11

STEEL FRAME CONSTRUCTION

Ironworkers place open-web steel joists on a frame of steel wide-flange beams as a crane lowers bundles of joists from above. *(Photo by Balthazar Korab. Courtesy Vulcraft Division of Nucor)*

Steel, strong and stiff, is a material of slender towers and soaring spans. Precise and predictable, light in proportion to its strength, it is also well suited to rapid construction, highly repetitive building frames, and architectural details that satisfy the eye with a clean, precise elegance. Among the metals, it is uniquely plentiful and inexpensive. If its weaknesses—a tendency to corrode in certain environments and a loss of strength during severe building fires—are held in check by intelligent construction measures, it offers the designer possibilities that exist with no other material.

HISTORY

Prior to the beginning of the 19th century, metals had little structural role in buildings except in connecting devices. The Greeks and Romans used hidden cramps of bronze to join blocks of stone, and architects of the Renaissance countered the thrust of masonry vaults with wrought iron chains and rods. The first all-metal structure, a cast iron bridge, was built in the late 18th century in England and still carries traffic across the Severn River more than two centuries after its construction. Cast iron, produced from iron ore in a blast furnace, and wrought iron, iron that has been purified by beating it repeatedly with a hammer, were used increasingly for framing industrial buildings in Europe and North America in the first half of the 19th century, but their usefulness was limited by the unpredictable brittleness of cast iron and the relatively high cost of wrought iron.

Until that time, steel had been a rare and expensive material,

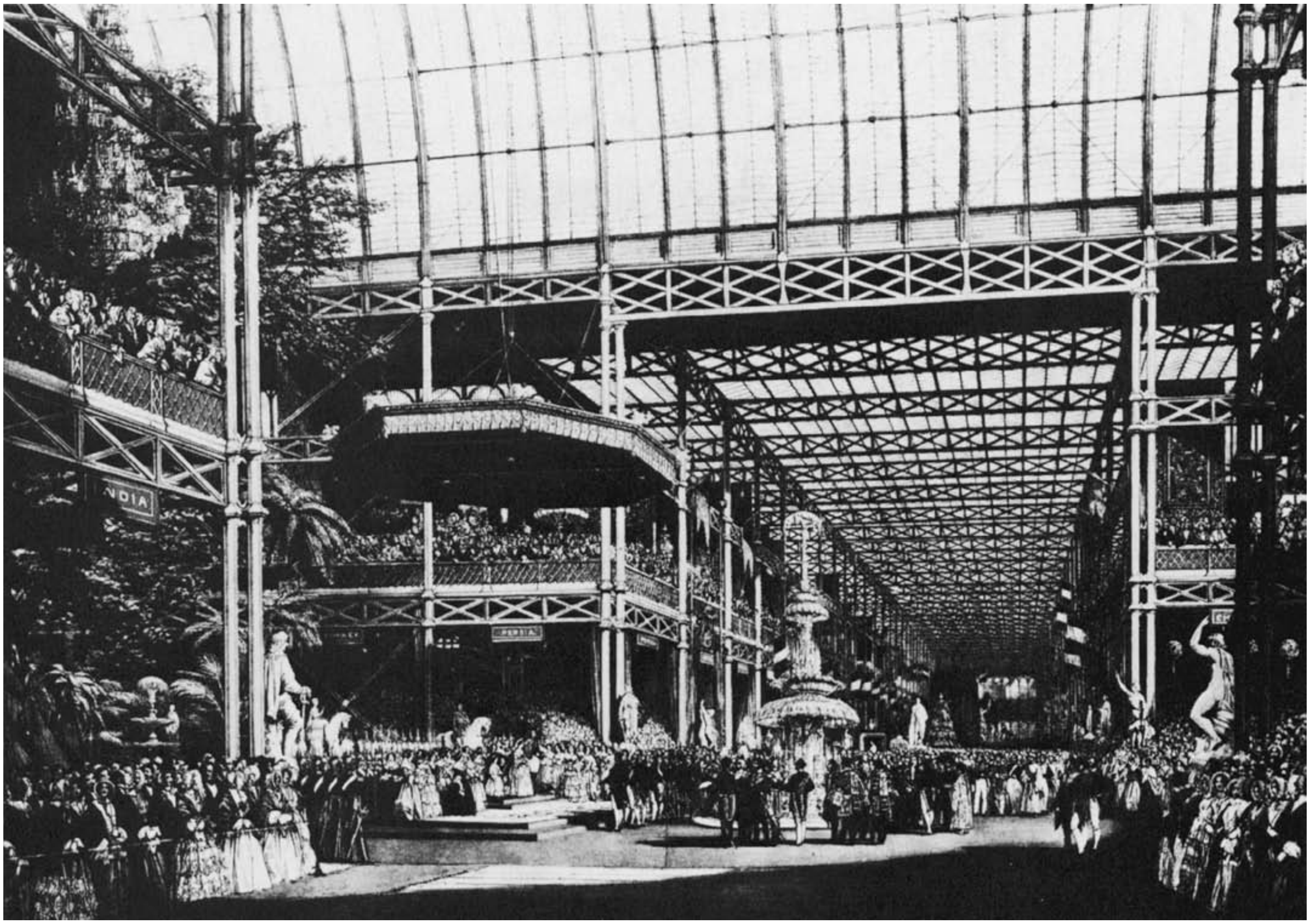

FIGURE 11.1
Landscape architect Joseph Paxton designed the Crystal Palace, an exposition hall of cast iron and glass, which was built in London in 1851. *(Bettmann Archive)*

FIGURE 11.2
Allied Bank Plaza, designed by Architects Skidmore, Owings, and Merrill. *(Permission of American Institute of Steel Construction)*


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produced only in small batches for such applications as weapons and cutlery. Plentiful, inexpensive steel first became available in the 1850s with the introduction of the *Bessemer process*, in which air was blown into a vessel of molten iron to burn out the impurities. By this means, a large batch of iron could be made into steel in about 20 minutes, and the structural properties of the resulting metal were vastly superior to those of cast iron. Another economical steelmaking process, the *open-hearth method*, was developed in Europe in 1868 and was soon adopted in America. By 1889, when the Eiffel Tower was built of wrought iron in Paris (Figure 11.3), several steel frame skyscrapers had already been erected in the United States (Figure 11.4). A new material of construction had been born.

THE MATERIAL STEEL

Steel

Steel is any of a range of alloys of iron that contain less than 2 percent carbon. Ordinary structural steel, called *mild steel*, contains less than three-tenths of 1 percent carbon, plus traces of beneficial elements such as manganese and silicon, and of detrimental impurities such as phosphorus, sulfur, oxygen, and nitrogen. In contrast, ordinary *cast iron* contains 3 to 4 percent carbon and greater quantities of impurities than steel, while *wrought iron* contains even less carbon than most steel alloys. Carbon content is a crucial determinant of the properties of any *ferrous* (iron-based) *metal*: Too much carbon makes a hard but brittle metal (like cast iron), while too little produces a malleable, relatively weak material (like wrought iron). Thus, mild steel is iron whose properties

FIGURE 11.3

Engineer Gustave Eiffel's magnificent tower of wrought iron was constructed in Paris from 1887 to 1889. *(Photo by James Austin, Cambridge, England)*

> **The gap between stone and steel-and-glass was as great as that in the evolutionary order between the crustaceans and the vertebrates.**
>
> **Lewis Mumford, *The Brown Decades,* New York, Dover Publications, Inc., 1955, pp. 130–131.**

have been optimized for structural purposes by controlling the amounts of carbon and other elements in the metal.

The process of converting iron ore to steel begins with the smelting of ore into cast iron. Cast iron is produced in a blast furnace charged with alternating layers of *iron ore* (oxides of iron), *coke* (coal whose volatile constituents have been distilled out, leaving only carbon), and crushed limestone (Figure 11.6). The coke is burned by large quantities of air forced into the bottom of the furnace to produce carbon monoxide, which reacts with the ore to reduce it to elemental iron. The limestone forms a slag with various impurities, but large amounts of carbon and other elements are inevitably incorporated into the iron. The molten iron is drawn off at the bottom of the furnace and held in a liquid state for processing into steel.

Most steel that is converted from iron is manufactured by the *basic oxygen process* (Figure 11.5), in which a hollow, water-cooled lance is lowered into a container of molten iron and recycled steel scrap. A stream of pure oxygen at very high pressure is blown from the lance into the metal to burn off the excess carbon and impurities. A flux of lime and fluorspar is added to the metal to react with other impurities, particularly phosphorus, and forms a slag that is discarded. New metallic elements may be added to the container at the end of the process to adjust the composition of the steel as desired: Manganese gives resistance to abrasion and impact, molybdenum gives strength, vanadium imparts strength and toughness, and nickel and chromium give corrosion resistance, toughness, and stiffness. The entire process takes place with the aid of careful sampling and laboratory analysis techniques to ensure the finished quality of the steel and takes less than an hour from start to finish.

Today, most structural steel for frames of buildings is produced from scrap steel in so-called mini-mills, utilizing *electric arc furnaces.* These mills are miniature only in comparison to the conventional mills that they have replaced; they are housed in enormous buildings and roll structural shapes up to 40 inches (1 m) deep. The scrap from which structural steel is made comes mostly from defunct automobiles, one mini-mill alone consuming 300,000 junk cars in an average year. Through careful metallurgical testing and control, these are recycled into top-quality steel.

FIGURE 11.4
The Home Insurance Company Building, designed by William LeBaron Jenney and built in Chicago in 1893, was among the earliest true skyscrapers. The steel framing was fireproofed with masonry, and the exterior masonry facings were supported on the steel frame. *(Photo by Wm. T. Barnum. Courtesy of Chicago Historical Society ICHi-18293)*

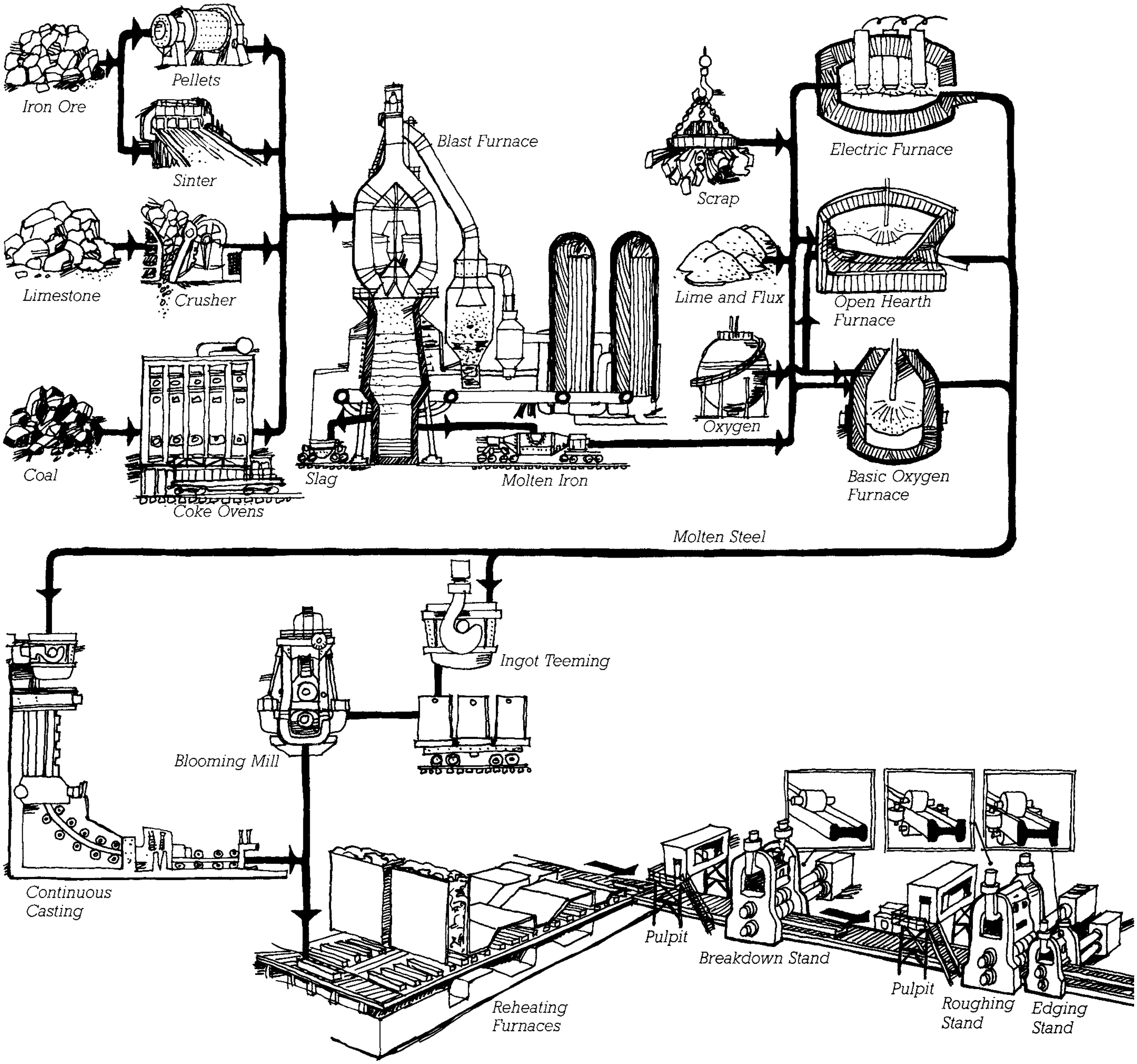


FIGURE 11.5
The steelmaking process, from iron ore to structural shapes. Notice particularly the steps in the evolution of a wide-flange shape as it progresses through the various stands in the rolling mill. Today, most structural steel in the United States is made from steel scrap in electric furnaces. *(Adapted from "Steelmaking Flowlines," by permission of the American Iron and Steel Institute)*

For Preliminary Design of a Steel Structure

Estimate the depth of **corrugated steel roof decking** at $\frac{1}{40}$ of its span. Standard depths are 1, 1½, 2, and 4 inches (25, 38, 50, and 100 mm).

Estimate the overall depth of **corrugated steel floor decking plus concrete topping** at $\frac{1}{24}$ of its span. Typical overall depths range from 2½ to 7 inches (65–180 mm).

Estimate the depth of **open-web steel joists** at $\frac{1}{20}$ of their span for heavily loaded floors or widely spaced joists and at $\frac{1}{24}$ of their span for roofs, lightly loaded floors, or closely spaced joists. The spacing of joists depends on the spanning capability of the decking material. Typical joist spacings range from 2 to 10 feet (0.6–3.0 m). Standard joist depths are given elsewhere in this chapter.

Estimate the depth of **steel beams** at $\frac{1}{20}$ of their span and the depth of **steel girders** at $\frac{1}{15}$ of their span. The width of a beam or girder is usually $\frac{1}{3}$ to $\frac{1}{2}$ of its depth. For composite beams and girders, use the same ratios but apply them to the overall depth of the beam or girder, including the floor deck and concrete topping. Standard depths of steel wide-flange shapes are given elsewhere in this chapter.

Estimate the depth of **triangular steel roof trusses** at $\frac{1}{4}$ to $\frac{1}{5}$ of their span. For rectangular trusses, the depth is typically $\frac{1}{8}$ to $\frac{1}{12}$ of their span.

To estimate the size of a **steel column**, add up the total roof and floor area supported by the column. A W8 column can support up to about 4000 square feet (370 m^2) and a W14 column 30,000 square feet (2800 m^2). Very heavy W14 shapes, which are substantially larger than 14 inches (355 mm) in dimension, can support up to 50,000–100,000 square feet (4600–9300 m^2). Steel column shapes are usually square or nearly square in proportion.

These approximations are valid only for purposes of preliminary building layout and must not be used to select final member sizes. They apply to the normal range of building occupancies such as residential, office, commercial, and institutional buildings and parking garages. For manufacturing and storage buildings, use somewhat larger members.

For more comprehensive information on preliminary selection and layout of a structural system and sizing of structural members, see Edward Allen and Joseph Iano, *The Architect's Studio Companion* (4th ed.), New York, John Wiley & Sons, Inc., 2007.

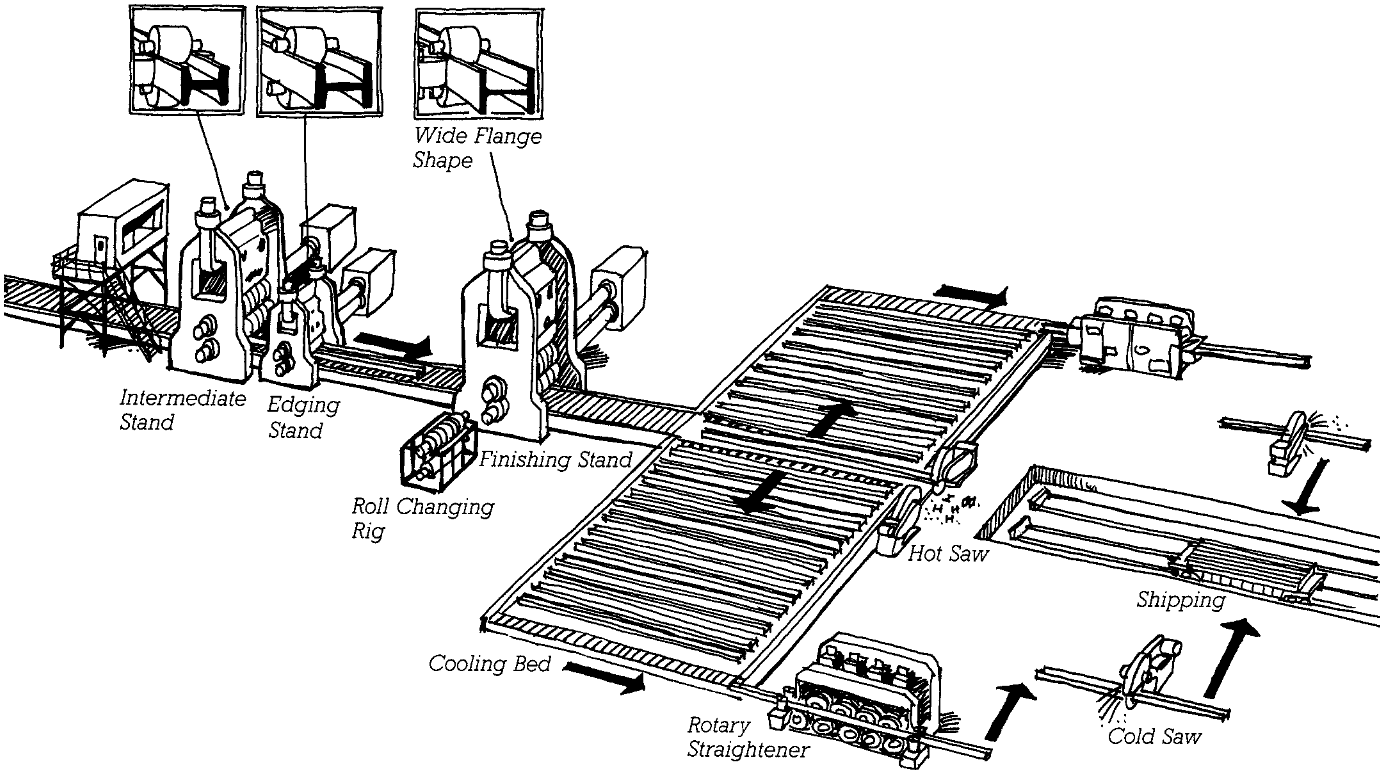


FIGURE 11.6
Molten iron is poured into a crucible to begin its conversion to steel in the basic oxygen process. *(Courtesy of U.S. Steel Corp.)*

Regardless of the particular steelmaking process, finished steel is cast continuously into *beam blanks* or *blooms*, very thick approximations of the desired final shape, which are then rolled into final form, as described later in this chapter.

Steel Alloys

By adjusting the mix of metallic elements used in the production of steel, its strength and other properties can be manipulated. Mild structural steel, known by its ASTM designation of A36, was for decades the predominant steel type used in building frames. But today's mini-mills, using scrap as their primary raw material, routinely produce stronger, less expensive *high-strength, low-alloy steels,* such as those designated ASTM A992 or ASTM A572. ASTM A992 steel is the preferred steel type for standard wide-flange structural shapes, while ASTM A36 steel, or, where higher strength is needed, ASTM A572 steel, are specified for angles, channels, plates, and bars. (For an explanation of standard steel shapes, see the discussion below.)

Where steel without any protective finish will remain exposed to exterior conditions in the completed construction, *weathering steel* (ASTM A588) may be specified. This steel alloy develops a tenacious oxide coating when exposed to the atmosphere that, once formed, protects against further corrosion and eliminates the need for paint or another protective coating. While mostly used for highway and bridge construction where it reduces maintenance costs, weathering steel also finds occasional use in buildings, where the deep, warm hue of the oxide coating can be exploited as an aesthetic feature. With the addition of nickel and chromium to steel, various grades of *stainless steel* (ASTM A240 and A276) with even greater corrosion resistance and costing significantly more than conventional structural steel, can be produced. Steel can also be protected from corrosion by galvanizing, the application of a zinc coating, which is discussed further on pages 507–508.

