright, Code of Standard Practice, Canadian Institute of Steel Construction.

of these elements are shown in Figure 3.1. All elements discussed within this text will meet the above definition.

3.3 STEEL FOR CONSTRUCTION

Since the introduction of the first AISC Specification, a variety of steels have been approved for use in steel construction. Which steels were specifically approved at any time has changed with the changing techniques of manufacture and steel chemistry. Steels available for use in construction have increased in strength as manufacturing has become more refined. One important aspect of all steel is that it generally behaves in a uniform and consistent manner. Thus, although the strength might be different for different grades of steel, the steel can be expected to behave the same, regardless of grade, up to its various strength limits.

The characteristics of steel that are important to the structural engineer can be determined through a simple uniaxial tension test. This standard test is conducted according to the requirements of ASTM A370 Standard Test Methods and Definitions for Mechanical Testing of Steel Products. A specimen of a specific dimension is subjected to a tensile force

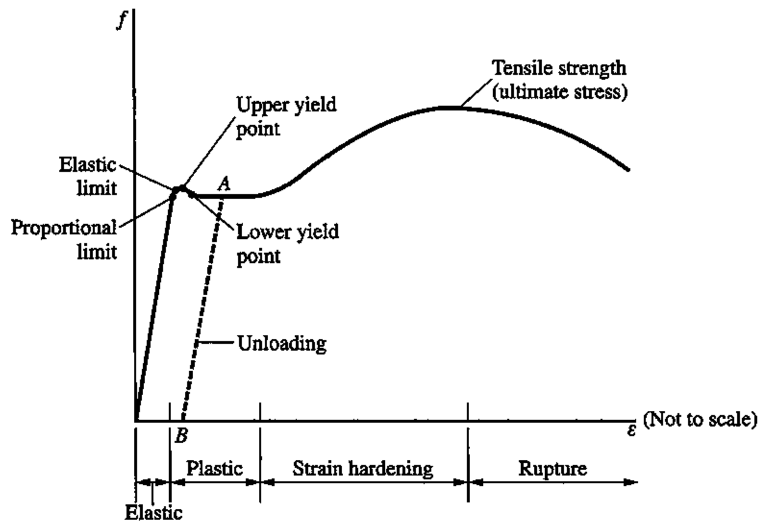


Figure 3.2 Typical Stress-Strain Plot for Mild Carbon Steel.

and the resulting stress and strain are plotted for the duration of the test. The stress, f, and strain, ε, are shown plotted in Figure 3.2 and defined as follows:

$$f = \frac{P}{A} \qquad \text{and} \qquad \varepsilon = \frac{\Delta L}{L}$$

where

$A =$ cross-sectional area at start of test
$L =$ length of specimen at start of test
$P =$ tensile force
$f =$ axial tensile stress
$\Delta L =$ change in length of specimen
$\varepsilon =$ axial strain

The curve shown in Figure 3.2 is typical of mild carbon steel. Several characteristics of this stress-strain curve are worth noting. First, the initial portion of the curve, which indicates the response that would be expected under most normal or service loading conditions, follows a straight line up to a point called the *proportional limit*. For structural steel with yield stresses at 65 ksi or less, this proportional limit is the point where the curve first deviates from linear and is called the *yield point*. The ratio of stress to strain in this region is constant and called Young's Modulus, or the Modulus of Elasticity, E. All structural steels exhibit the same initial stress-strain behavior and thus have the same E. The value of E obtained through a wide number of tests is consistently between 29,000 ksi and 30,000 ksi. For all calculations according to the AISC Specification, $E = 29{,}000$ ksi has historically been used. Within the straight-line portion of the curve, the material is said to behave elastically. A load can be applied and then removed with the structure returning to its original configuration, showing no permanent deformation.

After reaching the yield stress, the stress-strain curve for mild carbon steel exhibits a long plateau where the stress remains essentially constant while the strain increases. This region is called the *plastic region*. Any structure that is loaded into this region exhibits a permanent plastic deformation as shown by the unloading line in Figure 3.2. The length of this plastic region depends on the particular type of steel but typically is 15 to 20 times the strain at yield.

At the end of the plastic region, the curve again rises with increasing stress and strain. This increase is called *strain hardening* and continues until the specimen reaches its tensile strength, or ultimate stress, F_u, at the peak of the stress-strain curve. Once the tensile strength is reached, the specimen rapidly sheds load and increases strain until the specimen completely ruptures.

Yield stress, tensile strength, and modulus of elasticity are the engineering data used throughout design to fully describe the material and to determine the strength of the structural elements. The ratio of the tensile strength to the yield stress is also an important characteristic of steel. It is used to control the basic material behavior so that at various limit states, the expected behavior can be assured.

Figure 3.3 shows the lower strain region of the stress-strain curves for three steels with different yield stresses, 36 ksi, 50 ksi, and 100 ksi. Elastic behavior for the higher strength steels is the same as for lower strength steels as seen in the figure. As already noted, $E = 29{,}000$ ksi for all steel. The differences occur after the proportional limit is reached. For steels with a yield stress less than or equal to 65 ksi, the plateau defining the plastic region can be expected to occur. However, for steels with a yield stress greater than 65 ksi, it is expected that no well-defined yield point will exist and no well-defined plastic plateau will occur. For these steels it is necessary to define yield strength by some other means. ASTM A370 provides for yield strength determination by the 0.2% offset method or the 0.5% elongation method. In either case, the stress-strain curve must be obtained and the

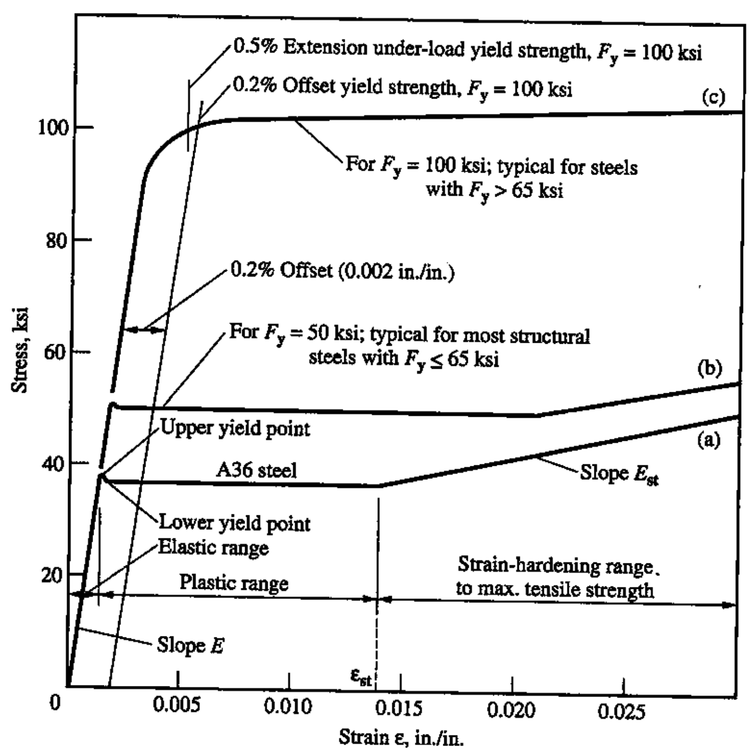


Figure 3.3 Enlarged Typical Stress-Strain Curves for Steels with Different Yield Stresses.