Production of Structural Shapes

In the *structural mill* or *breakdown mill,* the beam blank is reheated as necessary and then passed through a succession of rollers that squeeze the metal into progressively more refined approximations of the desired shape and size (Figure 11.7). The finished shape exits from the last set of rollers as a continuous length that is cut into shorter segments by a *hot saw* (Figure 11.8). These segments are cooled on a *cooling bed* (Figure 11.9). Then a *roller straightener* corrects any residual crookedness. Finally, each piece is cut to length and labeled with its shape designation and the number of the batch of steel from which it was rolled. Later, when the

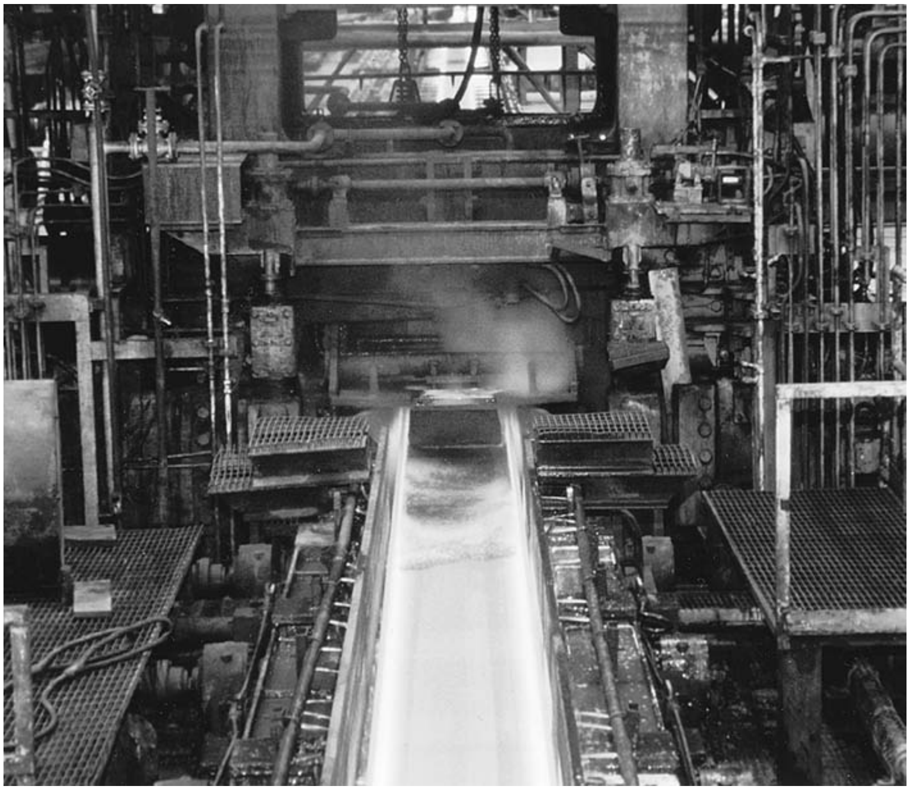


FIGURE 11.7
A glowing steel wide-flange shape emerges from the rolls of the finishing stand of the rolling mill. *(Photo by Mike Engestrom. Courtesy of Nucor-Yamato Steel Company)*

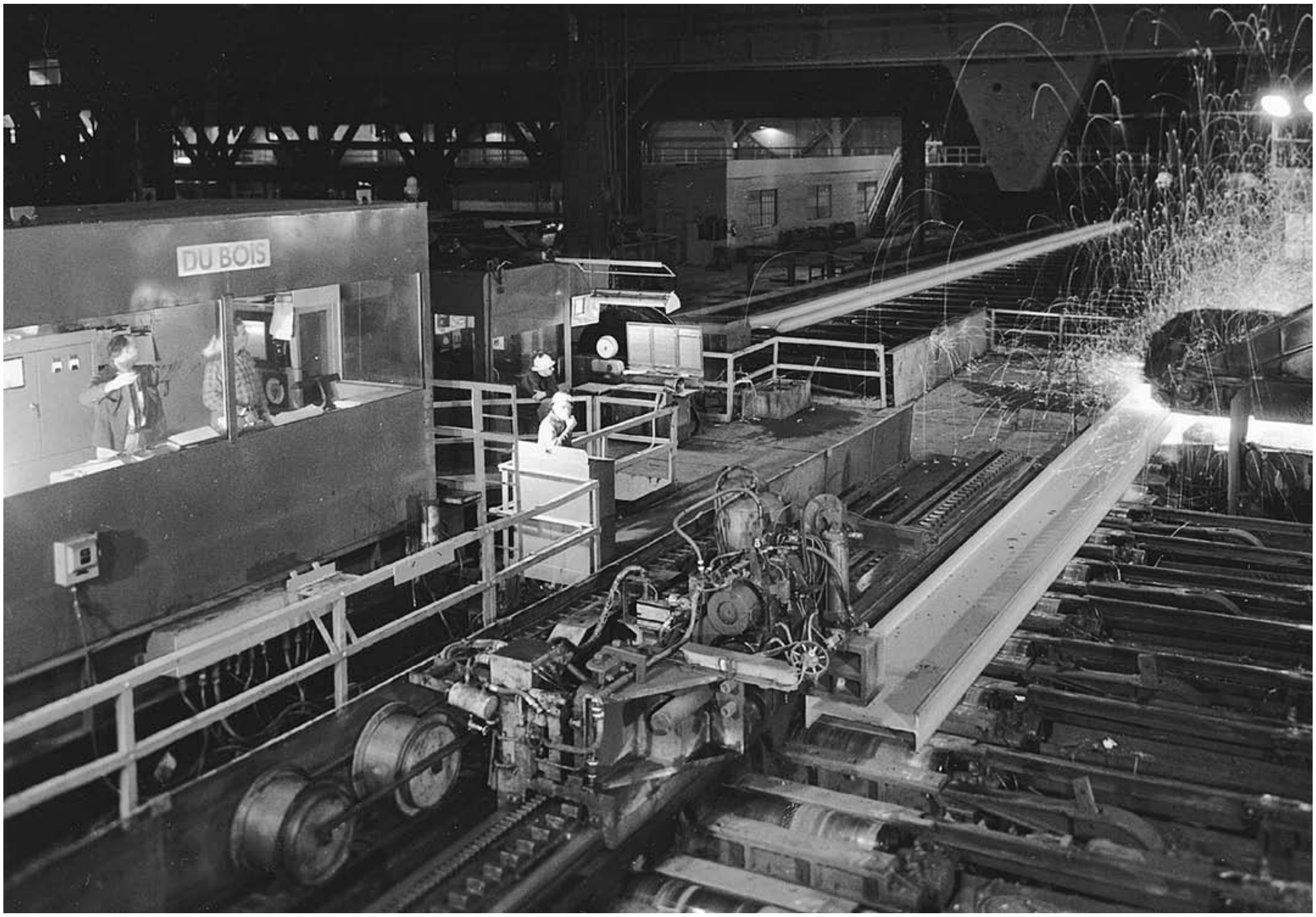


Figure 11.8
A hot saw cuts pieces of wide-flange stock from a continuous length that has just emerged from the finishing stand in the background. Workers in the booth control the process. *(Courtesy of U.S. Steel Corp.)*

Figure 11.9
Wide-flange shapes are inspected for quality on the cooling bed. *(Photo by Mike Engestrom. Courtesy of Nucor-Yamato Steel Company)*

piece is shipped to a fabricator, it will be accompanied by a certificate that gives the chemical analysis of that particular batch, as evidence that the steel meets standard structural specifications.

The roller spacings in the structural mill are adjustable; by varying the spacings between rollers, a number of different shapes with the same nominal dimensions can be produced (Figure 11.10). This provides the architect and the structural engineer with a finely graduated selection of shapes from which to select each structural member in a building, thereby avoiding the waste of steel through the specification of shapes that are larger than required.

Wide-flange shapes are used for most beams and columns, superseding the older *American Standard (I-beam)* shapes (Figure 11.11). American Standard shapes are less efficient structurally than wide flanges because the roller arrangement that produces them is incapable of increasing the amount of steel

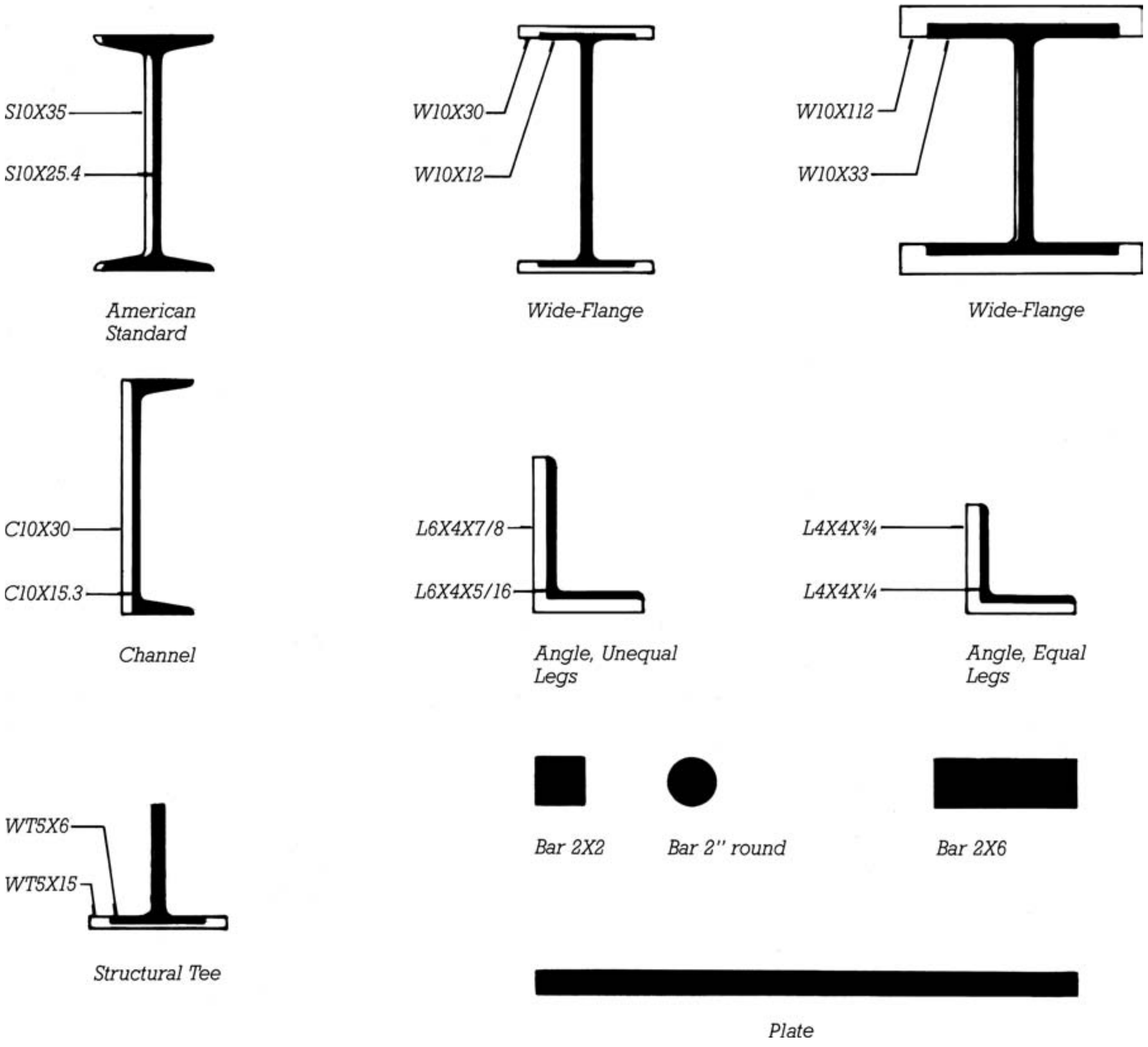


Figure 11.10

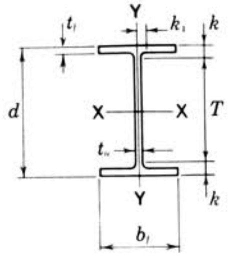
Examples of the standard shapes of structural steel. Where two shapes are superimposed, they illustrate different weights of the same section, produced by varying the spacing of the rollers in the structural mill. Structural steel shapes and their general requirements are defined in ASTM A6. *Bars* are round, rectangular, and hexagonal solid shapes generally not greater than 8 inches (203 mm) in any cross-sectional dimension. Wider solid shapes are called *plate* or *sheet*, depending on their thickness in relation to their width. Plate is thicker than sheet.

in the flanges without also adding steel to the web, where it does little to increase the load-carrying capacity of the member. Wide flanges are available in a vast range of sizes and weights. The smallest available depth in the United States is nominally 4 inches (100 mm), and the largest is 44 inches (1117 mm). Weights per linear foot of member range from 9 to 730 pounds (13–1080 kg/m), the latter for a nominal 14-inch (360-mm) shape with flanges nearly 5 inches (130 mm) thick. Some producers construct heavier wide-flange sections by welding together flange and web plates rather than rolling, a procedure that is also used for producing very deep, long-span plate girders (Figure 11.79).

Wide flanges are manufactured in two basic proportions: tall and narrow for beams and squarish for columns and foundation piles. The accepted nomenclature for wide-flange shapes begins with the letter W, followed by the nominal depth of

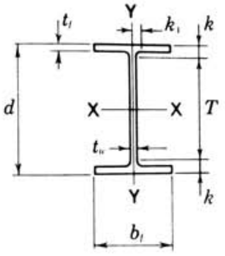
Shape	Sample Designation	Explanation	Range of Available Sizes
Wide-flange	W21 × 83	W denotes a wide-flange shape. The first number is the nominal depth in inches and the second number is the weight in pounds per foot of length.	Nominal depths from 4 to 18″ in 2″ increments, from 18 to 36″ in 3″ increments, and from 36 to 44″ in 4″ increments.
American Standard beam	S18 × 70	S denotes an American Standard beam. The first number is the nominal depth in inches, and the second number is the weight in pounds per foot of length.	Nominal depths of 3″, 4″, 5″, 6″, 8″, 10″, 12″, 15″, 18″, 20″, and 24″
Channel	MC10 × 33.6	MC denotes a channel. The first number is the nominal depth in inches, and the second number is the weight in pounds per foot of length.	Nominal depths of 6″, 7″, 8″, 9″, 10″, 12″, 13″, and 18″.
American Standard channel	C6 × 13	C denotes an American Standard channel. The first number is the nominal depth in inches, and the second number is the weight in pounds per foot of length.	Nominal depths of 3″, 4″, 5″, 6″, 7″, 8″, 9″, 10″, 12″, and 15″.
Structural tee	WT13.5 × 47	WT denotes a tee made by splitting a W shape. The first number is the nominal depth in inches, and the second number is the weight in pounds per foot. (The example tee listed here was made from a W27 × 94.) Tees split from American Standard beams are designated ST rather than WT.	See the available sizes of wide-flange and American Standard beams listed above, and divide by 2 to arrive at available depths for structural tees made from these shapes.
Angle	L4 × 3 × ⅜	L denotes an angle. The first two numbers are the nominal depths in inches of the two legs, and the last number is the thickness in inches of the legs.	Leg depths of 2″, 2½″, 3″, 3½″, 4″, 5″, 6″, 7″, and 8″. Leg thicknesses from ⅛″ to 11⁄8″.
HSS Square, Rectangular, Round, or Elliptical	HSS10 × 8 × ½	HSS denotes a hollow structural section. The first two numbers are the nominal size in inches of the two sides of a square, rectangular, or elliptical shape. For round tubes, a single number indicates nominal diameter. The last number is the thickness in inches of the wall of the tube.	For square or rectangular shapes, nominal depths from 1″ to 48″ and wall thickness from ⅛″ to ⅝″. For round shapes, nominal diameters from 1.66 to 20″ and wall thicknesses from 0.109 to 0.625″.

FIGURE 11.11
Commonly used steel shapes.



W SHAPES
Dimensions

Designation	Area A	Depth d		Web			Flange				Distance		
				Thickness t_w		$\frac{t_w}{2}$	Width b_f		Thickness t_f		T	k	k_1
	In.^{2}	In.		In.		In.	In.		In.		In.	In.	In.
W 12x336	98.8	16.82	16 7/8	1.775	1 3/4	7/8	13.385	13 3/8	2.955	2 15/16	9 1/2	3 11/16	1 1/2
x305	89.6	16.32	16 3/8	1.625	1 5/8	13/16	13.235	13 1/4	2.705	2 11/16	9 1/2	3 7/16	1 7/16
x279	81.9	15.85	15 7/8	1.530	1 1/2	3/4	13.140	13 1/8	2.470	2 1/2	9 1/2	3 3/16	1 3/8
x252	74.1	15.41	15 3/8	1.395	1 3/8	11/16	13.005	13	2.250	2 1/4	9 1/2	2 15/16	1 5/16
x230	67.7	15.05	15	1.285	1 5/16	11/16	12.895	12 7/8	2.070	2 1/16	9 1/2	2 3/4	1 1/4
x210	61.8	14.71	14 3/4	1.180	1 3/16	5/8	12.790	12 3/4	1.900	1 7/8	9 1/2	2 5/8	1 1/4
x190	55.8	14.38	14 3/8	1.060	1 1/16	9/16	12.670	12 5/8	1.735	1 3/4	9 1/2	2 7/16	1 3/16
x170	50.0	14.03	14	0.960	15/16	1/2	12.570	12 5/8	1.560	1 9/16	9 1/2	2 1/4	1 1/8
x152	44.7	13.71	13 3/4	0.870	7/8	7/16	12.480	12 1/2	1.400	1 3/8	9 1/2	2 1/8	1 1/16
x136	39.9	13.41	13 3/8	0.790	13/16	7/16	12.400	12 3/8	1.250	1 1/4	9 1/2	1 15/16	1
x120	35.3	13.12	13 1/8	0.710	11/16	3/8	12.320	12 3/8	1.105	1 1/8	9 1/2	1 13/16	1
x106	31.2	12.89	12 7/8	0.610	5/8	5/16	12.220	12 1/4	0.990	1	9 1/2	1 11/16	15/16
x 96	28.2	12.71	12 3/4	0.550	9/16	5/16	12.160	12 1/8	0.900	7/8	9 1/2	1 5/8	7/8
x 87	25.6	12.53	12 1/2	0.515	1/2	1/4	12.125	12 1/8	0.810	13/16	9 1/2	1 1/2	7/8
x 79	23.2	12.38	12 3/8	0.470	1/2	1/4	12.080	12 1/8	0.735	3/4	9 1/2	1 7/16	7/8
x 72	21.1	12.25	12 1/4	0.430	7/16	1/4	12.040	12	0.670	11/16	9 1/2	1 3/8	7/8
x 65	19.1	12.12	12 1/8	0.390	3/8	3/16	12.000	12	0.605	5/8	9 1/2	1 5/16	13/16
W 12x 58	17.0	12.19	12 1/4	0.360	3/8	3/16	10.010	10	0.640	5/8	9 1/2	1 3/8	13/16
x 53	15.6	12.06	12	0.345	3/8	3/16	9.995	10	0.575	9/16	9 1/2	1 1/4	13/16
W 12x 50	14.7	12.19	12 1/4	0.370	3/8	3/16	8.080	8 1/8	0.640	5/8	9 1/2	1 3/8	13/16
x 45	13.2	12.06	12	0.335	5/16	3/16	8.045	8	0.575	9/16	9 1/2	1 1/4	13/16
x 40	11.8	11.94	12	0.295	5/16	3/16	8.005	8	0.515	1/2	9 1/2	1 1/4	3/4
W 12x 35	10.3	12.50	12 1/2	0.300	5/16	3/16	6.560	6 1/2	0.520	1/2	10 1/2	1	9/16
x 30	8.79	12.34	12 3/8	0.260	1/4	1/8	6.520	6 1/2	0.440	7/16	10 1/2	15/16	1/2
x 26	7.65	12.22	12 1/4	0.230	1/4	1/8	6.490	6 1/2	0.380	3/8	10 1/2	7/8	1/2
W 12x 22	6.48	12.31	12 1/4	0.260	1/4	1/8	4.030	4	0.425	7/16	10 1/2	7/8	1/2
x 19	5.57	12.16	12 1/8	0.235	1/4	1/8	4.005	4	0.350	3/8	10 1/2	13/16	1/2
x 16	4.71	11.99	12	0.220	1/4	1/8	3.990	4	0.265	1/4	10 1/2	3/4	1/2
x 14	4.16	11.91	11 7/8	0.200	3/16	1/8	3.970	4	0.225	1/4	10 1/2	11/16	1/2