specified offset or elongation used to determine the appropriate stress value. The results of these two approaches are shown in Figure 3.3, and the two methods would yield different yield strength values.

3.4 STRUCTURAL STEEL SHAPES

Structural steel design serves to determine the appropriate shape and quantity of steel needed to carry a given applied load. This is normally accomplished by selecting, from a predetermined list of available shapes, the lightest-weight member. However, it could also result from the combination of steel elements into some particular desired form. The early days of steel construction had very little standardization of available shapes. Although each mill would produce its own shapes, the variety of available shapes was limited and most structural members were composed of these available shapes riveted together. One of AISC's original goals was to standardize the shapes being produced. Over the years, shapes became standardized and more shapes, designed specifically for the needs of building construction, became available. Modern production practices now make a wide variety of shapes available to the designer so that design can almost always be accomplished by selecting one of these standard shapes. In situations where these standard shapes do not meet the needs of a project, members composed of plate material can be produced to carry the imposed loading.

3.4.1 ASTM A6 Standard Shapes

The first standard shapes to be discussed are those defined by ASTM A6: W-shapes, S-shapes, HP-shapes, M-shapes, C-shapes, MC-shapes, and L-shapes. Cross-sections of these shapes are shown in Figure 3.4 where it can be seen that W-, M-, S-, and HP-shapes all take the form of an I. C- and MC-shapes are channels and L-shapes are called angles. Part 1 of the Manual contains tables of properties for all of the standard shapes.

W-Shapes

W-shapes are usually referred to as wide flange shapes and are the most commonly used shapes in buildings. They have two flanges with essentially parallel inner and outer faces and a single web located midway on the flanges. The overall shape of the wide flange may vary from being a fairly deep and narrow section, as shown in Figure 3.4a, to an almost square section, as shown in Figure 3.4b. These shapes have two axes of symmetry; the x-axis is the strong axis and the y-axis is the weak axis. Wide flange shapes can be as deep as 44 in. and as shallow as 4 in. A typical wide flange shape would be called out as a W16×26 where the W indicates it is a W-shape, the 16 indicates it has a nominal depth of 16 in., and the 26 indicates its weight is 26 pounds per foot. The nominal depth is part of the name of the shape and indicates an approximate member depth but does not indicate its actual depth. The production of wide flange shapes results in shapes being grouped in a family according to the size of the rolls that produce the shape. All shapes in a family have the same dimension between the inner faces of the flanges. The different weights are accomplished by increasing the actual depth of the member. Manual Table 1-1 provides the dimensions and section properties needed for design for all W-shapes.

HP-Shapes

HP-shapes are wide flange shapes normally used as bearing piles. These shapes have parallel face flanges like the wide flange shapes but unlike the W-shapes, their webs and flanges are of