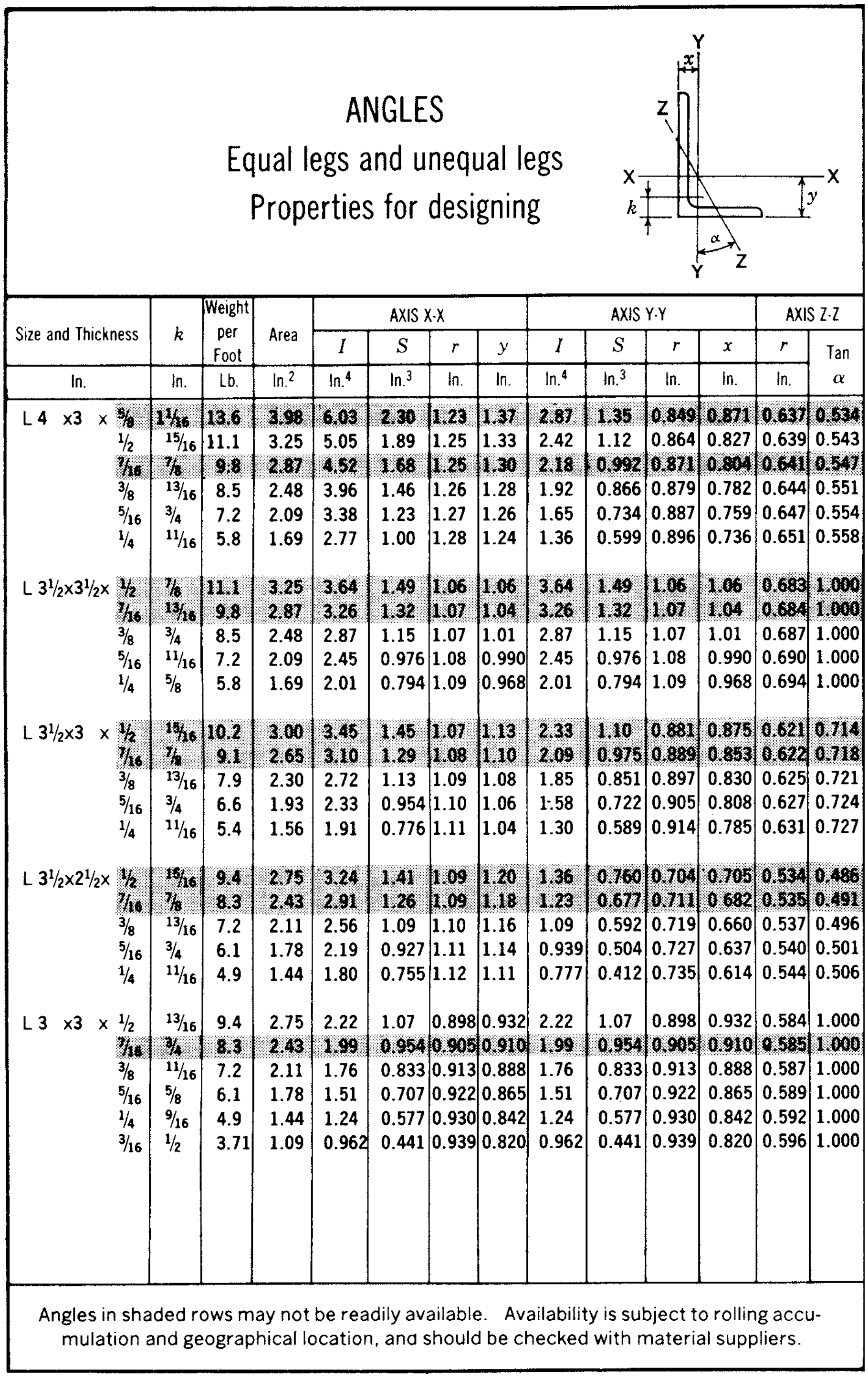
W SHAPES
Properties

Nom-inal Wt. per Ft.	Compact Section Criteria				r_T	$\frac{d}{A_f}$	Elastic Properties						Tor-sional con-stant J	Plastic Modulus	
							Axis X-X			Axis Y-Y					
	$\frac{b_f}{2t_f}$	F_y'	$\frac{d}{t_w}$	F_y'''			I	S	r	I	S	r		Z_x	Z_y
Lb.		Ksi		Ksi	In.		In.^{4}	In.^{3}	In.	In.^{4}	In.^{3}	In.	In.^{4}	In.^{3}	In.^{3}
336	2.3	—	9.5	—	3.71	0.43	4060	483	6.41	1190	177	3.47	243	603	274
305	2.4	—	10.0	—	3.67	0.46	3550	435	6.29	1050	159	3.42	185	537	244
279	2.7	—	10.4	—	3.64	0.49	3110	393	6.16	937	143	3.38	143	481	220
252	2.9	—	11.0	—	3.59	0.53	2720	353	6.06	828	127	3.34	108	428	196
230	3.1	—	11.7	—	3.56	0.56	2420	321	5.97	742	115	3.31	83.8	386	177
210	3.4	—	12.5	—	3.53	0.61	2140	292	5.89	664	104	3.28	64.7	348	159
190	3.7	—	13.6	—	3.50	0.65	1890	263	5.82	589	93.0	3.25	48.8	311	143
170	4.0	—	14.6	—	3.47	0.72	1650	235	5.74	517	82.3	3.22	35.6	275	126
152	4.5	—	15.8	—	3.44	0.79	1430	209	5.66	454	72.8	3.19	25.8	243	111
136	5.0	—	17.0	—	3.41	0.87	1240	186	5.58	398	64.2	3.16	18.5	214	98.0
120	5.6	—	18.5	—	3.38	0.96	1070	163	5.51	345	56.0	3.13	12.9	186	85.4
106	6.2	—	21.1	—	3.36	1.07	933	145	5.47	301	49.3	3.11	9.13	164	75.1
96	6.8	—	23.1	—	3.34	1.16	833	131	5.44	270	44.4	3.09	6.86	147	67.5
87	7.5	—	24.3	—	3.32	1.28	740	118	5.38	241	39.7	3.07	5.10	132	60.4
79	8.2	62.6	26.3	—	3.31	1.39	662	107	5.34	216	35.8	3.05	3.84	119	54.3
72	9.0	52.3	28.5	—	3.29	1.52	597	97.4	5.31	195	32.4	3.04	2.93	108	49.2
65	9.9	43.0	31.1	—	3.28	1.67	533	87.9	5.28	174	29.1	3.02	2.18	96.8	44.1
58	7.8	—	33.9	57.6	2.72	1.90	475	78.0	5.28	107	21.4	2.51	2.10	86.4	32.5
53	8.7	55.9	35.0	54.1	2.71	2.10	425	70.6	5.23	95.8	19.2	2.48	1.58	77.9	29.1
50	6.3	—	32.9	60.9	2.17	2.36	394	64.7	5.18	56.3	13.9	1.96	1.78	72.4	21.4
45	7.0	—	36.0	51.0	2.15	2.61	350	58.1	5.15	50.0	12.4	1.94	1.31	64.7	19.0
40	7.8	—	40.5	40.3	2.14	2.90	310	51.9	5.13	44.1	11.0	1.93	0.95	57.5	16.8
35	6.3	—	41.7	38.0	1.74	3.66	285	45.6	5.25	24.5	7.47	1.54	0.74	51.2	11.5
30	7.4	—	47.5	29.3	1.73	4.30	238	38.6	5.21	20.3	6.24	1.52	0.46	43.1	9.56
26	8.5	57.9	53.1	23.4	1.72	4.95	204	33.4	5.17	17.3	5.34	1.51	0.30	37.2	8.17
22	4.7	—	47.3	29.5	1.02	7.19	156	25.4	4.91	4.66	2.31	0.847	0.29	29.3	3.66
19	5.7	—	51.7	24.7	1.00	8.67	130	21.3	4.82	3.76	1.88	0.822	0.18	24.7	2.98
16	7.5	—	54.5	22.2	0.96	11.3	103	17.1	4.67	2.82	1.41	0.773	0.10	20.1	2.26
14	8.8	54.3	59.6	18.6	0.95	13.3	88.6	14.9	4.62	2.36	1.19	0.753	0.07	17.4	1.90

FIGURE 11.12
A portion of the table of dimensions and properties of wide-flange shapes from the *Manual of Steel Construction* of the American Institute of Steel Construction. One inch equals 25.4 mm. *(By permission of American Institute of Steel Construction)*

the shape in inches, a multiplication sign, and the weight of the shape in pounds per foot. Thus, a W12 × 26 is a wide-flange shape nominally 12 inches (305 mm) deep that weighs 26 pounds per foot of length (38.5 kg/m). More information about this shape is contained in a table of dimensions and properties in the *Manual of Steel Construction* published by the American Institute of Steel Construction (Figure 11.12): Its actual depth is 12.22 inches (310.4 mm), and its flanges are 6.49 inches (164.9 mm) wide. These proportions indicate that the shape is intended mainly for use as a beam or girder and not as a column or foundation pile. Reading across the table column by column, the designer can learn everything there is to know about this section, from its thicknesses and the radii of its fillets to various quantities that are useful in computing its structural behavior under load. At the upper end of the portion of the table dealing with 12-inch (305-mm)-wide flanges, we find shapes weighing up to 336 pounds per foot (501 kg/m), with actual depths of almost 17 inches (432 mm). These heavier shapes have flanges nearly as wide as the shapes are deep, suggesting that they are intended for use as columns. U.S. producers manufacture steel shapes only in conventional units of measurement, inches and pounds. In other parts of the world, a standard range of metric sizes is used. The United States has adopted a soft conversion to metric sizes, merely tabulating metric dimensions for shapes that are produced in conventional units.

Steel *angles* (Figure 11.13) are extremely versatile. They can be used for very short beams supporting small



ANGLES
Equal legs and unequal legs
Properties for designing

Size and Thickness	k	Weight per Foot	Area	AXIS X-X				AXIS Y-Y				AXIS Z-Z	
				I	*S*	*r*	*y*	*I*	*S*	*r*	*x*	*r*	Tan
In.	In.	Lb.	In.^{2}	In.^{4}	In.^{3}	In.	In.	In.^{4}	In.^{3}	In.	In.	In.	α
L 4 x3 x 5/8	1 1/16	13.6	3.98	6.03	2.30	1.23	1.37	2.87	1.35	0.849	0.871	0.637	0.534
1/2	15/16	11.1	3.25	5.05	1.89	1.25	1.33	2.42	1.12	0.864	0.827	0.639	0.543
7/16	7/8	9.8	2.87	4.52	1.68	1.25	1.30	2.18	0.992	0.871	0.804	0.641	0.547
3/8	13/16	8.5	2.48	3.96	1.46	1.26	1.28	1.92	0.866	0.879	0.782	0.644	0.551
5/16	3/4	7.2	2.09	3.38	1.23	1.27	1.26	1.65	0.734	0.887	0.759	0.647	0.554
1/4	11/16	5.8	1.69	2.77	1.00	1.28	1.24	1.36	0.599	0.896	0.736	0.651	0.558
L 3 1/2x3 1/2x 1/2	7/8	11.1	3.25	3.64	1.49	1.06	1.06	3.64	1.49	1.06	1.06	0.683	1.000
7/16	13/16	9.8	2.87	3.26	1.32	1.07	1.04	3.26	1.32	1.07	1.04	0.684	1.000
3/8	3/4	8.5	2.48	2.87	1.15	1.07	1.01	2.87	1.15	1.07	1.01	0.687	1.000
5/16	11/16	7.2	2.09	2.45	0.976	1.08	0.990	2.45	0.976	1.08	0.990	0.690	1.000
1/4	5/8	5.8	1.69	2.01	0.794	1.09	0.968	2.01	0.794	1.09	0.968	0.694	1.000
L 3 1/2x3 x 1/2	15/16	10.2	3.00	3.45	1.45	1.07	1.13	2.33	1.10	0.881	0.875	0.621	0.714
7/16	7/8	9.1	2.65	3.10	1.29	1.08	1.10	2.09	0.975	0.889	0.853	0.622	0.718
3/8	13/16	7.9	2.30	2.72	1.13	1.09	1.08	1.85	0.851	0.897	0.830	0.625	0.721
5/16	3/4	6.6	1.93	2.33	0.954	1.10	1.06	1:58	0.722	0.905	0.808	0.627	0.724
1/4	11/16	5.4	1.56	1.91	0.776	1.11	1.04	1.30	0.589	0.914	0.785	0.631	0.727
L 3 1/2x2 1/2x 1/2	15/16	9.4	2.75	3.24	1.41	1.09	1.20	1.36	0.760	0.704	0.705	0.534	0.486
7/16	7/8	8.3	2.43	2.91	1.26	1.09	1.18	1.23	0.677	0.711	0.682	0.535	0.491
3/8	13/16	7.2	2.11	2.56	1.09	1.10	1.16	1.09	0.592	0.719	0.660	0.537	0.496
5/16	3/4	6.1	1.78	2.19	0.927	1.11	1.14	0.939	0.504	0.727	0.637	0.540	0.501
1/4	11/16	4.9	1.44	1.80	0.755	1.12	1.11	0.777	0.412	0.735	0.614	0.544	0.506
L 3 x3 x 1/2	13/16	9.4	2.75	2.22	1.07	0.898	0.932	2.22	1.07	0.898	0.932	0.584	1.000
7/16	3/4	8.3	2.43	1.99	0.954	0.905	0.910	1.99	0.954	0.905	0.910	0.585	1.000
3/8	11/16	7.2	2.11	1.76	0.833	0.913	0.888	1.76	0.833	0.913	0.888	0.587	1.000
5/16	5/8	6.1	1.78	1.51	0.707	0.922	0.865	1.51	0.707	0.922	0.865	0.589	1.000
1/4	9/16	4.9	1.44	1.24	0.577	0.930	0.842	1.24	0.577	0.930	0.842	0.592	1.000
3/16	1/2	3.71	1.09	0.962	0.441	0.939	0.820	0.962	0.441	0.939	0.820	0.596	1.000

Angles in shaded rows may not be readily available. Availability is subject to rolling accumulation and geographical location, and should be checked with material suppliers.

FIGURE 11.13
A portion of the table of dimensions and properties of angle shapes from the *Manual of Steel Construction* of the American Institute of Steel Construction. One inch equals 24.5 mm. *(By permission of American Institute of Steel Construction)*

loads and are frequently found playing this role as lintels spanning door and window openings in masonry construction. In steel frame buildings, their primary role is in connecting wide-flange beams, girders, and columns, as we will see shortly. They also find use as diagonal braces in steel frames and as members of steel trusses, where they are paired back to back to connect conveniently to flat *gusset plates* at the joints of the truss (Figure 11.82). *Channel* sections are also used as truss members and bracing, and for short beams, lintels, and stringers in steel stairs. *Tees*, *plates*, *bars*, and *sheets* all have their various roles in a steel frame building, as shown in the diagrams that accompany this text.

The structural properties of steel can also be adjusted after rolling, using various so-called thermo-mechanical processes. For example, immediately after rolling, ASTM A913 steel is subjected to a process of *quenching* (rapid cooling) and then *tempering* (partial reheating) to give the steel an optimized balance of strength, toughness, and weldability characteristics.

Cast Steel

While the vast majority of structural steel is produced as rolled shapes, structural shapes can also be produced as *cast steel*, that is, by pouring molten steel directly into molds and allowing the steel to cool. Although steel castings are, pound for pound, more expensive than rolled steel shapes, they have other advantages: Because cast parts are produced in small quantities, they can economically utilize specialized steel alloys selected on the basis of a part's unique requirements. Because they are cast in discrete molds rather than formed through a continuous rolling process, cast steel parts can be nonuniform in section, they can readily incorporate curves or complex geometries, and their shapes can be carefully tailored to the particular requirements of the part. Cast steel is especially well suited for the production of custom-shaped connections for steel structures that are stronger, lighter, and more attractive than possible with those fabricated from conventional rolled steel.

Cold-Worked Steel

Steel can be *cold-worked* or *cold-formed* (rolled or bent) in a so-called cold state (at room temperature). Cold working causes the steel to gain considerable strength through a realignment of its crystalline structure. Light-gauge (thin) steel sheet is formed into C-shaped sections to make short-span framing members that are frequently used to frame partitions and exterior walls of larger buildings and floor structures of smaller buildings (see Chapter 12). Steel sheet stock is also rolled into corrugated configurations utilized as floor and roof decking in steel-framed structures (Figures 11.59–11.64).

Heavier sheet or plate stock may be cold-formed into square, rectangular, round, and elliptical hollow shapes that are then welded along the longitudinal seam to form *hollow structural sections (HSS)* (Figures 11.11, 11.14, and 11.84). Also called structural tubing, they are often used for columns and for members of welded steel trusses and space trusses. Their hollow shape makes them especially suitable for members that are subjected to torsional (twisting) stresses or to buckling associated with compressive loads.

The normal range of wide-flange shapes is too large to be cold-rolled, but cold rolling is used to produce small-section steel rods and steel components for open-web joists, where the higher strength can be utilized to good advantage. Steel is also cold-drawn through dies to produce the very high strength wires used in wire ropes, bridge cables, and concrete prestressing strands.

Open-Web Steel Joists

Among the many structural steel products fabricated from hot- and cold-rolled shapes, the most common is the *open-web steel joist (OWSJ)*, a mass-produced truss used in closely spaced arrays to support floor and roof decks (Figure 11.14). According to Steel Joist Institute (SJI) specifications, open-web joists are produced in three series: K series joists are for spans up to 60 feet (18 m) and range in depth from 8 to 30 inches (200–760 mm). LH series joists are designated as Longspan and can span as far as 96 feet (29 m). Their depths range from 18 to 48 inches (460–1220 mm). The DLH Deep Longspan series of open-web joists are 52 to 72 inches deep (1320–1830 mm) and can span up to 144 feet (44 m). Most buildings that use open-web joists utilize K series joists that are less than 2 feet (600 mm) deep to achieve spans of up to 40 feet (13 m). The spacings between joists commonly range from 2 to 10 feet (0.6–3 m), depending on the magnitude of the applied loads and the spanning capability of the decking. Some joist manufacturers also produce proprietary open-web steel joists types capable of longer spans than trusses designed to SJI specifications.

Joist girders are prefabricated steel trusses designed to carry heavy loads, particularly bays of steel joists (Figure 11.14). They range in depth from 20 to 72 inches (500–1800 mm). They can be used instead of wide-flange beams and girders in roof and floor structures where their greater depth is not objectionable. Open-web joists and joist girders are invariably made of high-strength steel.

FIGURE 11.14
The roof of a single-story industrial building is framed with open-web steel joists supported by joist girders. The girders rest on columns of square hollow structural sections. *(Courtesy Vulcraft Division of Nucor)*

Joining Steel Members

Rivets

Steel shapes can be joined into a building frame with any of three fastening techniques rivets, bolts, or welds and by combinations of these. A *rivet* is a steel fastener consisting of a cylindrical body and a formed head. It is brought to a white heat in a forge, inserted through holes in the members to be joined, and hot-worked with a pneumatic hammer to produce a second head opposite the first (Figure 11.15). As the rivet cools, it shrinks, clamping the joined pieces together and forming a tight joint. Riveting was for many decades the predominant fastening technique used in steel frame buildings, but it has been completely replaced in contemporary construction by the less labor-intensive techniques of bolting and welding.

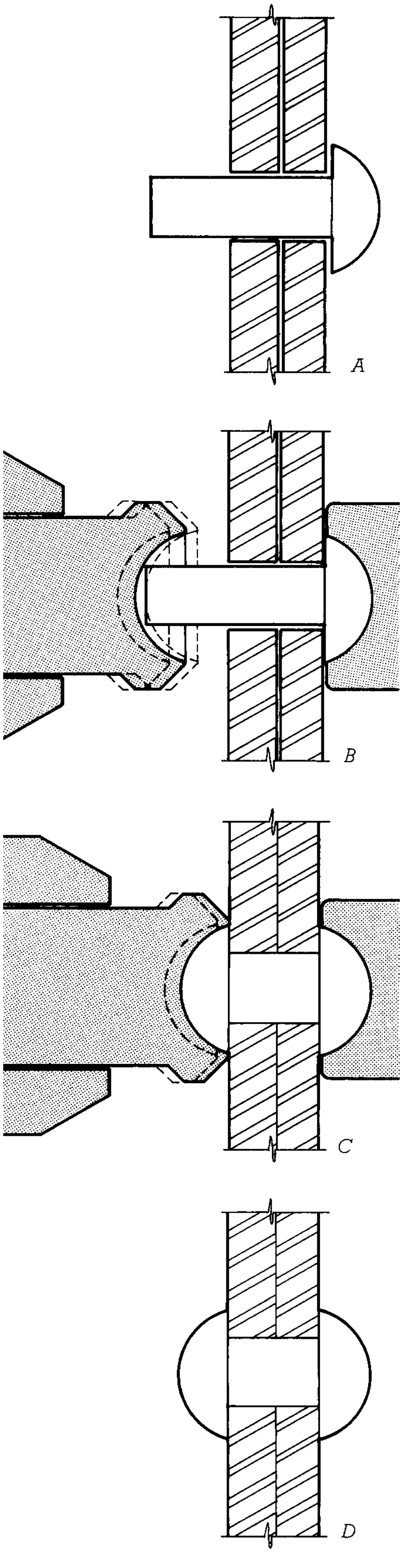


FIGURE 11.15
How riveted connections are made. (*a*) A hot steel rivet is inserted through holes in the two members to be joined. (*b, c*) Its head is placed in the cup-shaped depression of a heavy, hand-held hammer. A pneumatic hammer drives a rivet set repeatedly against the body of the rivet to form the second head. (*d*) The rivet shrinks as it cools, drawing the members tightly together.

Bolts

Bolts used in steel frame construction may be either *high-strength bolts* (ASTM A325 and A490), which are heat treated during manufacturing to develop their greater strength, or lower-strength *carbon steel bolts* (ASTM A307). In contemporary steel frame construction, bolted structural connections rely almost exclusively on high-strength bolts. Carbon steel bolts (also called unfinished or common bolts) find only limited use, such as in the fastening of minor framing elements or temporary connections.

The manner in which a bolted structural steel connection derives its strength depends on how the bolts are installed. In a *bearing-type connection*, bolts need only be installed to a *snug-tight* condition. In this case, movement between the joined members is resisted by the bolts themselves as the sides of the bolt holes in the connected members bear against the bodies of the bolts. In a *slip-critical* (or *friction type*) *connection*, bolts are *preloaded* (tightened during installation) to such an extent that friction between the adjoining faces of the steel members (the *faying surfaces*) resists movement between the members. Under normal load conditions, bolts in bearing-type connections are stressed primarily in shear, while those in slip-critical connections are stressed in tension.

When a bearing-type connection is first loaded, a slight slippage of the joint occurs as the sides of the bolt holes in the joined members achieve full bearing against the bodies of the bolts. In contrast, a slip-critical connection will reach its full design capacity with virtually no initial slippage. For this reason, only slip-critical connections are used where the small changes in alignment that can occur with bearing-type connections could be detrimental to the performance of a structure. For example, column splices and beam-to-column connections in tall buildings must be designed as slip-critical, as must connections that experience load reversals.

FIGURE 11.16
An ironworker tightens high-strength bolts with a pneumatic impact wrench. *(Courtesy of Bethlehem Steel Corporation)*

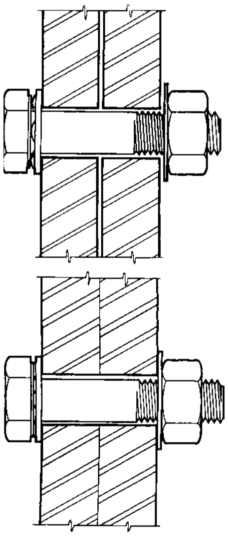


FIGURE 11.17
***Top*: An untightened high-strength bolt with a load indicator washer under the head. *Bottom*: The bolt and washer after tightening; notice that the protrusions on the load indicator washer have flattened.**

FIGURE 11.18
A splined tension control bolt. *(Courtesy of LeJeune Bolt Company)*

In a typical connection, bolts are inserted into holes $\frac{1}{16}$ inch (2 mm) larger than the diameter of the bolt. Depending on a variety of factors, hardened steel washers may be inserted under one or both ends of the fastener. Washers are required with slotted or oversized holes to ensure that the bolt head and nut have adequate contact with the surfaces of the joined members. When installing preloaded bolts, washers may be required to prevent damage, such as *galling* (tearing), to the surfaces of the joined members. Many bolt tension verification methods, discussed below, also require washers under at least one end of the bolt to ensure consistent tensioning results.

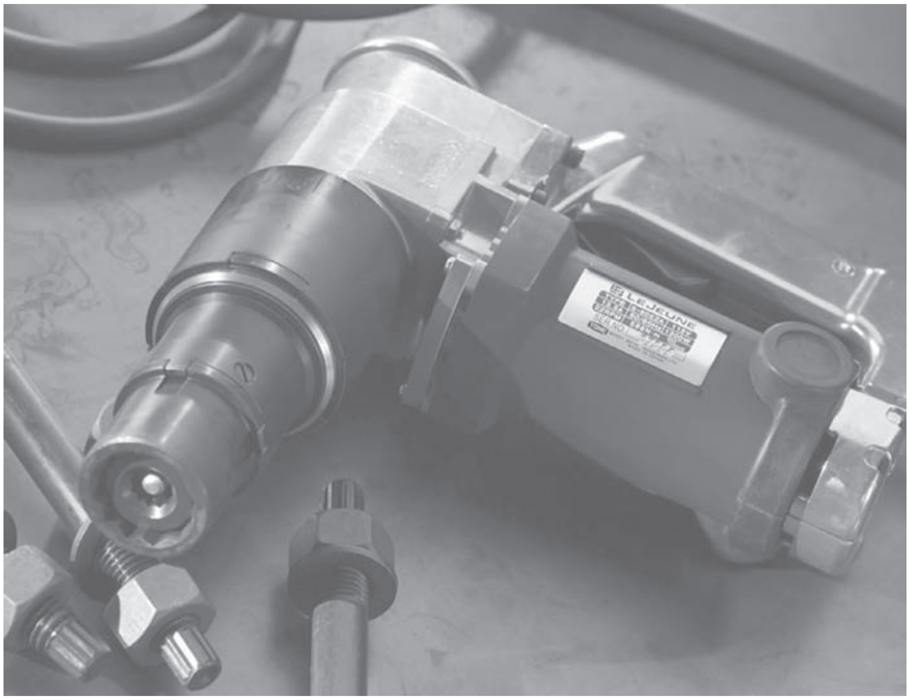


FIGURE 11.19
The compact design of the electric shear wrench used for tightening tension control bolts makes it easy to reach bolts in tight situations. *(Courtesy of LeJeune Bolt Company)*

Bolts are usually tightened using a pneumatic or electric *impact wrench* (Figure 11.16). In a bearing-type connection, the amount of tension in the bolts is not critical. In a slip-critical connection, bolts must be tightened reliably to at least 70 percent of their ultimate tensile strength.

A major problem in the assembly of slip-critical connections is how to verify that the necessary tension has been achieved in each bolt. This can be accomplished in any of several ways. In the *turn-of-nut method,* each bolt is tightened snug, then turned a specified additional fraction of a turn. Depending on bolt length, bolt alloy, and other factors, the additional tightening required will range from one-third of a turn to a full turn.