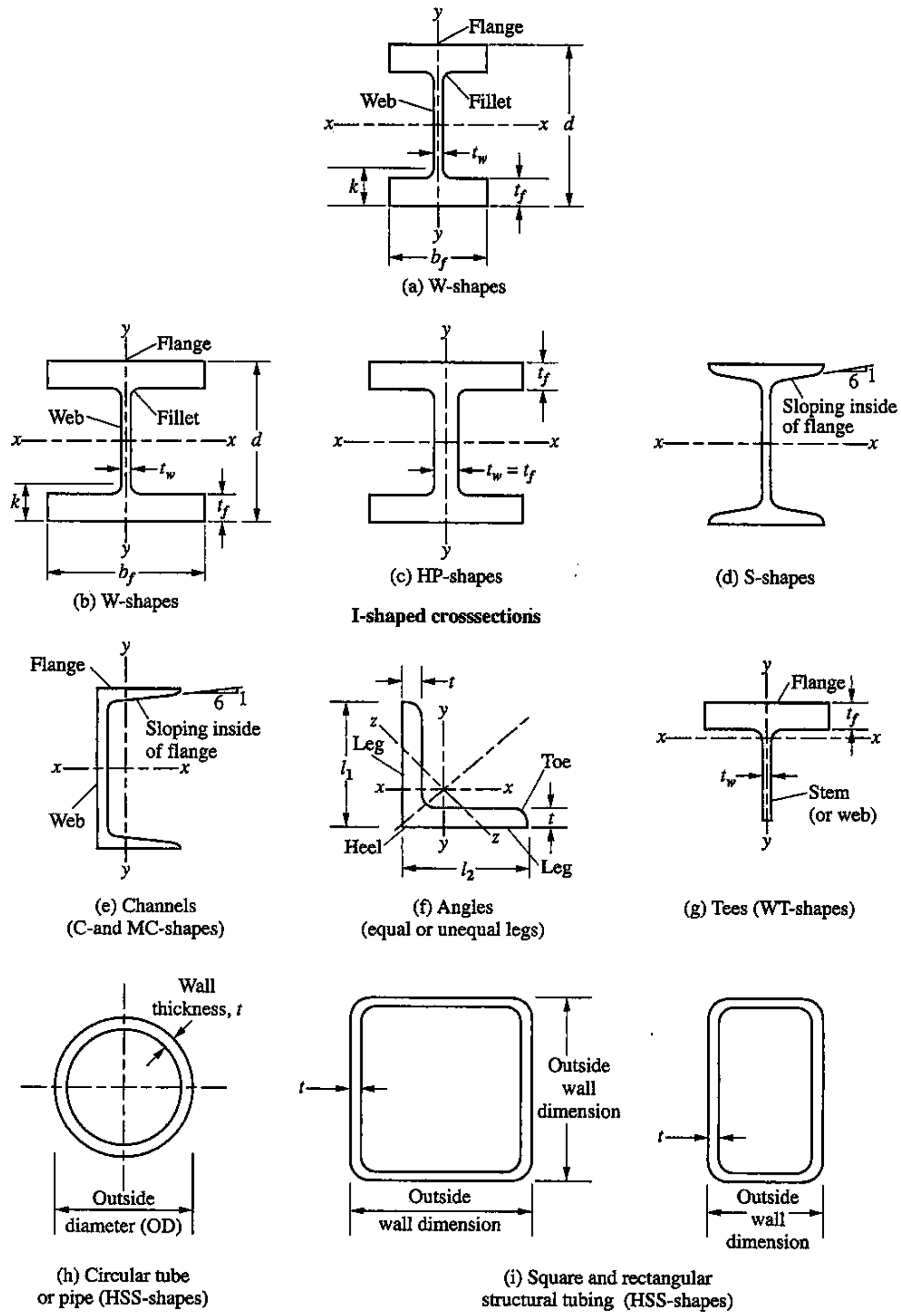


Figure 3.4 Structural Shapes.

the same nominal thickness and they are all close to being square, as shown in Figure 3.4c. An HP14×117 would be an HP-shape with a nominal depth of 14 in. and a weight of 117 pounds per foot. Manual Table 1-4 provides the dimensions and section properties needed for the design for all HP-shapes.

S-Shapes

S-shapes are American Standard Beams and were previously referred to as I-beams. They were the standard shapes used in construction prior to the development of the rolling process that permitted the introduction of the wide flange shapes. Although these shapes are still available, their use is infrequent and their availability should be confirmed prior to specifying them. These shapes have relatively narrow flanges compared to their depth and the flanges have a sloping interior face, as shown in Figure 3.4d. The Manual lists 28 S-shapes and their properties are found in Table 1-3. As with the shapes previously discussed, the numbers in the name refer to the nominal depth and the weight per foot. In all cases except the S24×121 and S24×106, the nominal depth and the actual depth are the same.

M-Shapes

M-shapes are miscellaneous shapes that do not fit into the definitions of W-, HP-, and S-shapes. The Manual lists 18 miscellaneous shapes. They are not particularly common and should be used in design only after confirmation that they are economically available. A typical designation would be M12×11.8. As with the other shapes, the 12 indicates the nominal depth and the 11.8 indicates the weight per foot. Dimensions and properties for these M-shapes are found in Manual Table 1-2.

C-Shapes

C-shapes are American Standard Channels and are produced by essentially the same process as S-shapes. They have two flanges and a single web located at the end of the flanges, as shown in Figure 3.4e. These shapes have only one axis of symmetry and, like the W-shapes, the x-axis is the strong axis and the y-axis is the weak axis. As with the S-shapes, the flanges have sloping inner faces. One of the 31 C-shapes found in Manual Table 1-5 is a C8×18.7. All C-shapes have an actual depth equal to the nominal depth.

MC-Shapes

MC-shapes are miscellaneous channels that cannot be classified as C-shapes. Their designations follow the same rules as the previous shapes with a typical shape being an MC6×18. Manual Table 1-6 lists 39 MC-shapes, and their sizes fit into the same overall range as the C-shapes.

L-Shapes

L-shapes are angles that can have equal or unequal legs. The largest angle legs are 8 in. and the smallest are 2 in., with the dimension taken from heel to toe of the angle. A typical angle designation would be L6×4×$^7/_8$ where the first two numbers are the dimensions of the legs and the third is the leg thickness. Leg dimensions are actual dimensions and the leg thickness is the same for both legs. For unequal leg angles, the longest leg is given first. Equal leg angles have one axis of symmetry whereas unequal leg angles have no axis of symmetry. All angles have three axes of interest to the designer: the geometric axes are the x-axis, parallel to the short leg; the y-axis is parallel to the long leg; and the minor principal axis, which for equal leg angles is perpendicular to the axis of symmetry, is the z-axis. Manual Table 1-7 provides the dimensions and section properties needed for the design for all angles.

WT-Shapes

WT-shapes are tees that have been cut from W-shapes. They are also called split tees. These shapes are designated as WT5×56 where both numbers are one-half of what would indicate the parent W-shape that they were cut from. Dimensions and properties for WT-shapes are given in Manual Table 1-8.

MT-Shapes and ST-Shapes

MT-shapes and *ST-shapes* are tees that have been cut from the parent M- and S-shapes. The properties and dimensions for these shapes are found in Manual Tables 1-9 and 1-10.

3.4.2 Hollow Shapes

Another group of shapes commonly found in building construction are the hollow shapes referred to as tubes or pipes. These shapes are produced by bending and welding flat plates or by hot rolling to form a seamless section. For all hollow structural shapes (HSS), ASTM specifications set the requirements for both the material and the sizes.

Round HSS

Round hollow structural shapes are round hollow structural sections. They are manufactured through a process called Formed-From-Round which takes a flat strip of steel and gradually bends it around its longitudinal axis and joins it by welding. Once the weld has cooled, the round shape is passed through additional shaping and sizing rolls to fix the final diameter. A round HSS would be indicated as HSS5.563×0.258 where the first number is the diameter and the second is the nominal thickness. These shapes are found in Manual Table 1-13.

Square and Rectangular HSS

Square and Rectangular HSS may be formed as Round HSS with the final sizing used to change the shape into a rectangle, or formed from a flat plate through a Formed-Square Weld-Square process wherein the plate is gradually bent into its near final size. Another process starts with two flat pieces that are each bent and then the two half sections are joined to form the final shape. A typical rectangular HSS would be HSS12×8×$^1/_2$. The first number indicates the actual height of the section, the second the actual width, and the third the nominal thickness of the section wall. Manual Tables 1-11 and 1-12 provide the dimensions and section properties needed for the design of rectangular and square HSS-shapes, respectively.

Steel Pipes

Steel pipes are another hollow round section used in building construction. They are produced to different material standards than the round HSS. Pipes are available as standard

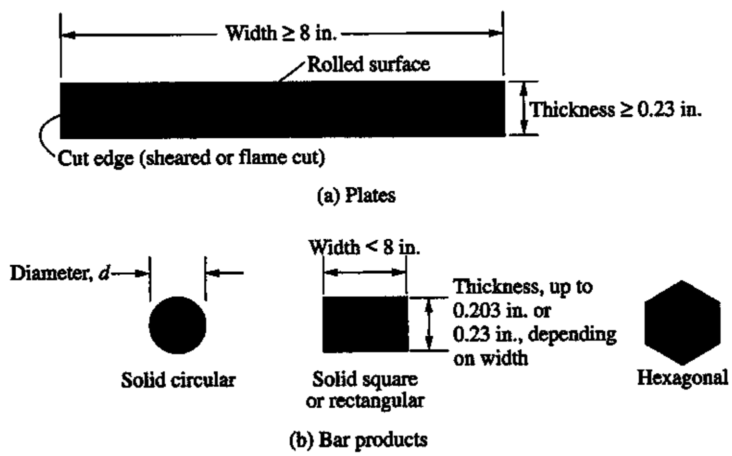


Figure 3.5 Plate and Bar Products.

weight (Std.), extra strong (x-Strong), and double-extra strong (xx-Strong), which refer to the wall thickness for a given outside diameter. The standard designation for a pipe section would be Pipe 5 x-Strong, indicating that it was to meet the pipe material standards, have a nominal 5-in. outside diameter, and a thickness corresponding to the extra strong designation. This particular pipe would have an actual outside diameter of 5.56 in. and a nominal wall thickness of 0.375 in. Manual Table 1-14 provides the properties for steel pipes.

3.4.3 Plates and Bars

In addition to the shapes already discussed, steel is available as plates and bars, as shown in Figure 3.5. These elements are rarely used alone as shapes but are combined to form built-up shapes or used alone as connecting elements to join other shapes.

Plates

Plates are flat rectangular elements hot rolled to a given thickness and sheared to the appropriate width. At one time, plates were also available that were rolled to a given width as well as thickness. These plates were called universal mill plates. Because of the manufacturing process, these plates had different patterns of residual stresses than the sheared plates that resulted in lower strength. Current manufacturing practice is to produce all plates as sheared plates. By industry definition, plates are a minimum of 8 in. in width and may vary in thickness from $^3/_{16}$ in. The designation for a plate is PL$^1/_2$×10×2 ft–4 in. where the first number is the thickness, the second the plate width, and the third the length. Table 3.2 gives the preferred standard practice for plate thickness increments.

Bars

Bars are available in rectangular, circular, and hexagonal shapes with the rectangular bar the most commonly used shape in building construction. The only difference between rectangular bars and plates is the width. Any rectangular solid element less than 8 in. in width is technically referred to as a bar. Because the distinction between bars and plates is not significant to the designer, the designation for these narrow elements is the same as for a plate. Thus, PL$^1/_2$×6×2 ft–4 in. is a 6-in. wide bar.

Table 3.2 Preferred Dimensions for Plates and Bars

	Range of Thicknesses/Diameters		
Product	$t \leq \frac{3}{8}$ in.	$\frac{3}{8} < t \leq 1$ in.	1 in. $< t$
Plates	$\frac{1}{16}$	$\frac{1}{8}$	$\frac{1}{4}$
Square and rectangular bars	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{8}$
Circular bars	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{8}$

Note. Table gives increments in thickness or diameter.

3.4.4 Built-up Shapes

Other shapes are available and may be found in the Manual but are of limited application in building construction. The manual also contains tables for combinations of standard shapes that have, over the years, been found to be useful to the designer. Figure 3.6 shows a variety of built-up shapes formed from combining plates and shapes.

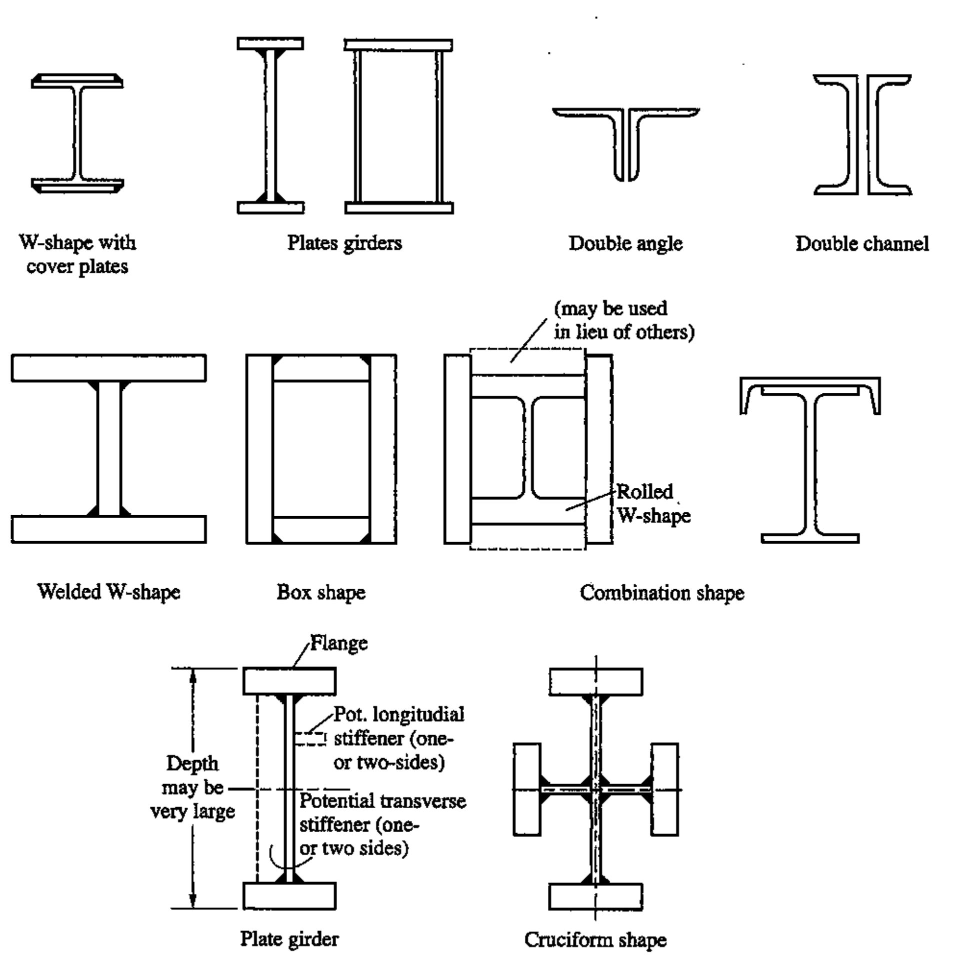


Figure 3.6 Examples of Built-up Shapes.