In another method, a *load indicator washer,* also called a *direct tension indicator (DTI),* is placed under the head or nut of the bolt. As the bolt is tightened, protrusions on the washer are progressively flattened in proportion to the tension in the bolt (Figure 11.17). Inspection for proper bolt tension then becomes a relatively simple matter of inserting a feeler gauge to determine whether the washer has flattened sufficiently to indicate the required tension. One washer manufacturer has made inspection even easier by attaching tiny dye capsules to the washer; when the protrusions on the washer flatten sufficiently, the capsules squirt a highly visible dye onto the surface of the washer.

Less frequently used to verify bolt tension is the *calibrated wrench method,* in which a special torque control wrench is used to tighten the bolts. The torque setting of the wrench is carefully calibrated for the particular size and type of fasteners being installed so as to achieve the required bolt tension. A washer under the turned end of the

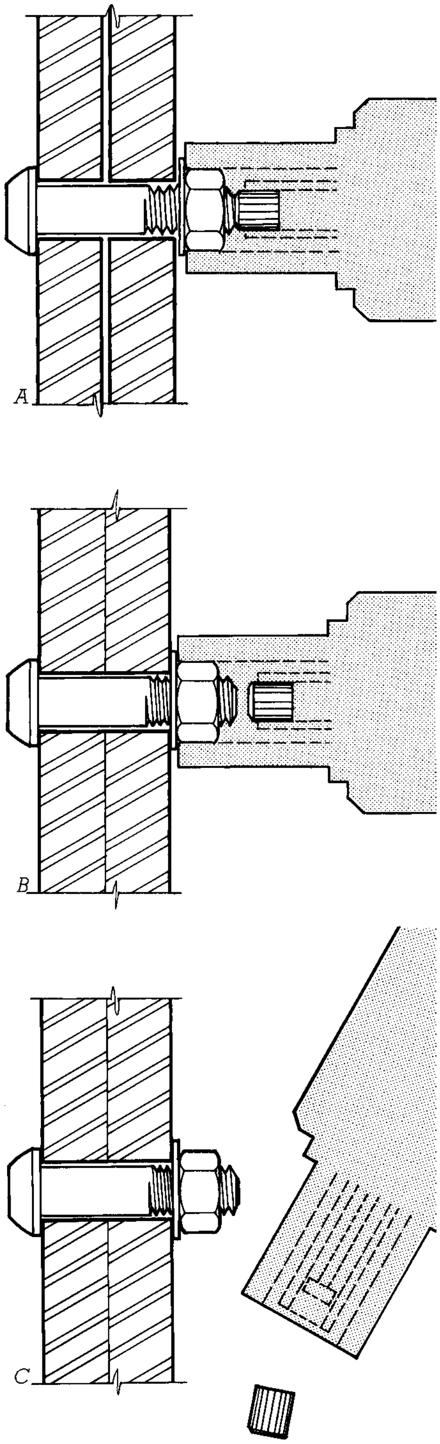


FIGURE 11.20
Tightening a tension control bolt. (*a*) The wrench holds both the nut and the splined body of the bolt and turns them against one another to tighten the bolt. (*b*) When the required torque has been achieved, the splined end twists off in the wrench. (*c*) A plunger inside the wrench discharges the splined end into a container. *(Courtesy of LeJeune Bolt Company)*

bolt minimizes friction and ensures a consistent relationship between the tightening force applied and the tension achieved in the bolt.

Yet another method of bolt tension verification employs *tension control bolts*. These have protruding splined ends that extend beyond the threaded portion of the body of the bolt (Figure 11.18). The nut is tightened by a special power-driven *shear wrench* (Figure 11.19) that grips both the nut and the splined end simultaneously, turning the one against the other. The splined end is formed in such a way that when the required torque has been reached, the end twists off (Figure 11.20). Verification of adequate bolt tensioning in installed bolts then becomes a simple matter of visually checking for the absence of splines. Another advantage of this fastener type is that it is installed by a single worker, unlike conventional bolts, which require a second worker with a wrench to prevent the other end of the bolt assembly from turning during tightening.

An alternative to the high-strength bolt is the *lockpin and collar fastener* or *swedge bolt*, a boltlike steel pin with annular rings that relies on a steel collar in lieu of a conventional nut to hold the pin. The swedge bolt is installed using a special power tool to hold the pin under high tension while cold forming (swaging, a crimpinglike action) the collar around its end to complete the connection. As the installation process is completed, the tail of the lockpin breaks off, furnishing visual evidence that the necessary tension has been achieved in the fastener. Like the tension control bolt, the swedge bolt can be installed by a single worker.

Welding

Welding offers a unique and valuable capability to the structural designer: It can join the members of a steel frame as if they were a monolithic whole. Welded connections, properly designed and executed, are stronger than the members they join in resisting both shear and moment forces. Although it is possible to achieve this same performance with high-strength bolted connections, such connections are often cumbersome compared to equivalent welded joints. Bolting, on the other hand, has its own advantages: It is quick and easy for field connections that need only to resist shearing forces, and it can be accomplished under conditions of adverse weather or difficult physical access that would make welding impossible. Often welding and bolting are combined in the same connections to take advantage of the unique qualities of each: Welding may be used in the fabricator's shop for its inherent economies and in the field for its structural continuity, whereas bolting is often employed in the simpler field connections and to hold connections in alignment prior to welding. The choice of bolting, welding, or combinations of the two is often dictated by the designer, but it may also be influenced by considerations such as the fabricator's and erector's equipment and expertise, availability of electric power, climate, and location.

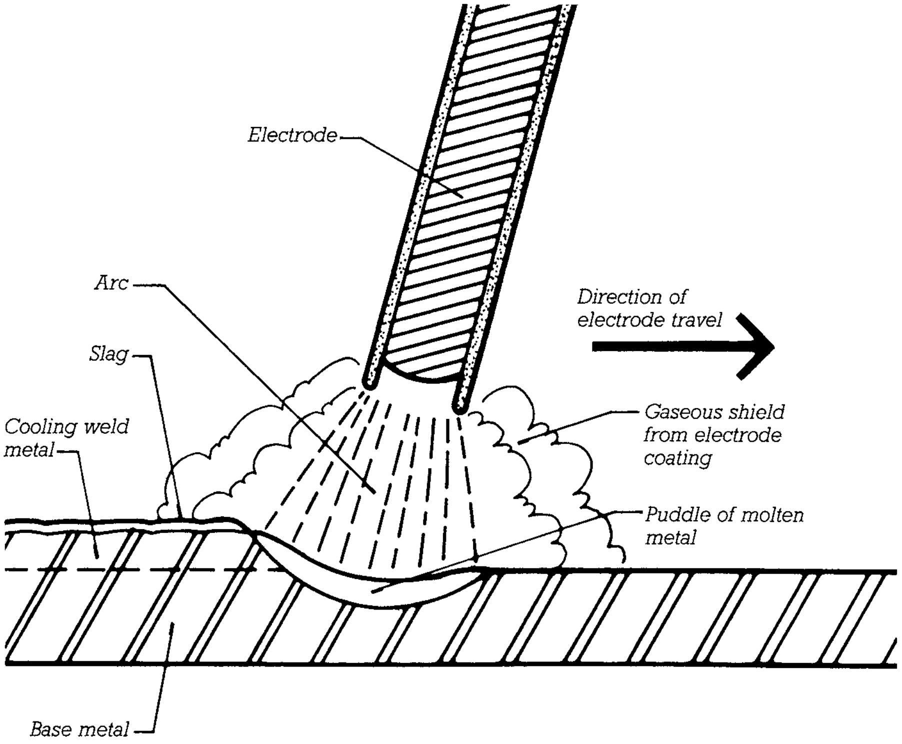
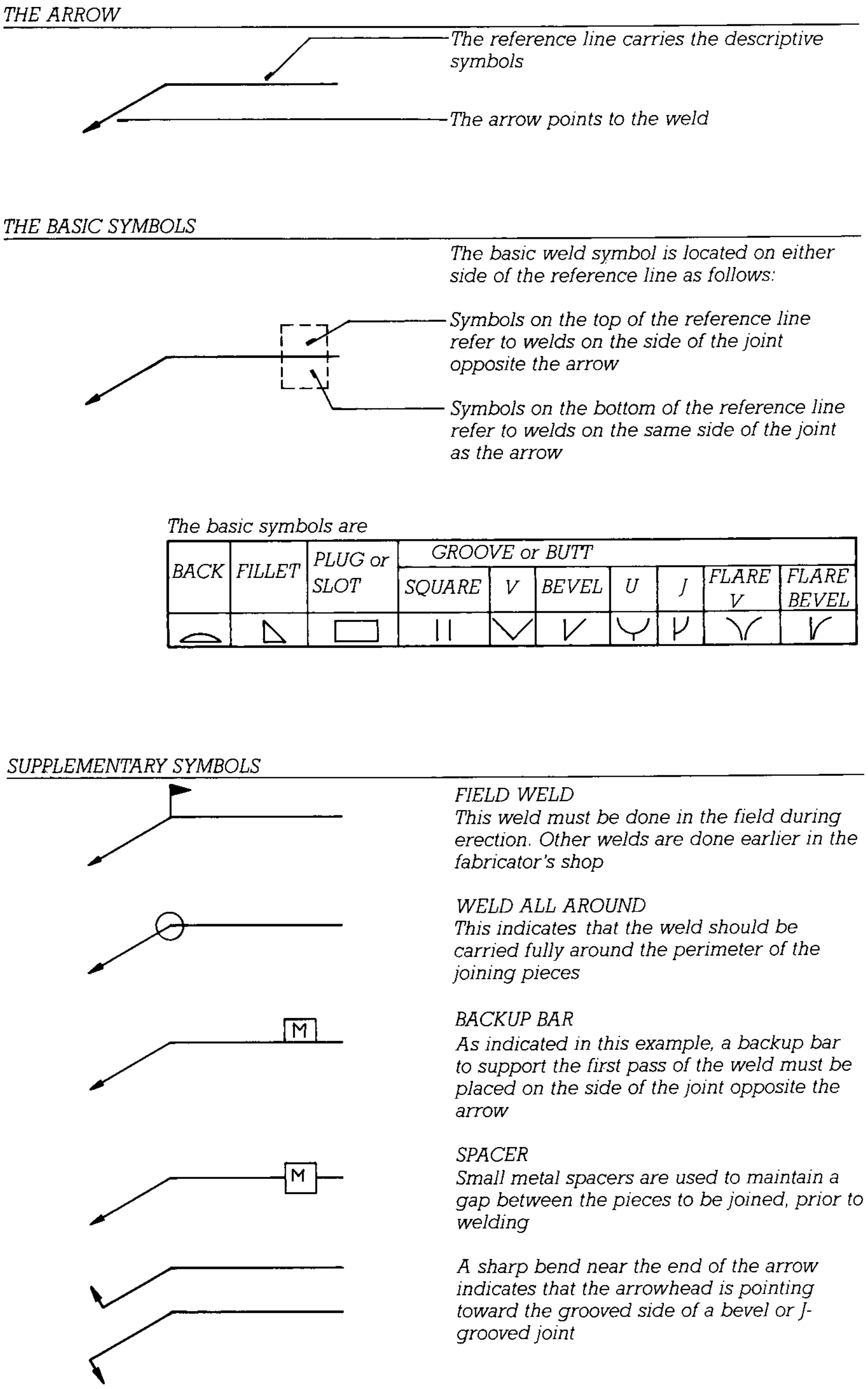


FIGURE 11.21
Close-up diagram of the electric arc welding process.

Electric arc welding is conceptually simple. An electrical potential is established between the steel pieces to be joined and a metal *electrode* held either by a machine or by a person. When the electrode is held close to the seam between the steel members, a continuous electric arc is established that generates sufficient heat to melt both a localized area of the steel members and the tip of the electrode (Figure 11.21). The molten steel from the electrode merges with that of the members to form a single puddle. The electrode is drawn slowly along the seam, leaving behind a continuous bead of metal that cools and solidifies to form a continuous connection between the members. For small members, a single pass of the electrode may suffice to make the connection. For larger members, a number of passes are made in order to build up a weld of the required depth.

In practice, welding is a complex science. The metallurgy of the structural steel and the welding electrodes must be carefully coordinated. Voltage, amperage, and polarity of the electric current are selected to achieve the right heat and penetration for the weld. Air must be kept away from the electric arc to prevent rapid oxidation of the liquid steel; this is accomplished in simple welding processes either by a thick coating on the electrode that melts to create a liquid and gaseous shield around the arc or by a core of vaporizing flux in a tubular steel electrode. It may also be done by means of a continuous flow of inert gas around the arc, or with a dry flux that is heaped over the end of the electrode as it moves across the work.

FIGURE 11.22
Standard weld symbols, as used on steel connection detail drawings.



The required thickness and length of each weld are calculated by the designer to match them to the forces to be transmitted between the members, and are indicated on fabrication drawings using standardized *weld symbols* (Figure 11.22). For deep welds, such as the full-penetration welds shown in Figure 11.23, the edges of the members are beveled to create a groove that permits access of the electrode to the full thickness of the piece. Small strips of steel called *backup bars* or *backing bars* are welded beneath the groove prior to beginning the actual weld to prevent the molten metal from flowing out the bottom of the groove. The weld then is deposited in a number of passes of the electrode until the groove is fully filled. In some cases, *runoff bars* are required at the ends of a groove weld to facilitate the formation of a full thickness of weld metal at the edges of the member (Figure 11.46).

Workers who do structural welding are methodically trained and periodically tested to ensure that they have the required level of skill and knowledge. When an important weld is completed, it is inspected to make sure that it is of the required size and quality; this often involves sophisticated magnetic particle, dye penetrant, ultrasonic, or radiographic testing procedures that search for hidden voids and flaws within each weld.

Welds in structural connections that may be subjected to very high stresses during a seismic event and that are critical to maintaining the stability of the building structure are termed *demand-critical welds.* They must meet special requirements related to their design, materials, installation, and inspection to ensure their reliability under these conditions.

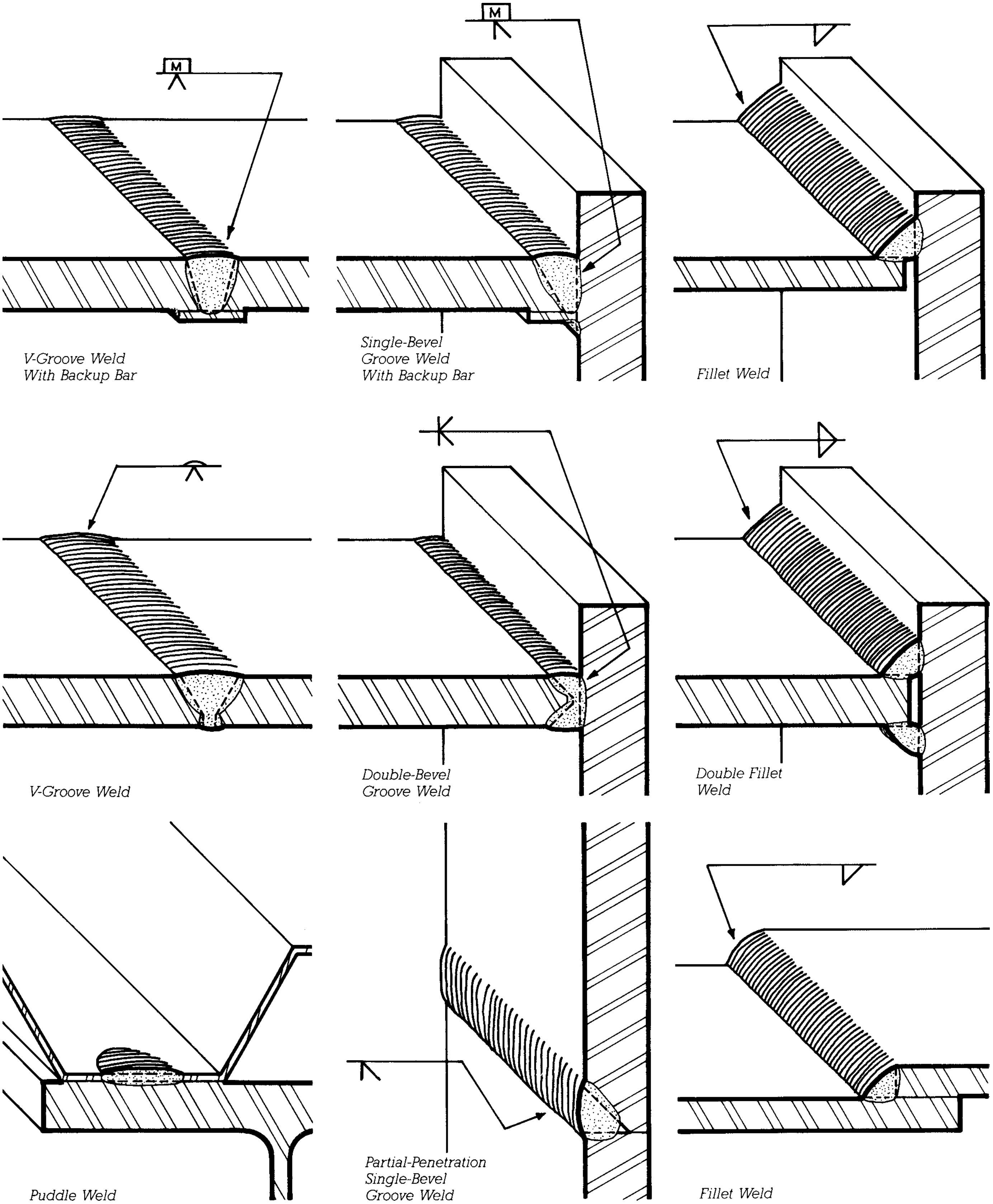


FIGURE 11.23
Typical welds used in steel frame construction. Fillet welds are the most economical because they require no advance preparation of the joint, but full-penetration groove welds are stronger. The standard symbols used here are explained in Figure 11.22.

DETAILS OF STEEL FRAMING

Typical Connections

Most steel frame connections use angles, plates, or tees as transitional elements between the members being connected. A simple bolted beam-to-column-flange connection requires two angles and a number of bolts (Figures 11.24–11.27). The angles are cut to length, and the holes are made in all the components prior to assembly. The angles are usually bolted to the web of the beam in the fabricator's shop. The bolts through the flange of the column are added as the beam is erected on the construction site. This type of connection, which joins only the web of the beam, but not the flanges, to the column is known as a *shear connection*. It is capable of transmitting vertical forces (*shear*) from a beam to a column. However, because it does not connect the beam flanges to the column, it is of no value in transmitting bending forces (*bending moment*) from one to the other.

To produce a *moment connection*, one capable of transmitting bending forces between a beam and column, it is necessary to connect the beam flanges strongly across the joint, most commonly by means of *full-penetration groove welds* (Figures 11.28 and 11.29). If the column flanges are insufficiently strong to accept the forces transmitted from the beam flanges, *stiffener plates* must be installed inside the flanges of the column to better distribute these forces into the body of the column. (Though much less common, it is also possible to design moment-transmitting connections that rely solely on bolting.)

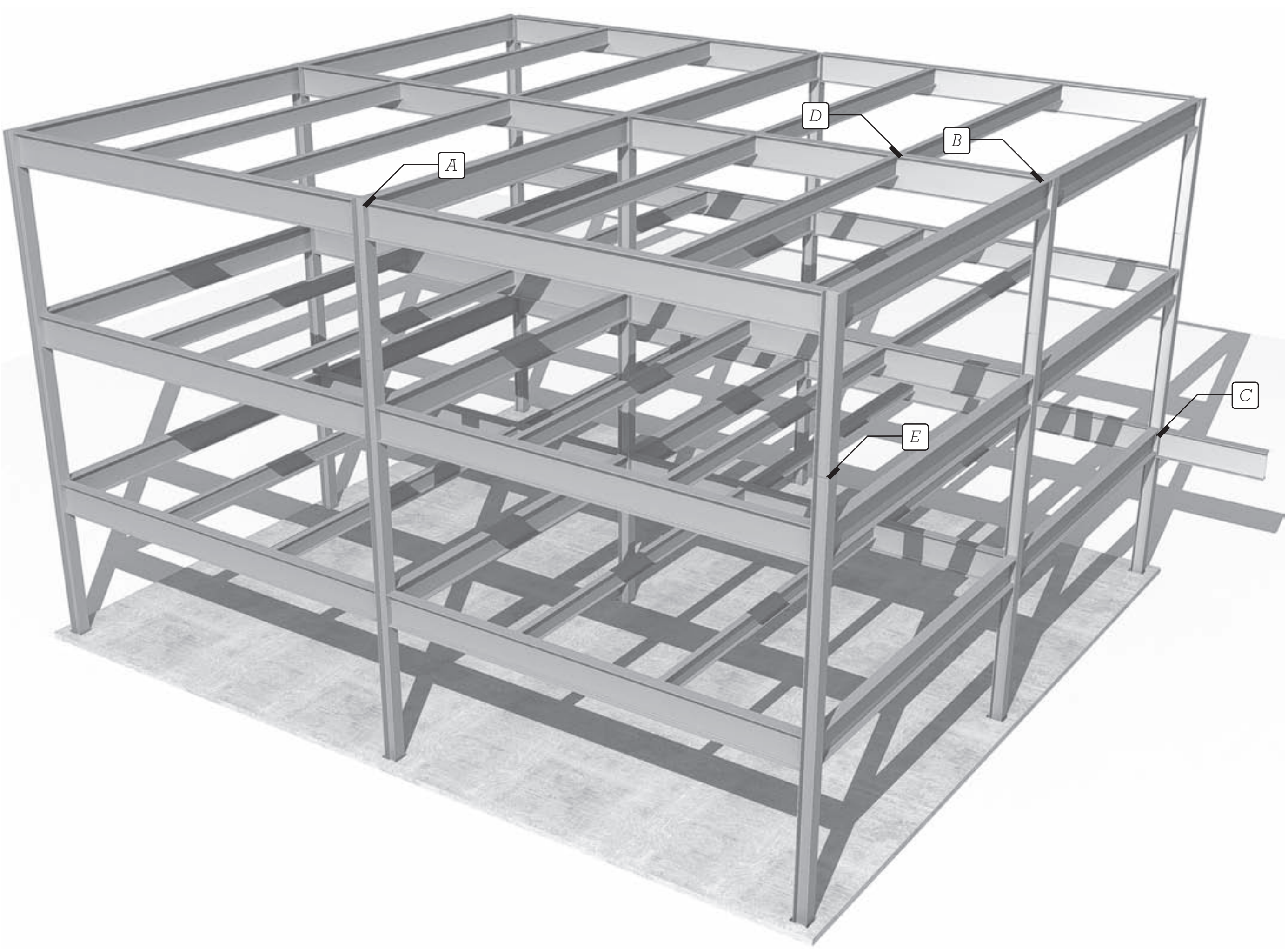


FIGURE 11.24
A generic steel building frame. The letters are keyed to the connection details in the figures that follow.