3.5 CHEMICAL COMPONENTS OF STRUCTURAL STEEL

The basic mechanical properties of structural steel were presented in Section 3.3 with a limited discussion of the types of steel available for use by the building industry. Essentially three types of steel are used for shapes in the construction industry: carbon steel, high-strength low-alloy steel, and corrosion-resistant high-strength low-alloy steel. For plates and bars, quenched and tempered steels are also available.

The chemical composition of steel significantly influences the properties that are of ultimate importance to the engineer. Steel is primarily made of iron but also contains such other elements as carbon, silicon, nickel, manganese, and copper. The primary element, in addition to iron, is carbon. The addition of carbon increases steel strength but decreases ductility and weldability. Even though carbon is the most significant component of steel, after iron, it is still a very small percent of the final product. Steels generally have a carbon content of up to 0.3% by weight.

Although the formula for any specific steel might be different from any other steel, certain elements are required in order to meet a specific set of criteria. These specifications come from the ASTM standards for each steel type and are discussed in Section 3.6. However, the chemical elements that may be found in the most dominant steel for wide flange shapes are reviewed here. The specific percentage requirements for ASTM A992 steel are given in Table 3.3.

Carbon

Carbon (*C*) is the most common element found in all steel. It is the most economical element used to increase strength. However, it also decreases ductility. Carbon content usually ranges from about 0.15% to 0.30%. Anything lower than 0.15% would produce steel with too low a strength, and anything higher than 0.30% would yield steel with poor characteristics for use in construction.

Manganese

Manganese (*Mn*) has an effect on strength similar to that of carbon. It is a necessary component because of the way it combines with oxygen and sulfur and its impact on the rolling process. In addition, manganese improves the notch toughness of steel. It is added

Table 3.3 Chemical Requirements for A992 Steel

Element	Composition, %
Carbon, max	0.23
Manganese	0.50 to 1.50
Silicon, max	0.40
Vanadium, max	0.11
Columbium, max	0.05
Phosphorus, max	0.035
Sulfur, max	0.045
Copper, max	0.60
Nickel, max	0.45
Chromium, max	0.35
Molybdenum, max	0.15
Nitrogen, max	0.015

to steel to offset reductions in notch toughness due to the presence of other elements. It has a negative effect on material weldability.

Silicon

Silicon (*Si*) is an important element for removing oxygen from hot steel.

Phosphorus

Phosphorus (*P*) increases strength and decreases ductility. It improves resistance to atmospheric corrosion, particularly when used in combination with copper. It has a negative impact on weldability that is more severe than that of manganese. It is generally an undesirable element but is permitted in very limited quantities in all steel.

Sulfur

Sulfur (*S*) is also permitted in very limited quantities in all steel. It has a similar negative impact to that of phosphorus.

Copper

Copper (*Cu*) in limited quantities is beneficial to the strength of steel. It increases strength with only a limited negative impact on ductility. If its content is held relatively low, it will have little effect on weldability. It is the most significant contributing element in the production of corrosion-resistant steel.

Vanadium

Vanadium (*V*) is another strengthening element. It refines the grain size and thus increases strength. Its biggest advantage is that while increasing strength, it does not negatively impact weldability or notch toughness.

Columbium

Columbium (*Cb*) is a strengthening element that, in small quantities, can increase the yield point and, to a lesser extent, the tensile strength. However, it has a significant negative impact on notch toughness.

Nitrogen

Nitrogen (*N*) is normally found in very low quantities but does provide some increase in strength. When used in combination with vanadium it can improve weldability.

Nickel

Nickel (*Ni*) can provide a moderate improvement in strength and enhances corrosion resistance. It can also improve resistance to corrosion for steel subjected to seawater when in combination with copper or phosphorous. It generally produces a slight improvement in notch toughness.

Chromium

Chromium (*Cr*) is typically used in combination with copper to improve corrosion resistance. It also provides some strengthening in steels containing copper and vanadium. Chromium is an integral component of stainless steel.

Molybdenum

Molybdenum (*Mo*) increases strength but significantly decreases notch toughness, although its negative impact can be lessened through appropriate processing or balancing with other elements.

3.6 GRADES OF STRUCTURAL STEEL

3.6.1 Steel for Shapes

More grades of steel are produced than approved by AISC for use in structures. An ASTM number designates each approved steel. The steels approved for structural shapes are grouped as carbon (A36, A53, A500, A501, and A529); high-strength low-alloy (A572, A618, A913, and A992); and corrosion-resistant high-strength low-alloy (A242, A588, and A847). Figure 3.7 shows these approved steels, their minimum yield and tensile stresses, and the shapes for which they are applicable.

A36 Steel

A36 steel was the most commonly available structural steel for many years. It was first introduced in the 1961 AISC Specification and until the late 1990s was the steel of choice for most steel shapes except for HSS, pipe, and plates. It is a mild carbon steel so it is well suited for bolted or welded construction and, even if higher strength steels were being used for members, this steel was the norm for connecting elements. It continues to be the preferred steel for M-, S-, C-, MC-, and L-shapes. It has a minimum yield stress, $F_y = 36$ ksi, and a tensile stress, $F_u = 58$ to 80 ksi, although $F_u = 58$ ksi is used for calculations throughout the specification.

A53 Steel

A53 steel is the single standard for steel pipe approved for construction. This standard provides for three types and two grades. These pipes are generally intended for mechanical and pressure applications and the only grade approved for construction is Grade B. This grade comes as Type E, which calls out electric-resistance welding of the seam, or Type S, which is a seamless pipe. A53 Grade B has a minimum yield stress, $F_y = 35$ ksi, and a minimum tensile stress, $F_u = 60$ ksi.

A500 Steel

A500 steel is a carbon steel used for structural tubing in rounds and shapes, otherwise known as HSS. It comes in two grades approved by AISC for construction: grade B, which is the preferred grade, and Grade C. The standard permits either welded or seamless manufacture. Round HSS Grade B has a minimum yield stress, $F_y = 42$ ksi, and a minimum tensile stress, $F_u = 58$ ksi, whereas rectangular HSS Grade B has a minimum yield stress, $F_y = 46$ ksi, with a minimum tensile stress, $F_u = 58$ ksi.