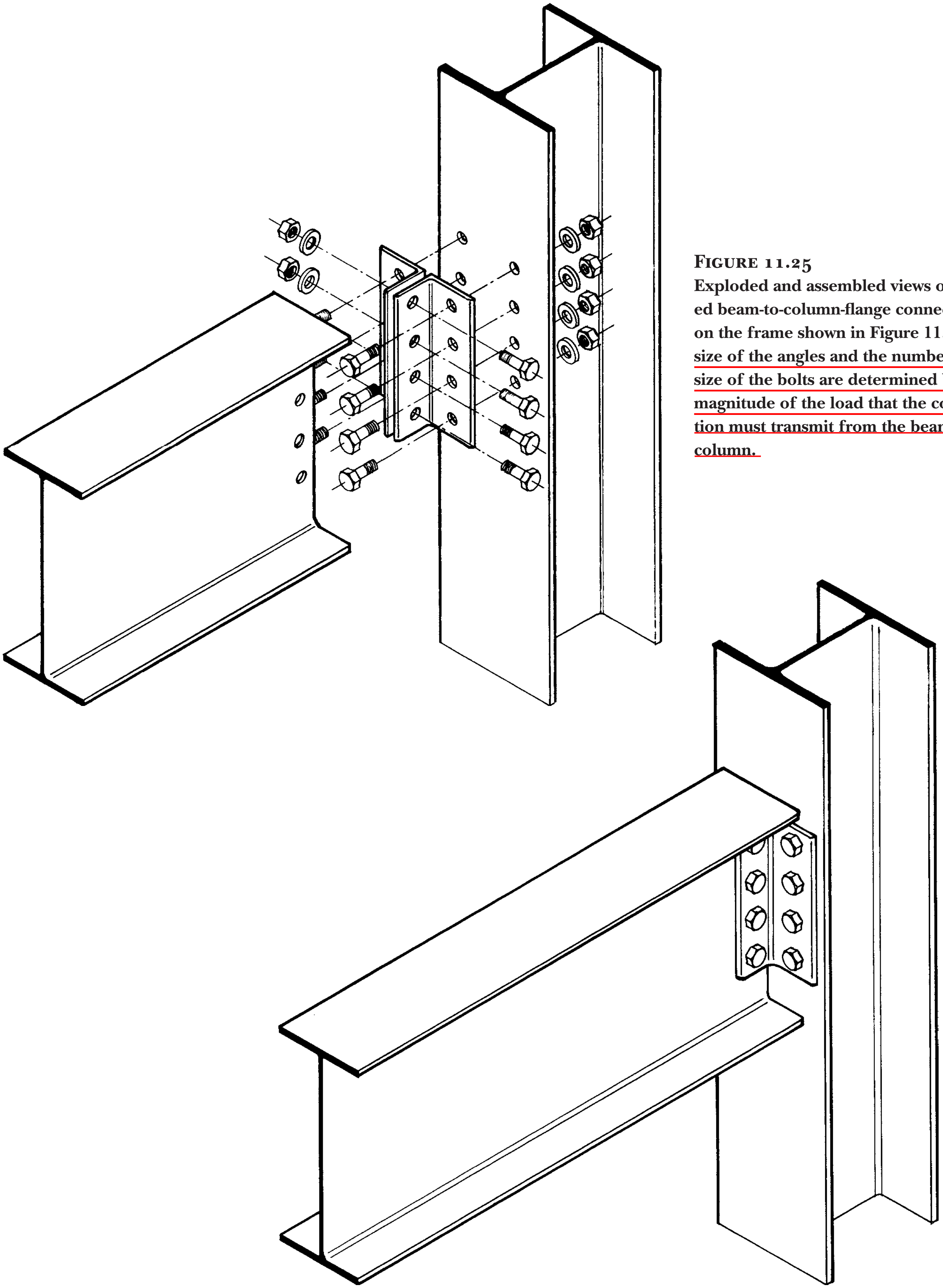


FIGURE 11.25
Exploded and assembled views of a bolted beam-to-column-flange connection, *A* on the frame shown in Figure 11.24. The size of the angles and the number and size of the bolts are determined by the magnitude of the load that the connection must transmit from the beam to the column.

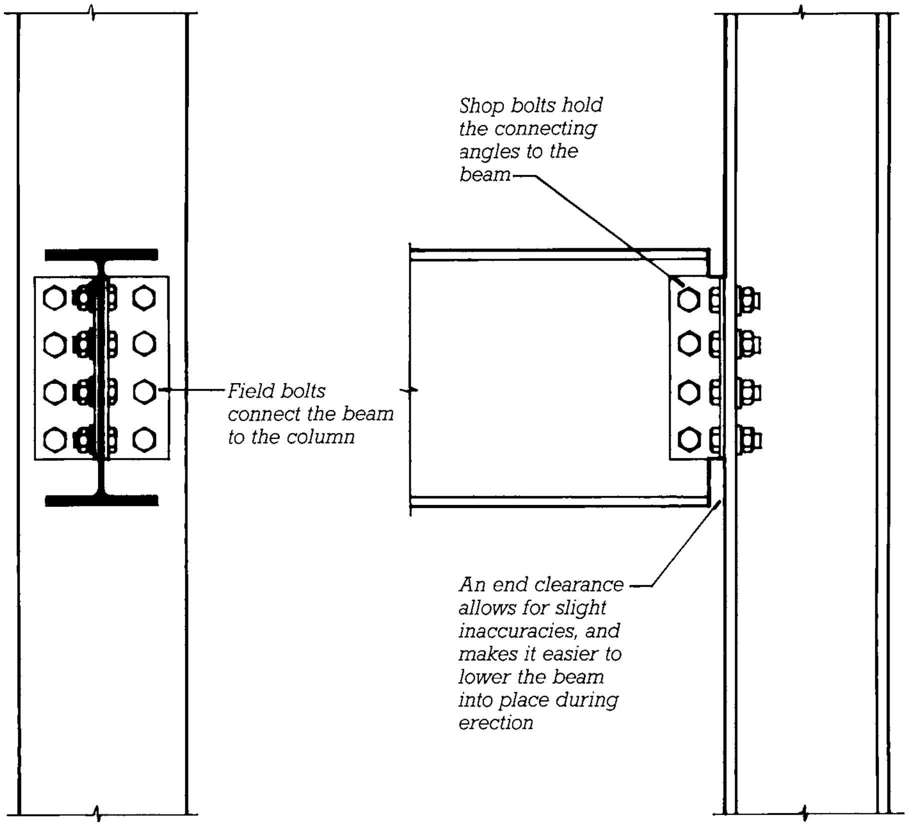


FIGURE 11.26
Two elevation views of the bolted beam-to-column-flange connection shown in Figure 11.25. This is a shear connection (AISC simple connection) and not a moment connection, because the flanges of the beam are not rigidly connected to the column. This type of shear connection, in which the beam is connected to the column by angles, plates, or tees fastened to the web of the beam, are also called *framed connections*. Alternatively, shear connections can be seated, as illustrated in Figure 11.32.

FIGURE 11.27
A pictorial view of a framed, bolted beam-to-column-flange shear connection.

FIGURE 11.28
A welded moment connection (AISC Fully Restrained) for joining a beam to a column flange. This is the type of connection that would be used instead of the shear connection at location *A* in Figure 11.24 if a moment connection were required. The bolts hold the beam in place for welding and also provide shear resistance. Small rectangular backup bars are welded beneath the end of each beam flange to prevent the welding arc from burning through. A clearance hole is cut from the top of the beam web to permit the backup bar to pass through. A similar clearance hole at the bottom of the beam web allows the bottom flange to be welded entirely from above for greater convenience. The groove welds develop the full strength of the flanges of the beam, allowing the connection to transmit moments between the beam and the column. If the column flanges are not stiff enough to accept the moments from the beam, stiffener plates are welded between the column flanges as shown here. The flanges of the beam are cut to a “dog bone” configuration to create a zone of the beam that is slightly weaker in bending than the welded connection itself. During a violent earthquake, the beam will deform permanently in this zone while protecting the welded connection against failure.

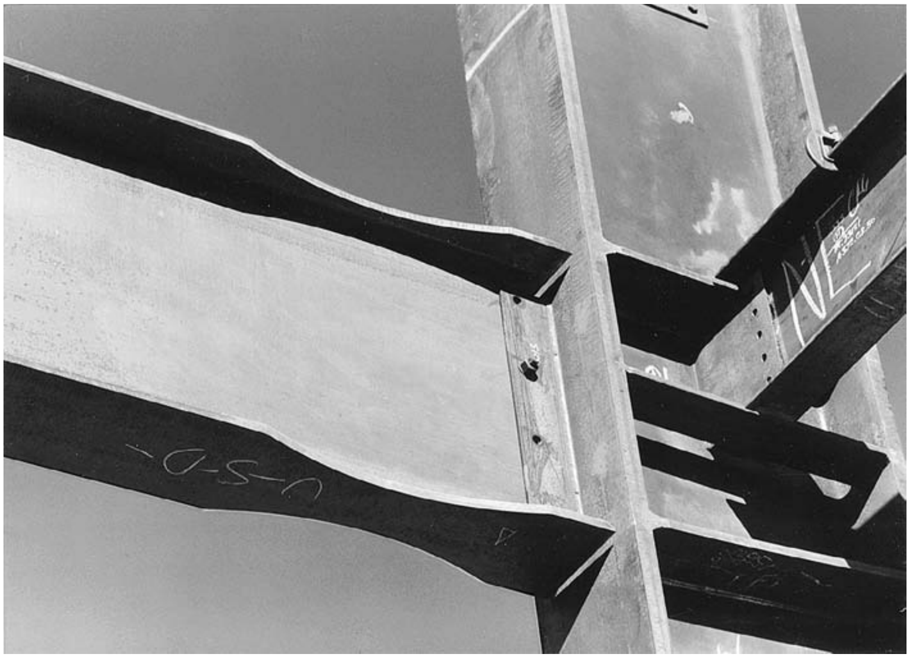


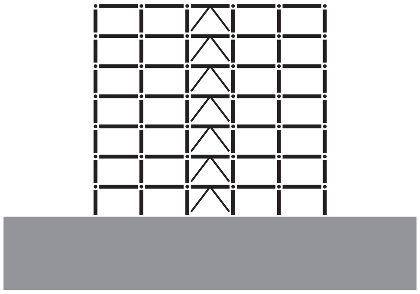
FIGURE 11.29
Photograph of a moment connection similar to the one shown in Figure 11.28. The beam has just been bolted to a shear tab that is welded to the column. Next, backup bars will be welded to the column just under the beam flanges, after which the flanges will be welded to the column. *(Permission of American Institute of Steel Construction)*

Stabilizing the Building Frame

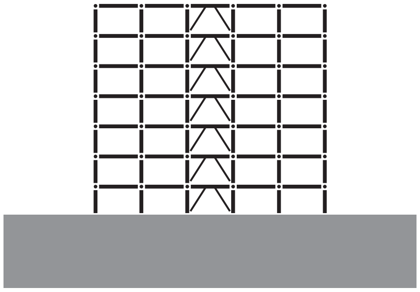
In order to understand the respective roles of shear connections and moment connections in a building frame, it is necessary to understand the means by which buildings may be made stable against the lateral forces of wind and earthquake. Three basic stabilizing mechanisms are commonly used: braced frames, shear walls, and moment-resisting frames (Figure 11.30). A *braced frame* works by creating stable triangular configurations, or *diagonal bracing*, within the otherwise unstable rectilinear geometry of a steel building frame. The connections between beams and columns within a braced frame need not transmit moments (bending forces); they can behave like pins or hinges, which is another way of saying that they can be shear connections such as the one in Figure 11.27. (Though it may not be readily apparent, this type of connection is capable of the small rotations necessary for it to behave essentially as if it is hinged.)

A special case of the braced frame is the *eccentrically braced frame*. Because the ends of the diagonal braces are offset some distance from each other, where they connect to the beams, the structure as a whole is more resilient than a frame with conventional bracing. Eccentric bracing is used primarily as a way of causing a building frame to absorb energy during an earthquake and thus to protect against collapse. Like conventional braced frames, eccentrically braced frames can rely exclusively on shear connections between beams and columns.

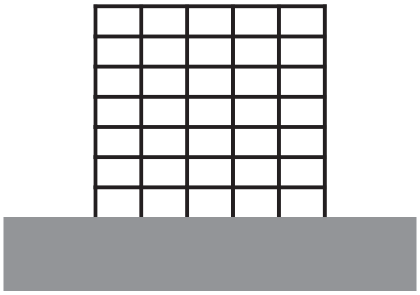
Shear walls are stiff walls made of steel, concrete, or reinforced concrete masonry. They serve the same purpose as the diagonal bracing within a braced frame structure and, like the braced frame, moment connections between beams and columns are not required.



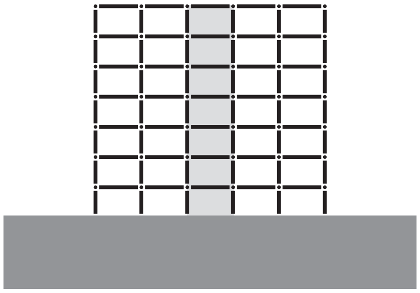
Braced Frame



Eccentrically Braced Frame



Moment-Resisting Frame

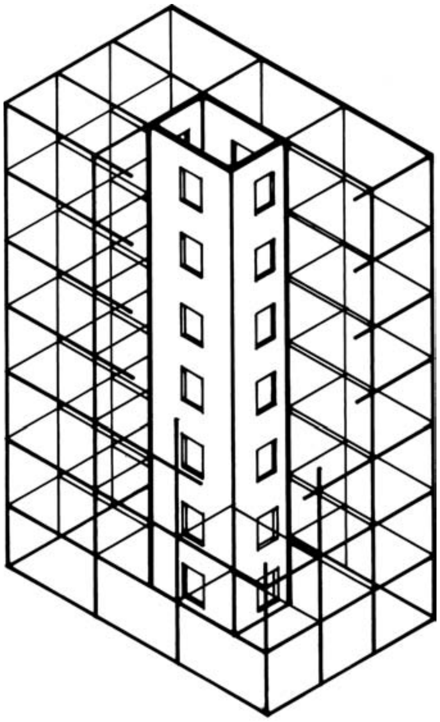


Shear walls

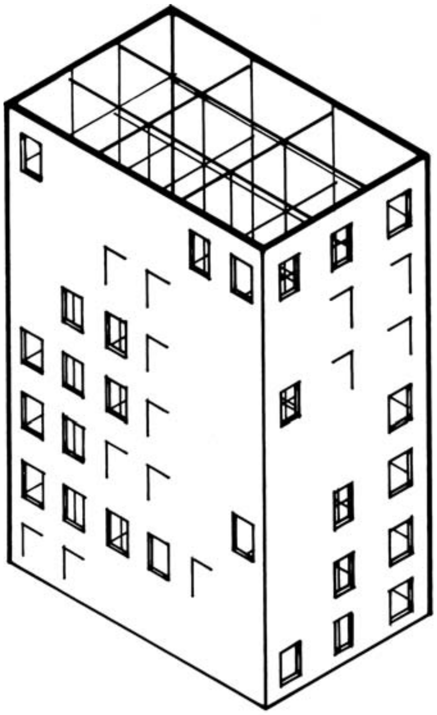
Figure 11.30
Elevation views of the basic means for imparting lateral stability to a structural frame. Connections made with dots are shear connections, and solid intersections indicate moment connections. The braced frame (*top*) is illustrated here with *Chevron* (or *inverted V*) *bracing*. *Crossbracing*, in which paired diagonals run from opposite corners of the braced bay, are also common. Eccentric bracing (*second from top*) is used in situations where it is advantageous for the frame to absorb seismic energy during an earthquake. The connections in the moment-resisting frame (*third from top*), called "moment connections," are sufficiently resistant to rotation to stabilize the structure against lateral forces without diagonal bracing or shear walls. Moment-resisting frames are also sometimes called "rigid frames," although this name can be misleading. While the connections in such frames are relatively rigid, whole frames that rely only on such connections for lateral stability are typically somewhat less stiff than those stabilized with diagonal bracing or shear walls.

Moment-resisting frames have neither diagonal bracing nor shear walls to provide lateral stability. Rather, they rely on moment connections between beams and columns that are resistant to rotation and thereby capable of stabilizing the frame against lateral forces. Depending on the configuration of the structure and the magnitude of the forces involved, not all of the connections in a moment-resisting frame necessarily need be moment connections. Since moment connections are more costly to make than shear connections, they are used only to the extent required, with the remainder of the frame relying on simpler, less costly shear connections.

There are two common methods of arranging stabilizing elements within the frame of a tall building (Figure 11.31). One is to provide a *rigid core* in the center of the building. The core, which is the area that contains the elevators, stairs, mechanical chases, and washrooms, is structured as a stiff tower, using diagonal bracing, shear walls, or moment connections. The remainder of the building frame may then be constructed with shear connections



Rigid Core



Rigid Perimeter

FIGURE 11.31
Rigid core versus rigid perimeter.

and stabilized by the *diaphragm action* (the rigidity possessed by a thin plate of material such as a welded steel deck with a concrete topping) of the floors and roof that connect these outer bays to the rigid core. Or, where additional resistance to lateral forces or greater stiffness is required, beam-to-column moment connections may be introduced into some portions of the building frame as well.

A second arrangement for achieving stability is to provide a *rigid perimeter*, again by using diagonal bracing, shear walls, or moment connections. When this is done, the entire interior of the structure can be assembled with shear connections, relying on diaphragm action in the floor and roof plates to impart stability to these portions of the structure.

In summary, shear connections between beams and columns are sufficient to transmit vertical loads through the building frame, but they are not, on their own, capable of providing resistance to lateral forces. Lateral force resistance may be provided by the introduction of diagonal bracing (braced frame), shear walls, beam-to-column moment connections (moment-resisting frame), or some combination of these elements into portions of the frame. Because shear connections are easier and less expensive to construct than moment connections, moment connections are used only to the extent necessary and often in combination with other stabilizing mechanisms.

Shear Connections and Moment Connections

The American Institute of Steel Construction (AISC) defines three types of beam-to-column connections, classified according to their moment-resisting capability. *Fully-Restrained* (*FR*) *moment connections* (formerly *AISC Type 1*) are sufficiently rigid that the geometric angles between members will remain virtually unchanged under normal loading. *Partially-Restrained* (*PR*) *moment connections* (formerly *AISC Type 3*) are not as rigid as FR connections, but nonetheless possess a dependable and predictable moment-resisting capacity that can be used to stabilize a building frame. FR and PR moment connections are also sometimes referred to as rigid and semirigid connections, respectively. Both connection types can be used to construct moment-resisting building frames. *Simple connections* (formerly *AISC Type 2*), otherwise known as shear connections, are considered to be capable of unrestrained rotation under normal loading conditions and to have negligible moment-resisting capacity. Buildings framed solely with simple connections must depend on diagonal bracing or shear walls for lateral stability.

A series of simple, fully bolted shear (AISC simple) connections are shown as a beginning basis for understanding steel connection details (Figures 11.25–11.27, 11.32, and 11.37). These are interspersed with a corresponding series of welded moment (AISC Fully- and Partially-Restrained) connections (Figures 11.28, 11.29, 11.33, and 11.36). Welding is also widely used for making shear connections, two examples of which are shown in Figures 11.34 and 11.35. A series of column connections is illustrated in Figures 11.38–11.41.

In practice, there are a number of different ways of making any of these connections, using various kinds of connecting elements and different combinations of bolting and welding. The object is to choose a method of stabilization and designs for individual connections that will result in the greatest possible economy of construction for the building as a whole. For standard joint conditions in simple structures, the choice of which connection to use may be left to the fabricator, who has first-hand knowledge of the safest, most erectable methods that will utilize the company's labor and equipment most efficiently. For more complex structures or for unique joining conditions, the structural engineer or architect may dictate a specific connection detail.

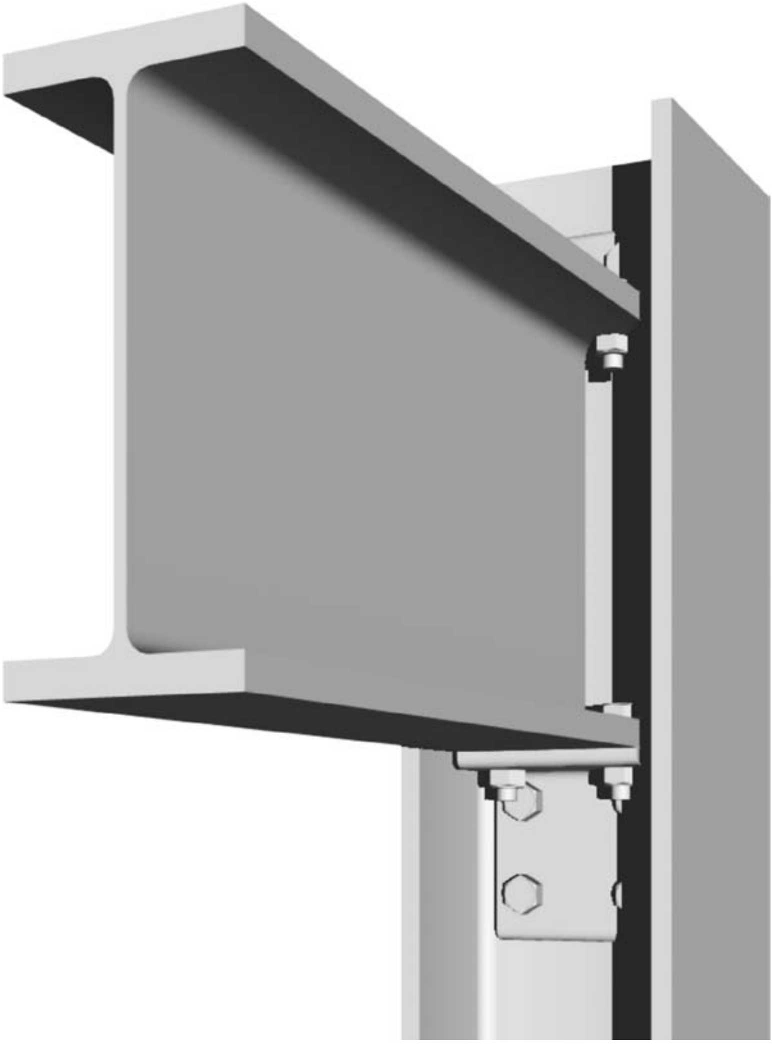


FIGURE 11.32
A *seated* beam-to-column-web *connection*, location *B* on the frame in Figure 11.24. Although the beam flanges are connected to the column by a seat angle below and a stabilizing angle above, this is a shear (AISC simple) connection, not a moment connection, because the two bolts are incapable of developing the full strength of the beam flange. This seated connection is used rather than a framed connection, as illustrated in Figure 11.27, to connect to a column web because there is usually insufficient space between the column flanges to insert a power wrench to tighten all the bolts in a framed connection.

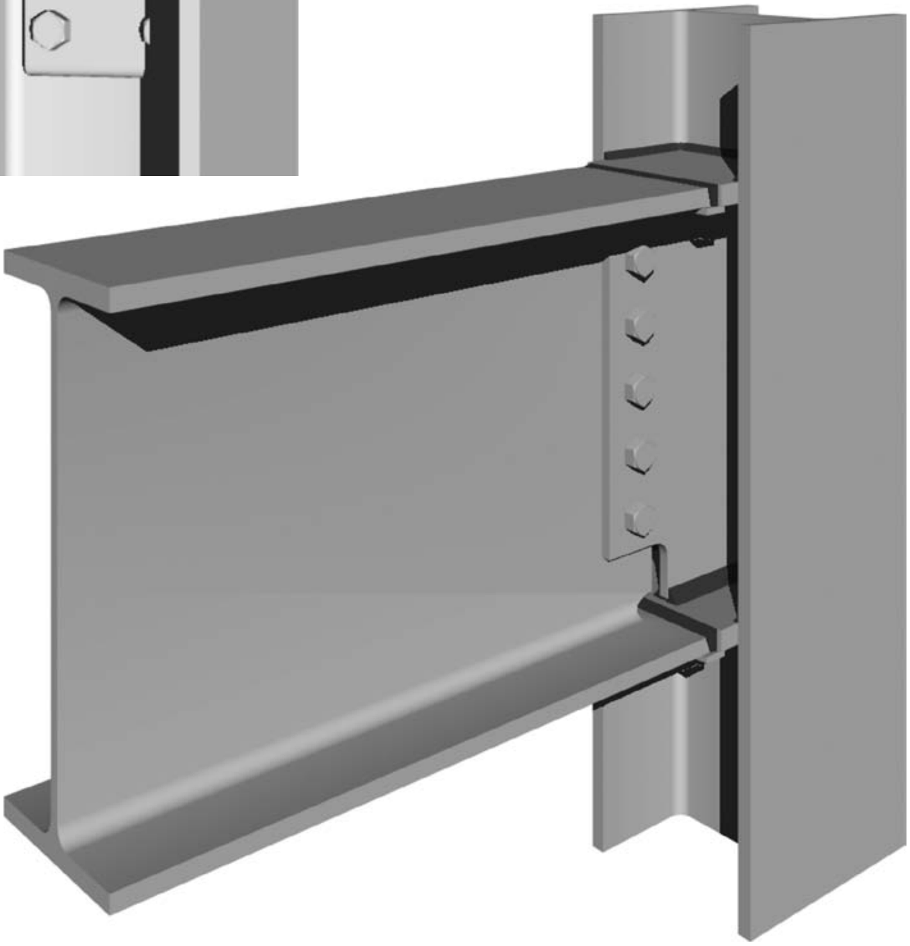


FIGURE 11.33
A welded beam-to-column-web moment(AISC Fully Restrained) connection, used at location *B* on Figure 11.24 when a rigid connection is required. A vertical *shear tab*, welded to the web of the column at its centerline, serves to receive bolts that join the column to the beam web and hold the beam in place during welding. The horizontal stiffener plates that are welded inside the column flanges are thicker than the beam flanges and extend out beyond the column flanges to reduce concentrations of stress at the welds.

FIGURE 11.34
A single-tab shear (AISC simple frame) connection is an economical alternative to the connection shown in Figures 11.26 and 11.27 when the load on the connection is relatively light. A single connector plate is welded to the column in the shop, and the beam is bolted to it on the construction site.

FIGURE 11.35
Shear (AISC simple frame) connections may also be made entirely by welding. The angles are welded to the beam in the shop. Bolts through the angles hold the beam in place while it is welded to the column. The angles are not welded to the column along their top and bottom edges. This permits the angles to flex slightly to allow the beam to rotate away from the column as it bends.

FIGURE 11.36
A welded/bolted *end plate* beam–column connection. As shown, this is a semi-rigid (AISC Partially-Restrained) connection. With more bolts, this can become a rigid, AISC Fully-Restrained connection, and could be used to support a short cantilever beam such as the one at location *C* in Figure 11.24. The plate is welded to the end of the beam in the shop and bolted to the column on the building site.

FIGURE 11.37
A coped beam–girder shear (AISC simple) connection, used at location *D* in Figure 11.24. A girder is a beam that supports other beams. This connection may also be made with single tabs rather than angles if the load is not too great. The top flanges of the beams are cut away (coped) so that the tops of the beams and the girder are all level with one another, ready to receive the floor or roof decking. Bending moments at the ends of a beam are normally so small that the flanges may be coped without compromising the strength of the beam.

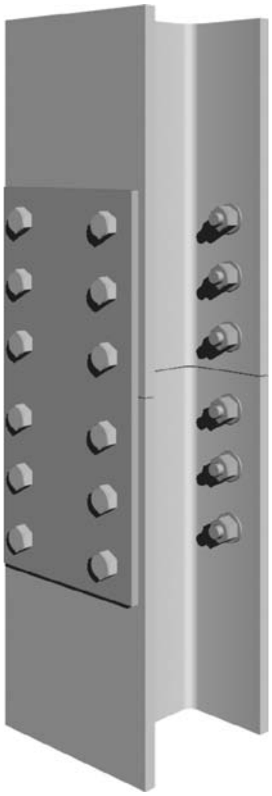


FIGURE 11.38
A bolted column–column connection for columns that are the same size. The plates are bolted to the lower section of the column in the shop and to the upper section on the site. All column connections are made at waist height above the floor, location *E* in Figure 11.24.

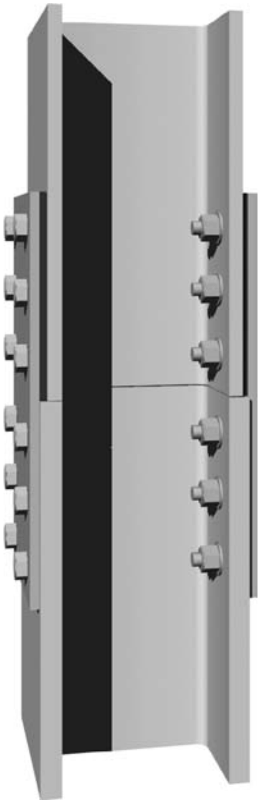


FIGURE 11.39
Column sizes diminish as the building rises, requiring frequent use of shim plates at connections to make up for differences in flange thicknesses.

FIGURE 11.40
Column connections may be welded rather than bolted. The connector plate is welded to the lower column section in the fabricator's shop. The hole in the connector plate is used to attach a lifting line during erection. The bolts hold the column sections in alignment, while the flanges are connected in the field with partial-penetration welds in bevel grooves. Partial-penetration welding allows one column to rest on the other prior to welding.

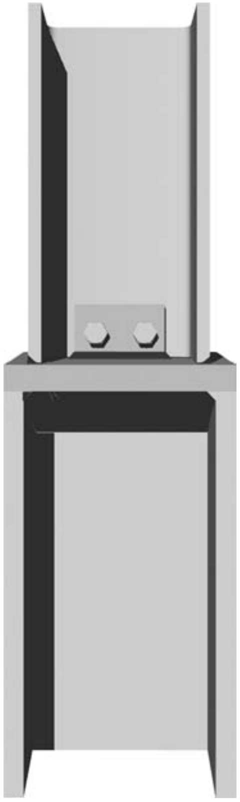


FIGURE 11.41
A welded butt plate connection is used where a column changes from one nominal size of wide flange to another. The thick butt plate, which is welded to the lower column section in the shop, transfers the load from one section of column to the other. The partial-penetration weld at the base of the upper column is made on the site.

THE CONSTRUCTION PROCESS

A steel building frame begins as a rough sketch on the drafting board of an architect or engineer. As the building design process progresses, the sketch evolves through many stages of drawings and calculations to become a finished set of structural drawings. These show accurate column locations, the shapes and sizes of all the members of the frame, and all the loads of the members, but they do not give the exact length to which each member must be cut to mate with the members it joins, and they do not give details of the more routine connections of the frame. These are left to be worked out by a subsequent recipient of the drawings, the *fabricator*.

The Fabricator

The fabricator's job is to deliver to the construction site steel components that are ready to be assembled without further processing. This work begins with the preparation in the fabricator's shop of detailed drawings that show exactly how each piece will be made and what its precise dimensions will be. The fabricator designs connections to transmit the loads indicated by the engineer's drawings. Within the limits of accepted engineering practice, the fabricator is free to design the connections to be made as economically as possible, using various combinations of welding and bolting that best suit available equipment and expertise. Drawings are also prepared by the fabricator to show the general contractor exactly where and how to install foundation anchor bolts to connect to the columns of the building and to guide the erector in assembling the steel frame on the building site. When completed, the fabricator's *shop drawings* are submitted to the engineer and the architect for review and approval to be sure that they conform exactly to the intentions of the design team. Meanwhile, the fabricator places an order with a producer of steel for the stock from which the structural steel members will be fabricated. (The major beams, girders, and columns are usually ordered cut to exact length by the mill.) When the approved shop drawings, with corrections and comments, are returned to the fabricator by the design team, revisions are made as necessary, and full-size templates of cardboard or wood are prepared as required to assist the shop workers in laying out the various connections on the actual pieces of steel.

Plates, angles, and tees for connections are brought into the shop and cut to size and shape with gas-fueled cutting torches, power shears, and saws. With the aid of the templates, bolt hole locations are marked. If the plates and angles are not unusually thick, the holes may be made rapidly and economically with a punching machine. In very thick stock, or in pieces that will not fit conveniently into the punching machines, holes are drilled rather than punched.

Pieces of steel stock for the beams, girders, and columns are brought into the fabricator's shop with an overhead traveling crane or conveyor system. Each piece is stenciled or painted with a code that tells which building it is intended for and exactly where it will go in the building. With the aid of the shop drawings, each piece is measured and marked for its exact length and for the locations of all holes, stiffeners, connectors, and other details. Cutting to length, for those members not already cut to length at the mill, is done with a power saw or a flame cutting torch. The ends of column sections that must bear fully on base plates or on one another are squared and made perfectly flat by sawing, milling, or facing. In cases where the columns will be welded to one another, and for beams and girders that are to be welded, the ends of the flanges are beveled as necessary. Beam flanges are *coped* as required. Bolt holes are punched or drilled (Figure 11.43). *Plasma* (high-temperature ionized gas) *cutting* and *laser*

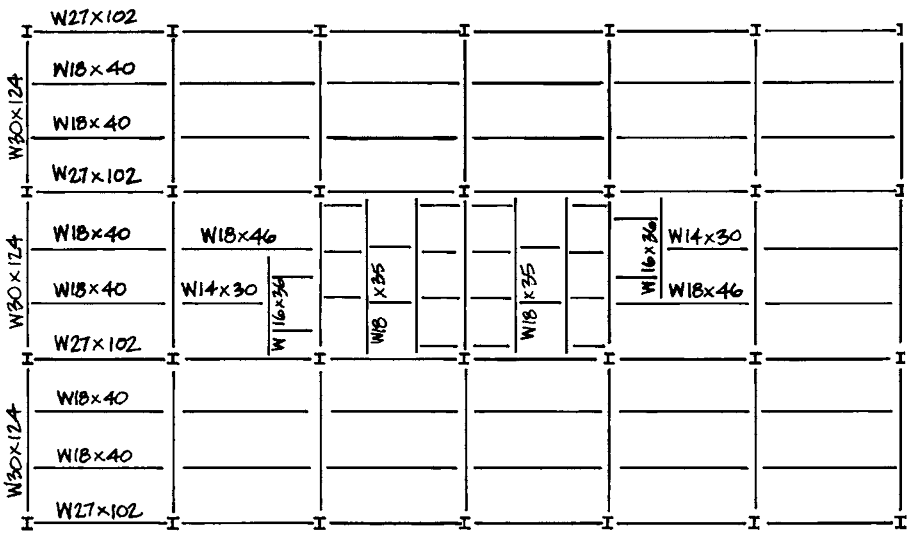


FIGURE 11.42
A typical framing plan for a multistory steel-framed building, showing size designations for beams and girders. Notice how this frame requires beam-to-column-flange connections where the W30 girders meet the columns, beam-to-column-web connections where the W27 beams meet the columns, and coped beam-girder connections where the W18 beams meet the W30 girders. The small squares in the middle of the building are openings for elevators, stairways, and mechanical shafts. An architect's or engineer's framing plan would also give dimensions between centers of columns, and would indicate the magnitudes of the loads that each joint must transfer, to enable the fabricator to design each connection.

cutting are also finding increased use in steel fabrication. Both of these types of cutting devices can be driven by machines that allow the fully automated cutting and shaping of parts from digitally prepared models.

Where called for, beams and girders are *cambered* (curved slightly in an upward direction) so that they will deflect into a straight line under load. Cambering may be accomplished by a hydraulic ram that bends the beam enough to force a permanent deformation. Steel shapes can also be bent to a smooth radius with a large machine that passes the shape through three rollers that flex it sufficiently to impart a permanent curvature (Figure 11.44). An older, much more costly means of cambering involves heating local areas of one flange of the member with a large oxyacetylene torch. As each area is heated to a cherry-red color, the metal softens, expands, and deforms to make a slight bulge in the width and thickness of the flange because the surrounding steel, which is cool, prevents the heated flange from lengthening. As the heated flange cools, the metal contracts, pulling the member into a slight bend at that point. By repeating this process at several points along the beam, a camber of the desired shape and magnitude is produced.

As a last step in fabricating beams, girders, and columns, stiffener plates are arc welded to each piece as required, and connecting plates, angles, and tees are welded or bolted at the appropriate locations (Figure 11.45). As much connecting as possible is done in the shop, where tools are handy and access is easy. This saves time and money during erection, when tools and working conditions are less optimal and total costs per worker-hour are higher.

Plate girders, built-up columns, trusses, and other large components are assembled in the shop in units as large as can practically be transported to the construction site, whether by truck, railway, or barge (Figure 1 1.46). Intricate assemblies such as large

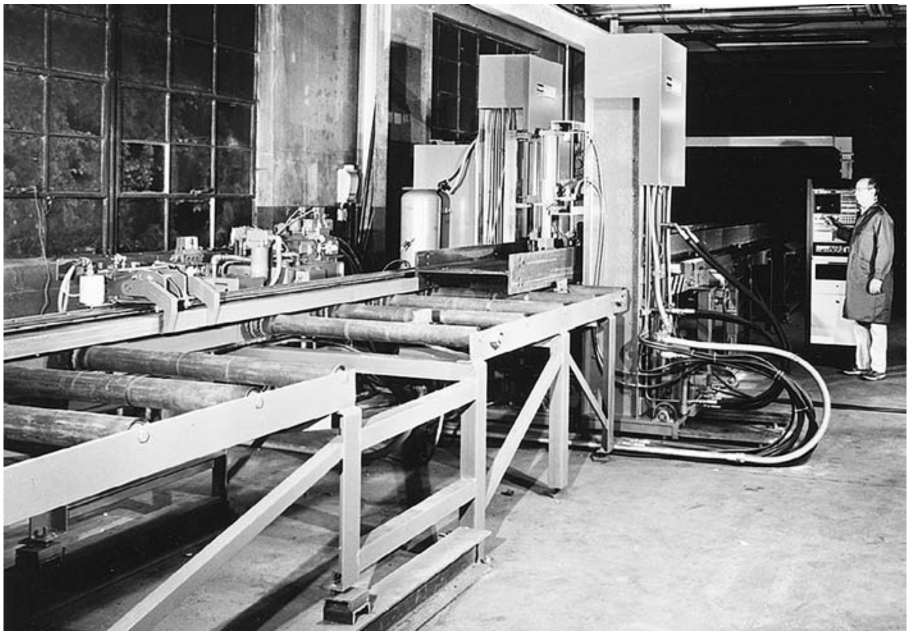


FIGURE 11.43
Punching bolt holes in a wide-flange beam. *(Courtesy of W. A. Whitney Corp.)*

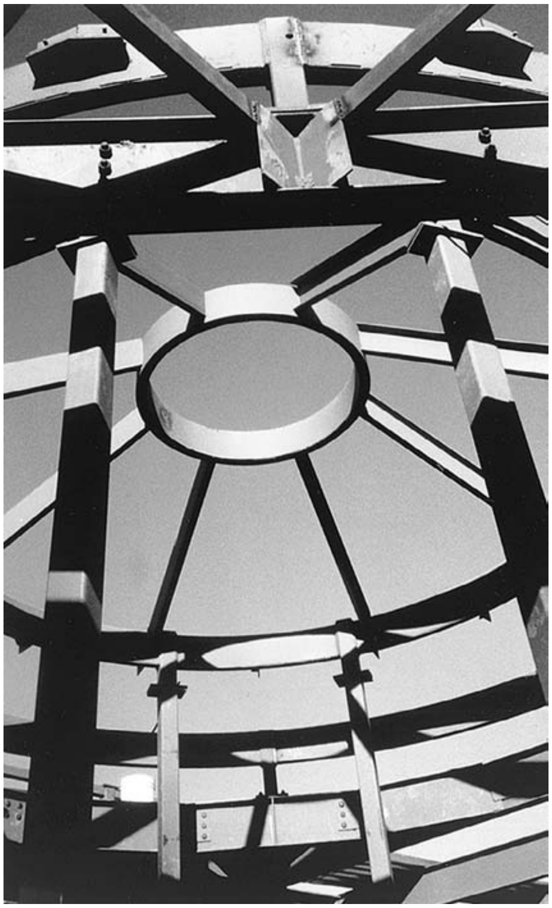


FIGURE 11.44
Rectangular hollow structural sections for this frame were bent into curves by the fabricator. Wide-flange shapes can also be bent. *(Photo by Eliot Goldstein, The Goldstein Partnership, Architects)*

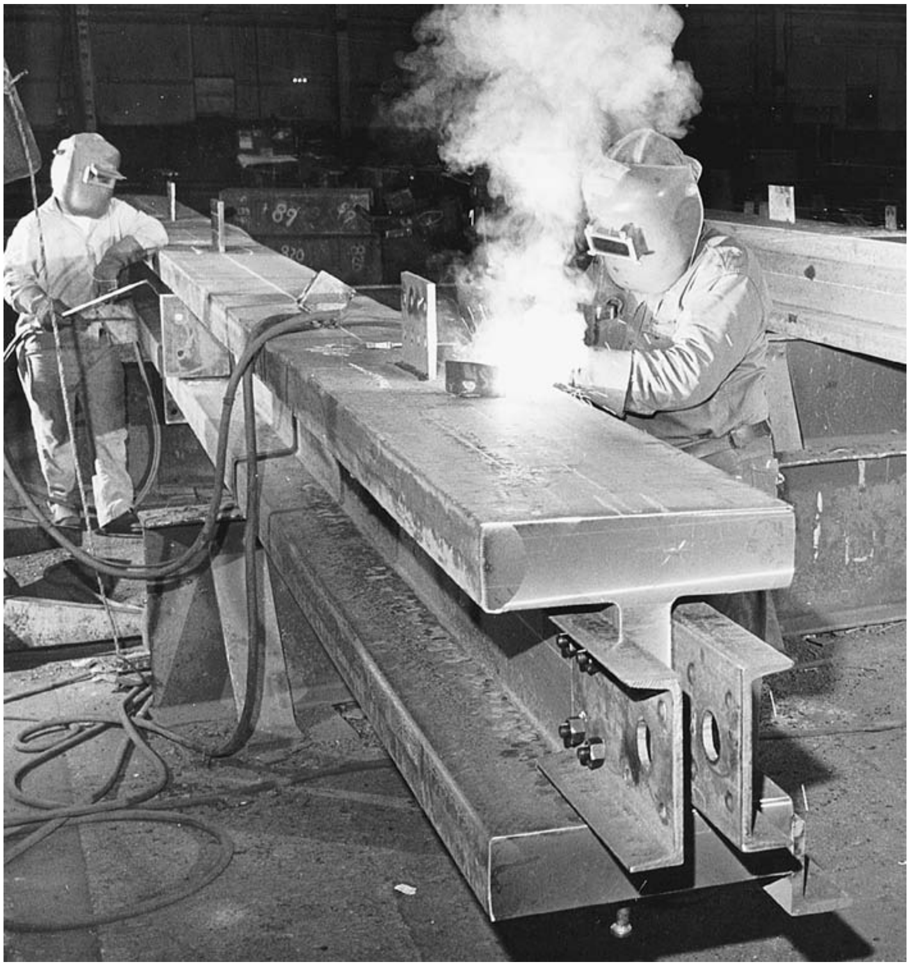


FIGURE 11.45
Welders attach connector plates to an exceptionally heavy column section in a fabricator's shop. The twin channels bolted to the end of the column will be used to attach a lifting line for erection, after which they will be removed and reused. *(Courtesy of U.S. Steel Corp.)*

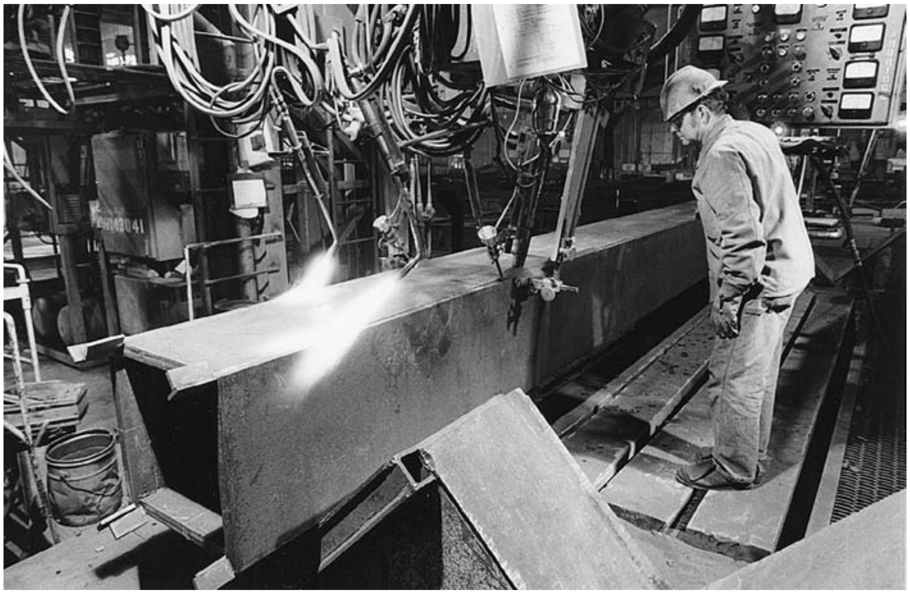


FIGURE 11.46
Machine welding plates together to form a box column. The torches to the left preheat the metal to help avoid thermal distortions in the column. Mounds of powdered flux around the electrodes in the center indicate that this is the submerged arc process of welding. The small steel plates tacked onto the corners of the column at the extreme left are runoff bars, which are used to allow the welding machine to go past the end of the column to make a complete weld. These will be cut off as soon as welding is complete. *(Courtesy of U.S. Steel Corp.)*

trusses are usually preassembled in their entirety in the shop, to be sure that they will go together smoothly in the field, then broken down again into transportable components.