Table 2–3
Applicable ASTM Specifications for Various Structural Shapes

Steel Type	ASTM Designation		F_y Min. Yield Stress (ksi)	F_u Tensile Stress[a] (ksi)	Applicable Shape Series									
					W	M	S	HP	C	MC	L	HSS Rect.	HSS Round	Pipe
Carbon	A36		36	58-80[b]	■	■	■	■	■	■	■			
	A53 Gr. B		35	60										■
	A500	Gr. B	42	58									■	
			46	58								■		
		Gr. C	46	62									■	
			50	62								■		
	A501		36	58								■	■	
	A529[c]	Gr. 50	50	65-100	■	■	■	■	■	■	■			
		Gr. 55	55	70-100	■	■	■	■	■	■	■			
High-Strength Low-Alloy	A572	Gr. 42	42	60	■	■	■	■	■	■	■			
		Gr. 50	50	65[d]	■	■	■	■	■	■	■			
		Gr. 55	55	70	■	■	■	■	■	■	■			
		Gr. 60[e]	60	75	■	■	■	■	■	■	■			
		Gr. 65[e]	65	80	■	■	■	■	■	■	■			
	A618[f]	Gr. I & II	50[g]	70[g]								■	■	
		Gr. III	50	65								■	■	
	A913	50	50[h]	60[h]	■	■	■	■	■	■	■			
		60	60	75	■	■	■	■	■	■	■			
		65	65	80	■	■	■	■	■	■	■			
		70	70	90	■	■	■	■	■	■	■			
	A992		50-65[i]	65[i]	■	■	■	■	■	■	■			
Corrosion Resistant High-Strength Low-Alloy	A242		42[j]	63[j]	■									
			46[k]	67[k]	■			■			■			
			50[l]	70[l]	■	■	■	■	■	■	■			
	A588		50	70	■	■	■	■	■	■	■			
	A847		50	70								■	■	

■ = Preferred material specification.
■ = Other applicable material specification, the availability of which should be confirmed prior to specification.
□ = Material specification does not apply.

[a] Minimum unless a range is shown.
[b] For shapes over 426 lb/ft, only the minimum of 58 ksi applies.
[c] For shapes with a flange thickness less than or equal to 1½ in. only. To improve weldability a maximum carbon equivalent can be specified (per ASTM Supplementary Requirement S78). If desired, maximum tensile stress of 90 ksi can be specified (per ASTM Supplementary Requirement S79).
[d] If desired, maximum tensile stress of 70 ksi can be specified (per ASTM Supplementary Requirement S91).
[e] For shapes with a flange thickness less than or equal to 2 in. only.
[f] ASTM A618 can also be specified as corrosion-resistant; see ASTM A618.
[g] Minimum applies for walls nominally ¾-in. thick and under. For wall thicknesses over ¾ in., F_y = 46 ksi and F_u = 67 ksi.
[h] If desired, maximum yield stress of 65 ksi and maximum yield-to-tensile strength ratio of 0.85 can be specified (per ASTM Supplementary Requirement S75).
[i] A maximum yield-to-tensile strength ratio of 0.85 and carbon equivalent formula are included as mandatory in ASTM A992.
[j] For shapes with a flange thickness greater than 2 in. only.
[k] For shapes with a flange thickness greater than 1½ in. and less than or equal to 2 in. only.
[l] For shapes with a flange thickness less than or equal to 1½ in. only.

Figure 3.7 Applicable ASTM Specifications for Various Structural Shapes.

A501 Steel

A501 steel is a carbon steel similar to A36 but used for round and rectangular HSS. It has a minimum yield stress, $F_y = 36$ ksi, and a minimum tensile stress, $F_u = 58$ ksi.

A529 Steel

A529 steel is a carbon-manganese steel available in Grades 50 and 55. It is approved for the smaller shapes with flange thickness no greater that 1.5 in. A529 Grade 50 has a minimum yield stress, $F_y = 50$ ksi, and a tensile stress, $F_u = 65$ to 100 ksi, whereas Grade 55 has a minimum yield stress, $F_y = 55$ ksi, and a tensile stress, $F_u = 70$ to 100 ksi.

A572 Steel

A572 is a high-strength low-alloy steel, also referred to as columbium-vanadium structural steel, available in five grades. It is a versatile high-strength steel with good weldability. Availability of shapes and plates is a function of grade, generally depending on element thickness. It is available in all shapes other than HSS and pipe. The full range of minimum yield stress is 42 ksi to 65 ksi, depending on grade, and the minimum tensile stress ranges from 60 ksi to 80 ksi, again depending on grade. A572 is the preferred steel for HP-shapes.

A618 Steel

A618 is a high-strength low-alloy steel used for HSS. Grades I, II, and III are approved for use in structures by AISC. It is the only high-strength low-alloy steel available in HSS. Grade II has limited atmospheric corrosion resistance and Grade III can be produced with increased corrosion resistance if required. The minimum yield stress depends on the particular product and may vary from 46 to 50 ksi. The minimum tensile stress varies from 65 to 70 ksi, again depending on grade and product wall thickness.

A913 Steel

A913 is a high-strength low-alloy steel produced by quenching and self-tempering. It is available in Grades 50, 60, 65, and 70. This steel is currently not produced domestically but can be obtained from one foreign producer. The minimum yield stress ranges from 50 to 70 ksi and the minimum tensile stress ranges from 60 to 90 ksi.

A992 Steel

A992 steel has become the steel of choice for wide flange shapes. It was first approved for use in 1998 as a replacement for A572 Grade 50. This standard was developed partly as a result of an improved understanding of the impact of material property variations on structural behavior and partly as a result of the changes occurring in properties resulting from the use of scrap as the main resource for steel production. The chemical components for A992 steel were given in Table 3.3 and discussed in Section 3.5. It has a minimum yield stress, $F_y = 50$ ksi, and a minimum tensile stress, $F_u = 65$ ksi. An additional requirement is that the yield-to-tensile ratio can not exceed 0.85.

A242 Steel

A242 is a high-strength low-alloy corrosion-resistant steel also called *weathering steel.* It was one of the first corrosion-resistant steels and has a corrosion resistance approximately four times that of normal carbon steel. It is available in three grades but is now less common than the newer A588. The minimum yield stress ranges from 42 to 50 ksi and the minimum tensile stress ranges from 63 to 70 ksi.

A588 Steel

A588 is a high-strength low-alloy corrosion-resistant steel with substantially better corrosion resistance than carbon steel with or without copper. It is available for all shapes, except HSS and pipe, as well as plate. For all shapes, and for plates up to 4 in., it has a minimum yield stress, $F_y = 50$ ksi, and a minimum tensile stress, $F_u = 70$ ksi. Plates up to 8 in. are available at reduced stress values.