As the members are completed, each is straightened, cleaned and prime painted as necessary, and inspected for quality and for conformance to the job specifications and shop drawings. The members are then taken from the shop to the fabricator's yard by crane, conveyor, trolley, or forklift, where they are organized in stacks according to the order in which they will be needed on the building site.

As an alternative to the traditional process in which the fabricator produces the final design for the steel connections and submits these designs for review by the structural engineer, a structural engineer may use three-dimensional modeling software to design the steel connections and supply digital data to the fabricator to drive the fabricator's automated equipment. While this method requires the engineer to assume more responsibility for the final design of the steel connection details, it also can shorten the time required for steel to arrive on site and can improve the coordination between the structural steel and other building systems.

The Erector

Where the fabricator's job ends, the *erector's* job begins. Some companies both fabricate and erect, but more often the two operations are done by separate companies. The erector is responsible for assembling into a frame on the building site the steel components furnished by the fabricator. The erector's workers, by tradition, are called *ironworkers*.

Erecting the First Tier

Erection of a multistory steel building frame starts with assembly of the first two-story *tier* of framing. Lifting of the steel components is begun with a truck-mounted or crawler-mounted mobile crane. In accordance with the erection drawings prepared by the fabricator, the columns for the first tier, usually furnished in sections two stories high, are picked up from organized piles on the site and lowered carefully over the anchor bolts and onto the foundation, where the ironworkers bolt them down.

> **There are 175,000 ironworkers in this country . . . and apart from our silhouettes ant-size atop a new bridge or skyscraper, we are pretty much invisible.**
>
> **Mike Cherry, *On High Steel: The Education of an Ironworker*, New York, Quadrangle/The New York Times Book Co., 1974, p. xiii**

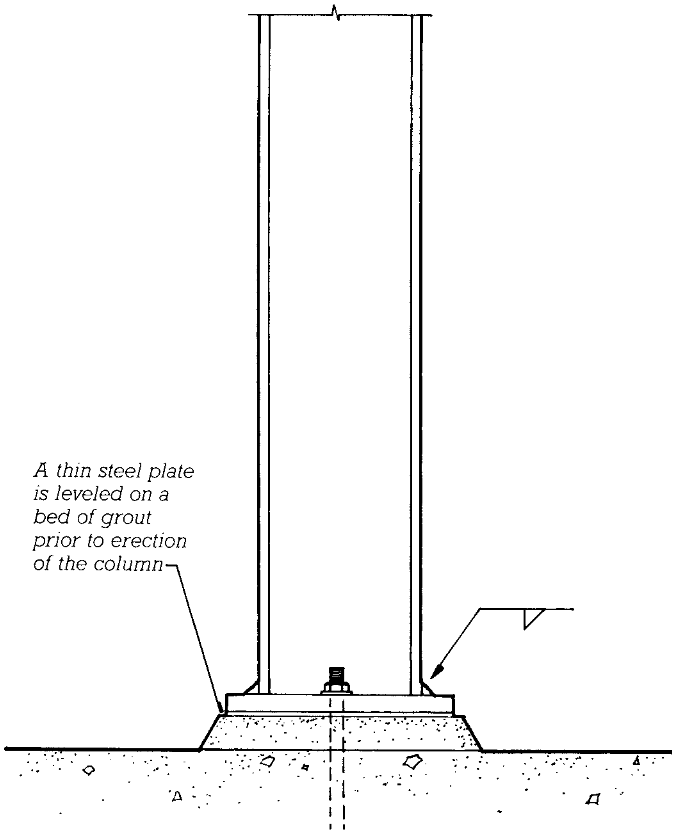
FIGURE 11.47

Three typical column base details. *Upper left*: A small column with a welded baseplate set on a steel leveling plate. *Upper right*: A larger column with a welded baseplate set on leveling nuts. *Below*: A heavy column field welded to a loose baseplate that has been previously leveled and grouted.

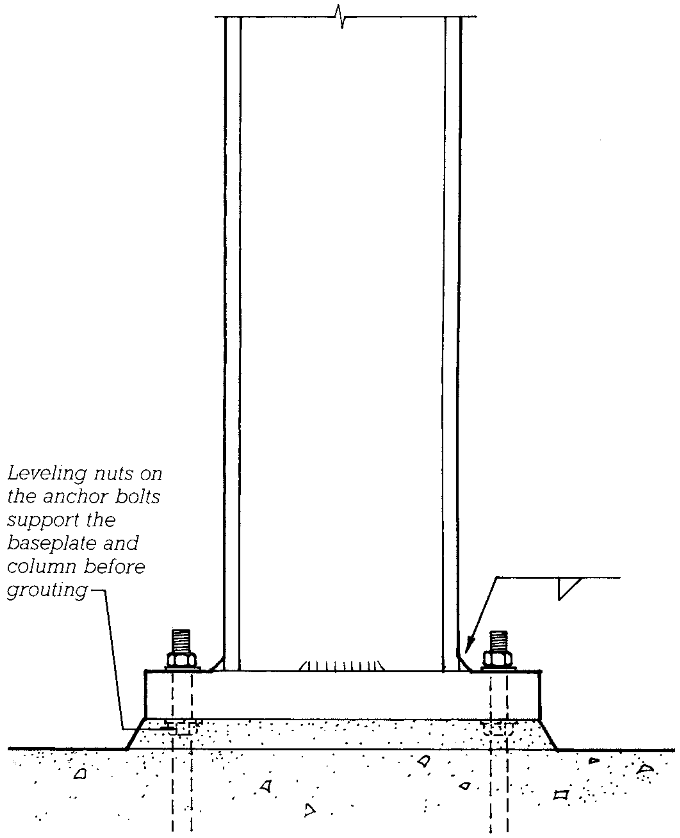
Foundation details for steel columns vary (Figure 11.47). Steel *baseplates*, which distribute the concentrated loads of the steel columns across a larger area of the concrete foundation, are shop welded to all but the largest columns. The foundations and anchor bolts were put in place previously by the general contractor, following the plan prepared by the fabricator. The contractor may, if requested, provide thin steel *leveling plates* that are set perfectly level at the proper height on a bed of *grout* atop each concrete foundation. The baseplate of the column rests upon the leveling plate and is held down with the protruding anchor bolts. Alternatively, especially for larger baseplates with four anchor bolts, the leveling plate is omitted. The column is supported at the proper elevation on stacks of steel shims inserted between the baseplate and the foundation, or on leveling nuts placed beneath the baseplate on the anchor bolts. After the first tier of framing is plumbed up as described below, the baseplates are grouted and the anchor bolts tightened. For very large, heavy columns, baseplates are shipped independently of the columns (Figure 11.48). Each is leveled in place with shims, wedges, or shop-attached leveling screws, then grouted prior to column placement.

After the first tier of columns has been erected, the beams and girders for the first two stories are bolted in place (Figures 11.50–11.55). First, a *raising gang*, working with a crane, positions the components and inserts enough bolts to hold them together temporarily. A gang of bolters follows behind, inserting bolts in all the holes and partially tightening them. The two-story tier of framing is then *plumbed up* (straightened and squared) with diagonal cables and turnbuckles while checking the alignment with plumb bobs, transits, or laser levels. When the tier is plumb, connections are tightened, baseplates are grouted if necessary, welds are made, and permanent diagonal braces, if called for, are rigidly attached. Ironworkers scramble back and forth, up and down on the columns and beams, protected from falling by safety harnesses that are connected to steel cable lifelines (Figure 11.50).

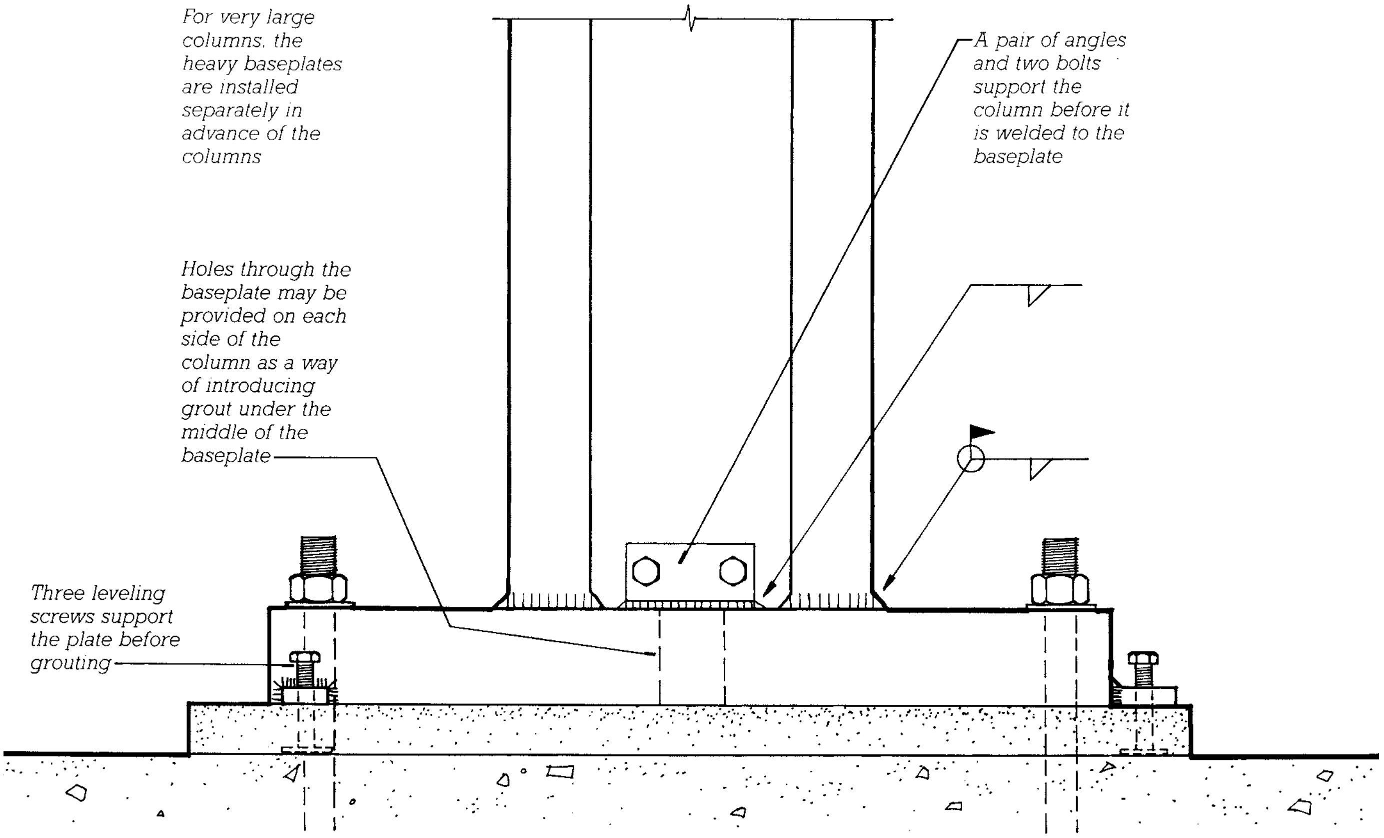
At the top of each tier, a temporary working surface of 2- or 3-inch (50- or 75-mm) wood planks or corrugated steel decking may be laid over the steel framing. Similar platforms will be placed every second story as the frame rises, unless safety nets are used instead or the permanent floor decking is installed as erection



A thin steel plate is leveled on a bed of grout prior to erection of the column



Leveling nuts on the anchor bolts support the baseplate and column before grouting



For very large columns, the heavy baseplates are installed separately in advance of the columns

A pair of angles and two bolts support the column before it is welded to the baseplate

Holes through the baseplate may be provided on each side of the column as a way of introducing grout under the middle of the baseplate

Three leveling screws support the plate before grouting progresses. The platforms protect workers on lower levels of the building from falling objects. They also furnish a convenient working surface for tools, materials, and derricks. Column splices are made at waist level above this platform, both as a matter of convenience and as a way of avoiding conflict between the column splices and the beam-to-column connections. Columns are generally fabricated in two-story lengths, a transportable size that also corresponds to the two-story spacing of the plank surfaces.

Erecting the Upper Tiers

Erection of the second tier proceeds much like that of the first. Two-story column sections are hoisted into position and connected by splice plates to the first tier of columns. The beams and columns for the two floors are set, the tier is plumbed and tightened up, and another layer of planks, decking, or safety netting is installed.

If the building is not too tall, the mobile crane will do the lifting for the entire building. For a taller building, the mobile crane does the work until it gets to the maximum height to which it can lift a *tower crane* (Figure 11.49). The tower crane builds itself an independent tower as the building rises, either alongside the building or within an elevator shaft or a vertical space temporarily left open in the frame.

Figure 11.48

Ironworkers guide the placement of a very heavy column fabricated by welding together two rolled wide-flange sections and two thick steel plates. It will be bolted to its baseplate through the holes in the small plate welded between the flanges on either side. *(Courtesy of Bethlehem Steel Corporation)*

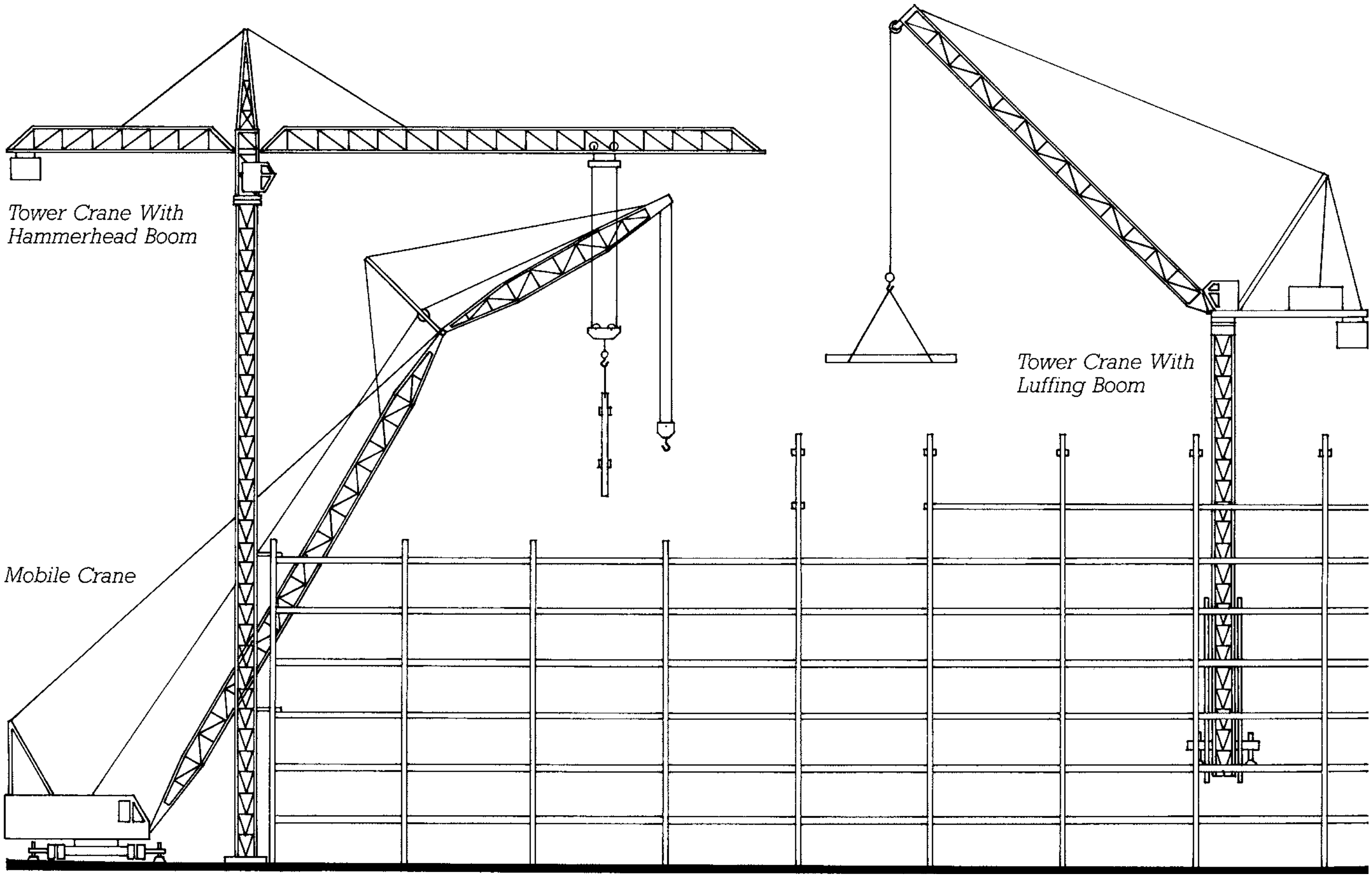


Figure 11.49
Two common types of tower cranes and a mobile crane. The *luffing-boom crane* can be used in congested situations where the movement of the *hammerhead boom crane* would be limited by obstructions. Both can be mounted on either external or internal towers. The internal tower is supported in the frame of the building, whereas the external tower is supported by its own foundation and braced by the building. Tower cranes climb as the building rises by means of self-contained hydraulic jacks.

Figure 11.50
An ironworker clips his body harness to a safety line as he moves around a column. *(Photo by James Digby. Courtesy of LPR Construction Company)*

FIGURE 11.51
A tower crane lowers a series of beams to ironworkers. The worker to the left uses a tagline to maneuver the beam into the proper orientation. *(Photo by James Digby. Courtesy of LPR Construction Company)*

As each piece of steel is lowered toward its final position in the frame, it is guided by an ironworker who holds a rope called a *tagline*, the other end of which is attached to the piece. Other ironworkers in the raising gang guide the piece by hand as soon as they can reach it, until its bolt holes align with those in the mating pieces (Figure 11.53). Sometimes crowbars or hammers must be used to pry, wedge, or drive components until they fit properly, and bolt holes may, on occasion, have to be reamed larger to admit bolts through slightly misaligned pieces. When an approximate alignment has been achieved, tapered steel *drift pins* from the ironworker's tool belt are shoved into enough bolt holes to hold the pieces together until a few bolts can be inserted. The bolters follow behind the raising gang, filling the remaining holes with bolts from leather carrying baskets and tightening them first with hand wrenches and then with impact wrenches. Field-welded connections are initially held in alignment with bolts, then welded when the frame is plumb.

The last beam is placed at the top of the building with a degree of ceremony appropriate to the magnitude of the building. At the very least, a small evergreen tree, a national flag, or both are attached to the beam before it is lifted (Figure 11.56). For major buildings, assorted dignitaries are likely to be invited to a building-site *topping-out* party that includes music and refreshments. After the party, work goes on as usual, for although the frame is complete, the building is not. Roofing, cladding, and finishing operations will continue for many months.

FIGURE 11.52
Connecting a beam to a column. *(Courtesy of Bethlehem Steel Corporation)*

FIGURE 11.53
Ironworkers attach a girder to a box column. Each worker carries two combination wrench–drift pin tools in a holster on his belt and inserts the tapered drift pins into each connection to hold it until a few bolts can be added. Bundles of corrugated steel decking are ready to be opened and distributed over the beams to make a floor deck. *(Courtesy of Bethlehem Steel Corporation)*

Figure 11.54
Bolting joist girders to a column.
(Courtesy Vulcraft Division of Nucor)

Figure 11.55
Welding open-web steel joists to a wide-flange beam. *(Courtesy Vulcraft Division of Nucor)*

FIGURE 11.56
Topping out: The last beam in a steel frame is special. *(Courtesy of U.S. Steel Corp.)*

FIGURE 11.57
A 10-story steel frame nears completion. The lower floors have already been decked with corrugated steel decking. *(Courtesy Vulcraft Division of Nucor)*

> **If nobody plumbed-up, all the tall buildings in our cities would lean crazily into each other, their elevators would scrape and bang against the shaft walls, and the glaziers would have to redress all the windowglass into parallelograms. . . . What leaned an inch west on the thirty-second floor is sucked back east on the thirty-fourth, and a column that refused to quit leaning south on forty-six can generally be brought over on forty-eight, and by the time the whole job is up the top is directly over the bottom.**
>
> **Mike Cherry, *On High Steel: The Education of an Ironworker,* New York, Quadrangle/The New York Times Book Co., 1974, pp. 110–111.**

Floor and Roof Decking

If plank decks are used during erection of the frame, they must be replaced with permanent floor and roof decks of incombustible materials. In early steel frame buildings, shallow arches of brick or tile were often built between the beams, tied with steel tension rods, and filled over with concrete to produce level surfaces (Figure 11.58). These were heavier than the metal deck systems commonly used today and required larger framing members to carry their weight. They were also much more labor intensive.

Metal Decking

Metal decking at its simplest is a thin sheet of steel that has been corrugated to increase its stiffness. The spanning capability of the deck is determined mainly by the thickness of the sheet from which it is made and the depth and spacing of the corrugations. It also depends on whether the decking sheets are single or cellular. Single corrugated sheets are commonly used for *roof decking,* where concentrated loads are not expected to be great and deflection criteria are not as stringent as in floors. They are also used as permanent formwork for concrete floor decks, with a reinforced concrete slab supported by the steel decking until the slab can support itself and its live loads (Figures 11.59–11.61). *Cellular decking* is manufactured by welding together two sheets, one corrugated and one flat. It can be made sufficiently stiff to support normal floor loads without structural assistance from the concrete topping that is poured over it. Cellular decking can offer the important side benefit of providing spaces for electrical and communications wiring, as illustrated in Chapter 24.

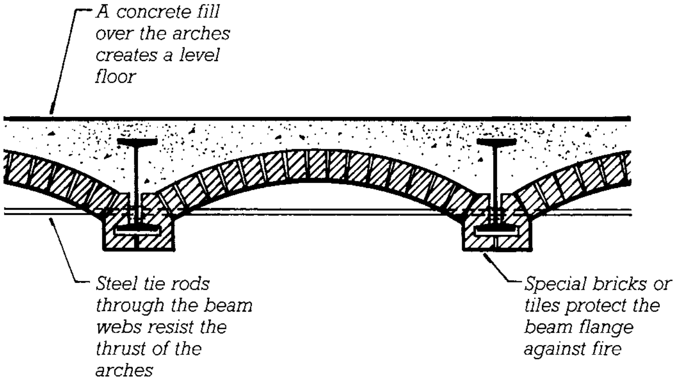


FIGURE 11.58
Tile or brick arch flooring is found in many older steel frame buildings.