A847 Steel

A847 is the high-strength low-alloy corrosion-resistant steel used for HSS. It has the same minimum yield and tensile stresses as A588.

3.6.2 Steel for Plates and Bars

Many of the steels already discussed for shapes are also available for plates and bars. Figure 3.8 shows the ASTM designation, the corresponding yield and tensile stresses, and the plate thickness for which they apply. The only steels available for plates and bars that are not also available for shapes are the two quenched and tempered steels, A514 and A852.

A514 Steel

A514 is a high-yield strength-quenched and tempered alloy steel suitable for welding. It is available only as plate material up to 6 in. There are 14 different grades, which vary according to the chemical content and maximum thickness. The minimum yield stress is either 90 or 100 ksi and the ultimate tensile stress ranges from 100 to 130 ksi. This is the highest yield stress steel approved for use according to the AISC Specification.

A852 Steel

A852 is a quenched and tempered high-strength low-alloy corrosion-resistant steel. It is intended primarily for use in welded construction where durability and notch toughness are important. It is available as plate only up to 4 in. It has a minimum yield stress, $F_y = 70$ ksi, and a tensile strength, $F_u = 90$ to 110 ksi.

3.6.3 Steel for Fasteners

Fasteners for steel construction today include high-strength bolts, common bolts, threaded rods, and anchor rods. In addition, nuts, washers, and direct-tension-indicators must be specified. The ASTM steels approved for these elements are shown in Figure 3.9. Many grades of steel are appropriate for the variety of mechanical fasteners used in steel construction but only the three steels commonly specified for bolts are discussed here.

Table 2–4
Applicable ASTM Specifications for Plates and Bars

Steel Type	ASTM Designation		F_y Min. Yield Stress (ksi)	F_u Tensile Stress[a] (ksi)	Plates and Bars: to 0.75 incl.	over 0.75 to 1.25	over 1.25 to 1.5	over 1.5 to 2 incl.	over 2 to 2.5 incl.	over 2.5 to 4 incl.	over 4 to 5 incl.	over 5 to 6 incl.	over 6 to 8 incl.	over 8
Carbon	A36		32	58-80	□	□	□	□	□	□	□	□	□	■
			36	58-80	■	■	■	■	■	■	■	■	■	□
	A529	Gr. 50	50	70-100	▩	▩	▩	▩	▩	□	□	□	□	□
		Gr. 55	55	70-100	▩	▩	▩	□	□	□	□	□	□	□
High-Strength Low-Alloy	A572	Gr. 42	42	60	▩	▩	▩	▩	▩	▩	▩	▩	□	□
		Gr. 50	50	65	▩	▩	▩	▩	▩	▩	□	□	□	□
		Gr. 55	55	70	▩	▩	▩	▩	□	□	□	□	□	□
		Gr. 60	60	75	▩	▩	□	□	□	□	□	□	□	□
		Gr. 65	65	80	▩	▩	□	□	□	□	□	□	□	□
Corrosion Resistant High-Strength Low-Alloy	A242		42	63	□	□	□	▩	▩	▩	□	□	□	□
			46	67	□	▩	▩	□	□	□	□	□	□	□
			50	70	▩	□	□	□	□	□	□	□	□	□
	A588		42	63	□	□	□	□	□	□	□	▩	▩	□
			46	67	□	□	□	□	□	□	▩	□	□	□
			50	70	▩	▩	▩	▩	▩	▩	□	□	□	□
Quenched and Tempered Alloy	A514[c]		90	100-130	□	□	□	□	□	▩	▩	▩	□	□
			100	110-130	▩	▩	▩	▩	▩	□	□	□	□	□
Quenched and Tempered Low-Alloy	A852[c]		70	90-110	▩	▩	▩	▩	▩	▩	□	□	□	□

■ = Preferred material specification.
▩ = Other applicable material specification, the availability of which should be confirmed prior to specification.
□ = Material specification does not apply.

a Minimum unless a range is shown.
b Applicable to bars only above 1-in. thickness.
c Available as plates only.

Figure 3.8 Applicable ASTM Specifications for Plates and Bars.

A307 Bolts

A307 bolts are also called *common bolts* or *black bolts*. Although the ASTM standard specifies three grades, only Grade A is approved for use as bolts in general applications. These bolts have an ultimate tensile strength of 60 ksi and are thus at a strength level similar to A36 steel. Although these bolts continue to be listed by AISC, they are rarely used in steel-to-steel structural connections.

A325 Bolts

A325 bolts are a quenched and tempered steel-heavy hex structural bolt. They are the dominant high-strength bolts used in construction. Two types are available: type 1, the

Table 2-5
Applicable ASTM Specifications for Various Types of Structural Fasteners

ASTM Designation	F_y Min. Yield Stress (ksi)	F_u Tensile Stress[a] (ksi)	Diameter Range (in.)	High-Strength Bolts: Conventional	High-Strength Bolts: Twist-Off-Type Tension-Control[d]	Common Bolts	Nuts	Washers	Direct-Tension-Indicator Washers	Threaded Rods	Shear Stud Connectors	Anchor Rods: Hooked	Anchor Rods: Headed	Anchor Rods: Threaded & Nutted
A108	—	65	0.375 to 0.75, incl.								■			
A325[d]	—	105	over 1 to 1.5 incl.	■										
A325[d]	—	120	0.5 to 1, incl.	■										
A490	—	150	0.5 to 1.5	■										
F1852	—	105	1.125		■									
F1852	—	120	0.5 to 1, incl.		■									
A194 Gr. 2H	—	—	0.25 to 4				■							
A563	—	—	0.25 to 4				■							
F436[b]	—	—	0.25 to 4					■						
F959	—	—	0.5 to 1.5						■					
A36	36	58-80	to 10							■		■		■
A193 Gr. B7[e]	—	100	over 4 to 7							■		■		■
A193 Gr. B7[e]	—	115	over 2.5 to 4							■		■		■
A193 Gr. B7[e]	—	125	2.5 and under							■		■		■
A307 Gr. A	—	60	0.25 to 4			■							■	
A307 Gr. C	—	58-80	0.25 to 4							■		■		■
A354 Gr. BD	—	140	2.5 to 4 incl.							■		■	■	■
A354 Gr. BD	—	150	0.25 to 2.5, incl.							■		■	■	■
A449	—	90	1.75 to 3 incl.	c						■		■	■	■
A449	—	105	1.125 to 1.5, incl.	c						■		■	■	■
A449	—	120	0.25 to 1, incl.	c						■		■	■	■
A572 Gr. 42	42	60	to 6							■		■		■
A572 Gr. 50	50	65	to 4							■		■		■
A572 Gr. 55	55	70	to 2							■		■		■
A572 Gr. 60	60	75	to 1.25							■		■		■
A572 Gr. 65	65	80	to 1.25							■		■		■
A588	42	63	Over 5 to 8, incl.							■		■		■
A588	46	67	Over 4 to 5, incl.							■		■		■
A588	50	70	4 and under							■		■		■
A687	105	150 max.	0.625 to 3							■		■		■
F1554 Gr. 36	36	58-80	0.25 to 4									■	■	■
F1554 Gr. 55	55	75-95	0.25 to 4									■	■	■
F1554 Gr. 105	105	125-150	0.25 to 3									■	■	■

■ = Preferred material specification.
▩ = Other applicable material specification, the availability of which should be confirmed prior to specification.
□ = Material specification does not apply.

— Indicates that a value is not specified in the material specification.
[a] Minimum unless a range is shown or maximum (max.) is indicated.
[b] Special washer requirements may apply per RCSC Specification Table 6.1 for some steel-to-steel bolting applications and per Part 14 for anchor-rod applications.
[c] See AISC Specification Section A3.3 for limitations on use of ASTM A449 bolts.
[d] When atmospheric corrosion resistance is desired, Type 3 can be specified.
[e] For anchor rods with temperature and corrosion resistance characteristics.

Figure 3.9 Applicable ASTM Specifications for Various Types of Structural Fasteners.

normal medium carbon bolt; and type 3, which is the same bolt, provided in a weathering steel. The tensile strength of these bolts is 120 ksi for bolts up to 1 in. diameter and 105 ksi for bolts with a $1^1/_8$ to $1^1/_2$ in. diameter.

A490 Bolts

A490 bolts are also a quenched and tempered steel-heavy hex structural bolt. These fasteners are used when a higher tensile strength is required. As with the A325 bolts, they are available as type 1 or type 3 with the same distinction. The minimum tensile strength for bolts with diameters from $\frac{1}{2}$ to $1\frac{1}{2}$ in. diameter is 150 ksi.

F1852 Bolts

F1852 provides the standard specification for "twist-off" tension control bolt-nut-washer assemblies. These structural fasteners are unique in that they do not have a hex head but rather a splined shank that permits installation through the use of a special torque wrench. These connectors are essentially A325 bolts but must be manufactured to a separate standard because their geometric characteristics differ from normal bolts. The tensile strength of these fasteners is 120 ksi for diameters of $\frac{1}{2}$ to 1 in. inclusive and 105 ksi for $1^1/_8$ in.

3.6.4 Steel for Welding

Steel used for welding is callled *filler metal* because it essentially fills in the gap between the base metal pieces that it is joining. The most critical aspect of selecting filler metal, actually the welding electrode, is matching the welding electrode with the base metal. In all cases, the weld must not be the weak part of the joint. The American Welding Society provides the specification for appropriate matching of the base metal and electrode in Table 3.1 of their standard, ANSI/AWS D1.1. The most commonly used weld strength is 70 ksi. A discussion of welding processes and material matching is presented in Chapter 10.

3.6.5 Steel for Shear Studs

Shear studs are mechanical fasteners welded to structural shapes and embedded in concrete that permit steel and concrete to work together. This is called *composite construction*. Because these studs are welded to the steel shape, their properties are specified jointly between AWS and ASTM. ANSI/AWS D1.1 specifies that Type B shear stud connectors made from ASTM A108 material be used. These studs have a tensile strength of 65 ksi.

3.7 AVAILABILITY OF STRUCTURAL STEEL

Structural engineers normally use the list of shapes found in the Manual as the basis for design. Unfortunately, all shapes are not equally available in the marketplace and the selection of difficult shapes to obtain could negatively impact the overall cost of a project. For instance, some shapes are available from a wide variety of producers, such as a W10×30, which can be obtained from eight different foreign and domestic mills as of January 2006. However, the largest shapes like the W44×335 are available only from one offshore mill. Also, several of the smaller M-shapes are not rolled by any mill. In order to judge availability of shapes from the 12 mills identified, the annual January issue of *Modern Steel Construction* should be consulted. Shape availability data is also maintained by the mills on the AISC Web site at www.asic.org/steelavailability.

Another important source of steel are the service centers. These organizations obtain steel directly from the mills and stock the full range of shapes. Although obtaining the steel needed for any given project falls to the steel fabricator, it is always beneficial to the engineer to have some knowledge of availability.

3.8 PROBLEMS

1. When was the first AISC Specification published and what was its purpose?

2. In addition to buildings, what other types of structures are included in the scope of the 2005 AISC Specification?

3. Sketch and label a typical stress-strain curve for steel subjected to a simple uniaxial tension test.

4. What is the value of the Modulus of Elasticity used for calculations according to the AISC Specification, and what does this value represent in relation to the graph of stress versus strain for steel?

5. What happens to a steel element when it is loaded beyond the elastic limit and then unloaded?

6. Describe the difference between the yield stress and ultimate stress of a steel element.

7. Sketch and label 10 different structural shape cross sections whose properties are given in the AISC Specification.

8. What is the nominal and actual depth of a W36×135 wide flange member? What is the weight of this member per linear foot? (Hint: use your AISC Manual.)

9. What is the weight per linear foot of a L5×3×$^1/_2$ member? (Hint: Use your AISC Manual.)

10. What is the outside diameter and wall thickness of a Pipe 4 xx-Strong? (Hint: Use your AISC Manual.)

11. What is the difference between a rectangular bar section and a plate?

12. What are the three types of steel used for shapes in the construction industry?

13. What effects does the addition of carbon have on steel?

14. Name three elements that help to improve the corrosion resistance of steel.

15. What grade of steel is most commonly used today in the production of W-shapes and what is its yield stress and tensile stress?

16. What grade of steel is preferred for the fabrication of most structural shapes other than W-shapes, and what is its yield stress and tensile stress? (Hint: see Figure 3.7.)

17. What grade of steel is typically used for high-strength bolts used in construction?

18. What resources can be consulted to determine the availability of a particular steel structural shape?