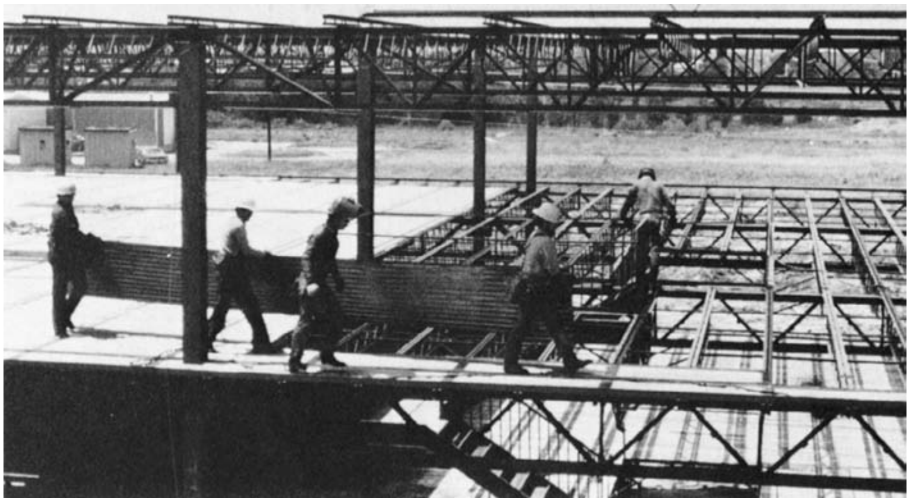


FIGURE 11.59
Workers install corrugated steel form decking over a floor structure of open-web steel joists supported by joist girders. *(Photo by Balthazar Korab. Courtesy Vulcraft Division of Nucor)*

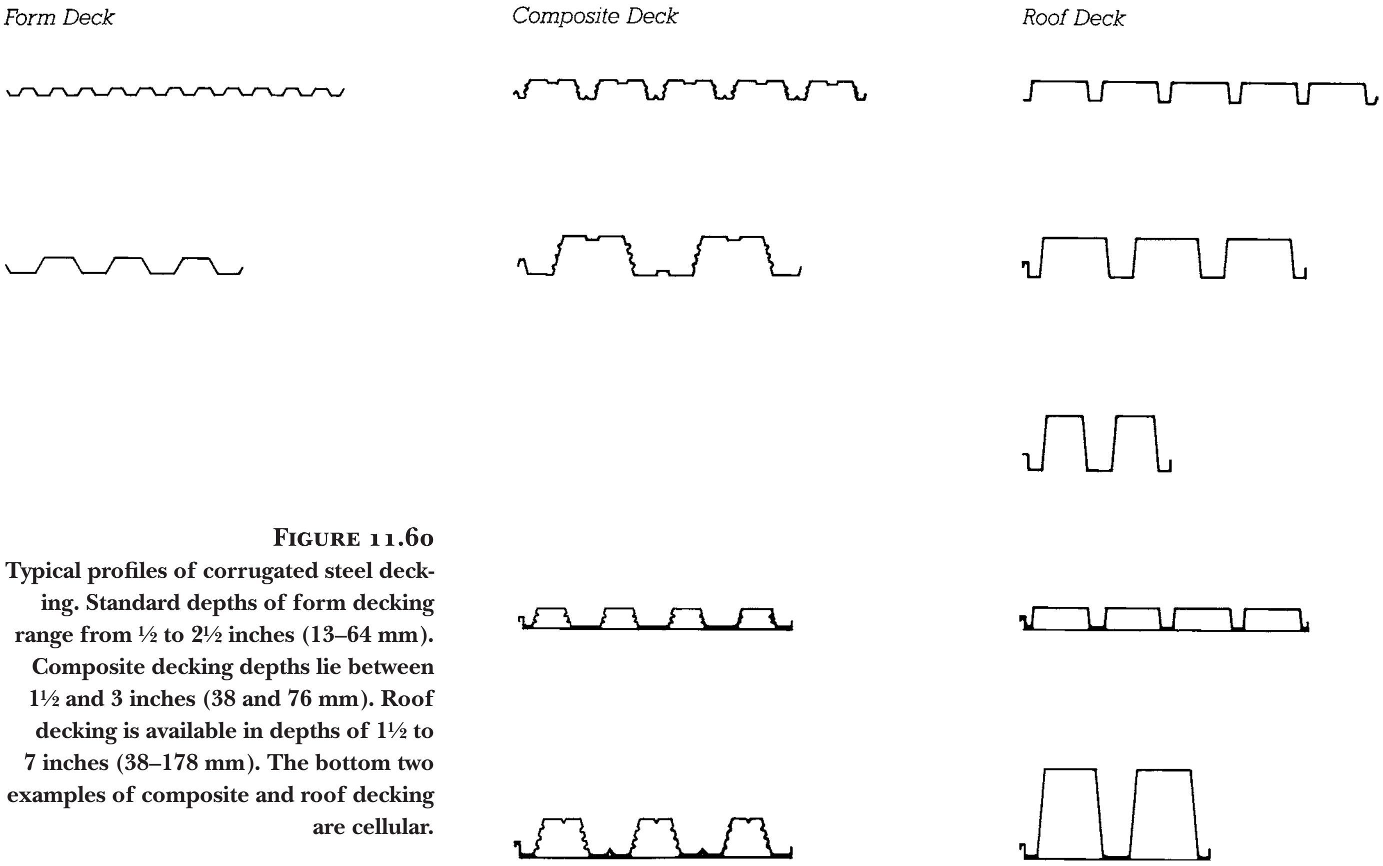


FIGURE 11.60
Typical profiles of corrugated steel decking. Standard depths of form decking range from ½ to 2½ inches (13–64 mm). Composite decking depths lie between 1½ and 3 inches (38 and 76 mm). Roof decking is available in depths of 1½ to 7 inches (38–178 mm). The bottom two examples of composite and roof decking are cellular.

Metal decking is usually *puddle welded* to the joists, beams, and girders by melting through the decking to the supporting members below with a welding electrode. Self-drilling, self-tapping screws or powder-driven pins may also be used for decking attachment. If the deck is required to act as a diaphragm, the longitudinal edges of the decking panels must be connected to one another at frequent intervals with screws or welds.

Composite Construction

Composite metal decking (Figures 11.60 11.62) is designed to work together with the concrete floor topping to make a stiff, lightweight, economical deck. The metal decking serves as

FIGURE 11.61
Samples of corrugated steel decking. The second sample from the bottom achieves composite action by keying of the concrete topping to the deformations in the decking. The bottom sample has a closed end, which is used at the perimeter of the building to prevent the concrete topping from escaping during pouring. *(Courtesy of Wheeling Corrugating Company Division, Wheeling-Pittsburgh Steel Corp.)*

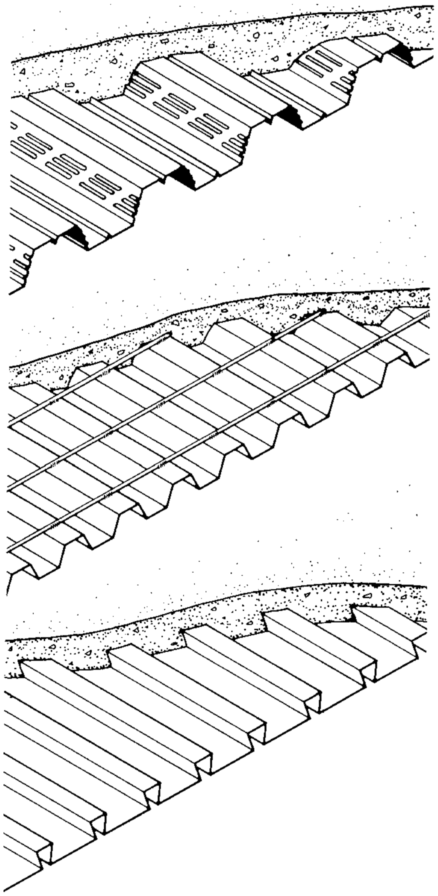


FIGURE 11.62
Composite decking acts as steel reinforcing for the concrete topping installed over it. The top example bonds to the concrete with deformed ribs and the middle example with welded steel rods. The bottom type makes an attractive ceiling texture if left exposed and furnishes dovetail channels for the insertion of special fastening devices to hang ductwork, piping, conduits, and machinery from the ceiling.

tensile reinforcing for the concrete, to which it bonds by means of special rib patterns in the sheet metal or by small steel rods or wire fabric welded to the tops of the corrugations.

Composite construction is often carried a step beyond the decking to include the beams of the floor. Before the concrete is poured over the metal deck, *shear studs* are welded every few inches to the top of each beam, using a special electric welding gun (Figures 11.63 and 11.64). It would be more economical to attach the shear studs in the shop rather than in the field, but the danger that ironworkers would trip on the studs during the erection process delays their installation until the steel decking is in place. The purpose of the studs is to create a strong shear connection between the concrete slab and the steel beam. A strip of the slab can then be assumed to act together with the top flange of the steel shape to resist compressive forces. The result of the composite action of the two materials is a steel member whose loadbearing capacity has been greatly enhanced at relatively low cost by taking advantage of the unused strength of the concrete topping that must be present in the construction anyway. The payoff is a stiffer, lighter, less expensive frame.

Concrete Decks

Concrete floor and roof slabs are often used in steel building frames instead of metal decking and concrete fill. Concrete may be poured in place over removable plywood forms, or it may be erected in the form of precast concrete planks lifted into place much like the metallic elements of the building (Figure 11.65). Precast concrete decks are relatively light in weight and are quick to erect, even under weather conditions that would preclude the pouring of concrete, but they usually require the addition of a thin, poured-in-place concrete topping to produce a smooth floor.

Roof Decking

For roofs of low steel-framed buildings, many different types of decks are available. Corrugated metal may be used, with or without a concrete fill; many types of rigid insulation

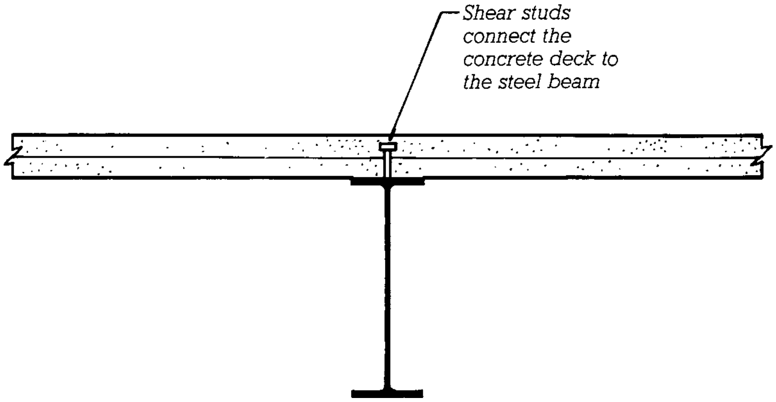


FIGURE 11.63
Composite beam construction.

FIGURE 11.64
Pouring a concrete fill on a steel roof deck, using a concrete pump to deliver the concrete from the street below to the point of the pour. Shear studs are plainly visible over the lines of the beams below. The welded wire reinforcing strengthens the concrete against cracking. *(Courtesy of Schwing America, Inc.)*

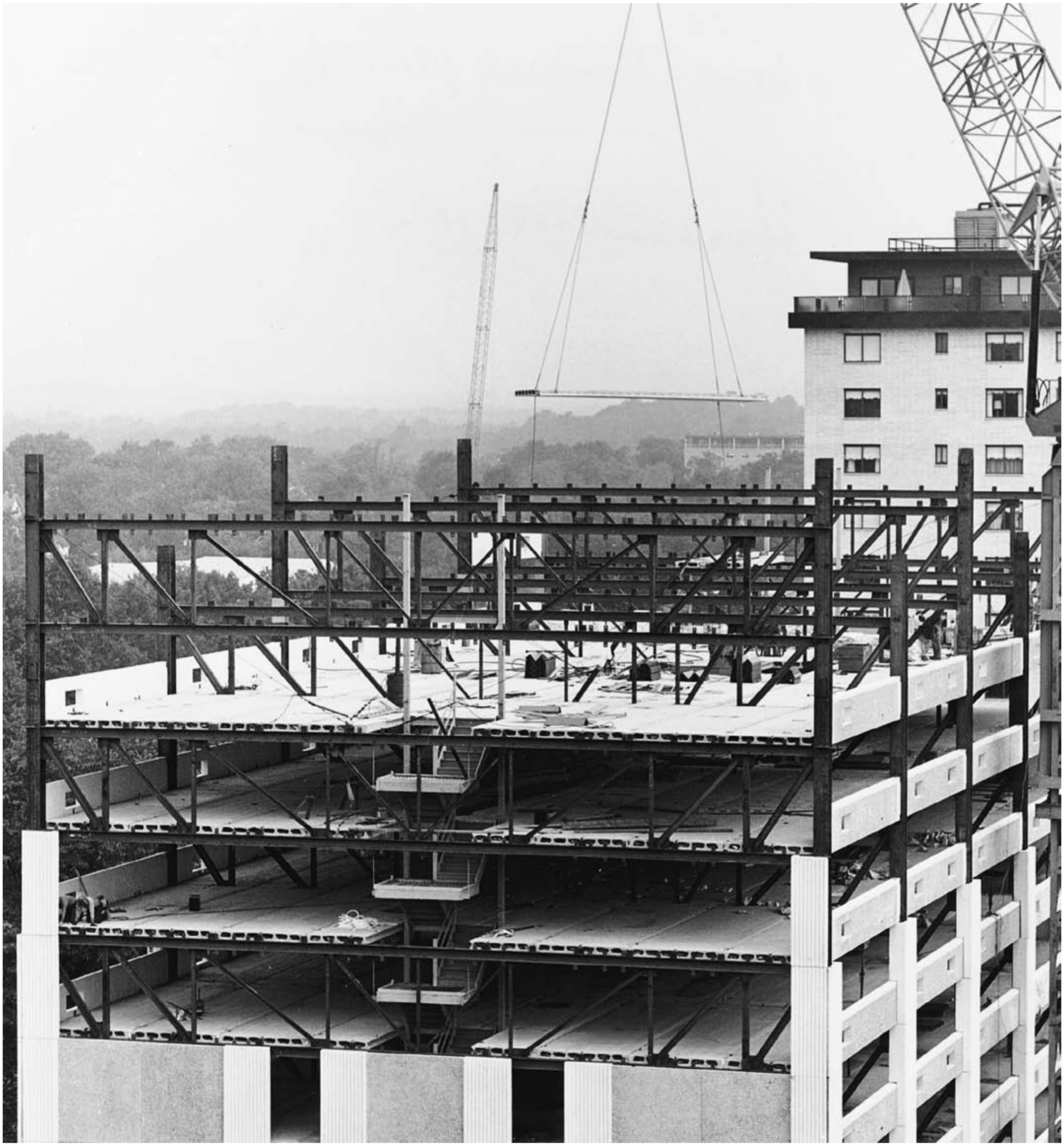


FIGURE 11.65
A tower crane installs precast concrete hollow-core planks for floor decks in an apartment building. Precast concrete is also used for exterior cladding of the building. The steel framing is a design known as the "staggered truss" system, in which story-height steel trusses at alternate levels of the building support the floors. The trusses are later enclosed with interior partitions. An advantage of the staggered truss system is that the floor structure is very thin, allowing overall floor-to-floor heights as small as 8⅔ feet (2.6 m). *(Courtesy of Blakeslee Prestress, Inc.)*

boards are capable of spanning the corrugations to make a flat surface for the roof membrane. Some corrugated decks are finished with a weather-resistant coating that allows them to serve as the water-resistive surface of the roof. Many different kinds of insulating deck boards are produced of wood fibers or glass fibers bonded with portland cement, gypsum, or organic binders. Many of these insulating boards are designed as permanent formwork for reinforced, poured slabs of gypsum or lightweight concrete. In this application, they are usually supported on steel *subpurlins* (Figures 11.66 and 11.67). Heavy timber decking, or even wood joists and plywood sheathing, are also used over steel framing in situations where building codes permit combustible materials.

Corrugated steel sheets are also often used for siding of industrial buildings, where they are supported on *girts*, which are horizontal Z-shapes or channels that span between the outside columns of the building (Figure 11.80).

Architectural Structural Steel

Where structural steel members will remain exposed in the finished building and a high standard of appearance quality is desired, steel may be specified as *architecturally exposed structural steel* (AESS). AESS specifications may include special requirements for dressing and finishing of welds, closer tolerances in connections between members, removal of marks made on the steel during fabrication, application of high-quality finishes, and other considerations.

FIGURE 11.66
Welding truss-tee subpurlins to open-web steel joists for a roof deck. *(Courtesy of Keystone Steel & Wire Co.)*

FIGURE 11.67
Installing insulating formboard over truss-tee subpurlins. A light wire reinforcing mesh and poured gypsum fill will be installed over the formboards. The trussed top edges of the subpurlins become embedded in the gypsum slab to form a composite deck. *(Courtesy of Keystone Steel & Wire Co.)*

FIREPROOFING OF STEEL FRAMING

Building fires are not hot enough to melt steel, but are often able to weaken it sufficiently to cause structural failure (Figures 11.68 and 11.69). For this reason, building codes generally limit the use of exposed steel framing to buildings of one to five stories, where escape in case of fire is rapid. For taller buildings, it is necessary to protect the steel frame from heat long enough for the building to be fully evacuated and the fire extinguished or allowed to burn out on its own.

Fireproofing (fire protection might be a more accurate term) of steel framing was originally done by encasing steel beams and columns in brick masonry or poured concrete (Figures 11.70 and 11.71). These heavy encasements were effective, absorbing heat into their great mass and dissipating some of it through dehydration of the mortar and concrete, but their weight added considerably to the load that the steel frame had to bear. This added, in turn, to the weight and cost of the frame. The search for lighter-weight fireproofing led first to thin enclosures of metal lath and plaster around the steel members (Figures 11.70 11.72). These derive their effectiveness from the large amounts of heat needed to dehydrate the water of crystallization from the gypsum plaster. Plasters based on lightweight aggregates such as vermiculite instead of sand have come into use to further reduce the weight and increase the thermal insulating properties of the plaster.

FIGURE 11.68
An exposed steel structure following a prolonged fire in the highly combustible contents of a warehouse. *(Courtesy of National Fire Protection Association, Quincy, Massachusetts)*

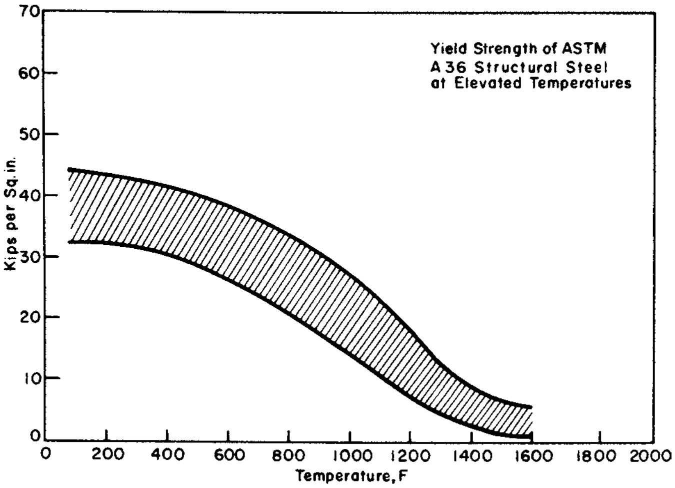


FIGURE 11.69
The relationship between temperature and strength in structural steel. *(Courtesy of American Iron and Steel Institute)*

Today's designers can also choose from a group of fireproofing techniques that are lighter still. Plaster fireproofing has largely been replaced by beam and column enclosures made of boards or slabs of gypsum or other fire-resistive materials (Figures 11.70–11.75). These are fastened mechanically around the steel shapes, and in the case of gypsum board fireproofing, they can also serve as the finished surface on the interior of the building.

Where the fireproofing material need not serve as a finished

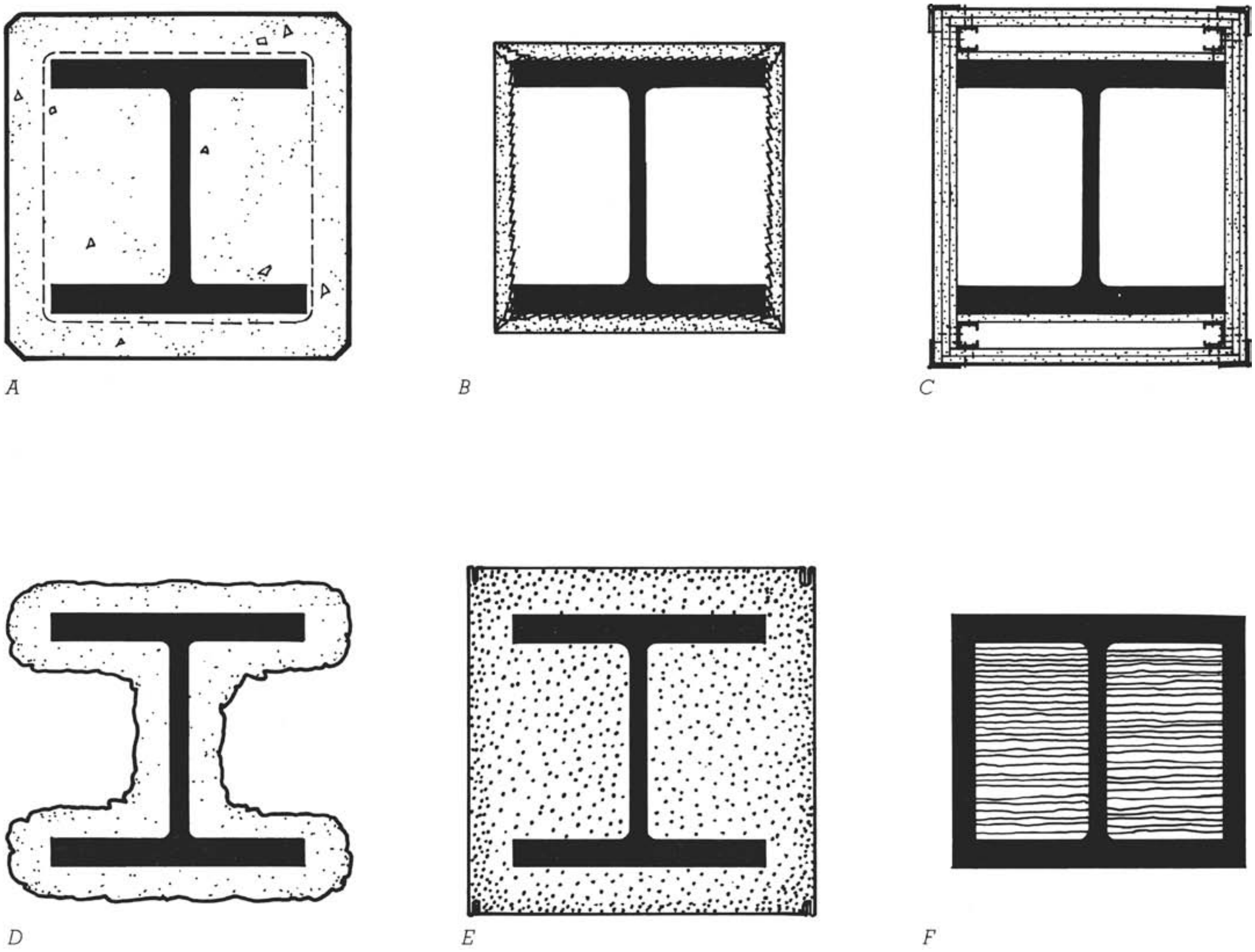


FIGURE 11.70
Some methods for fireproofing steel columns. (*a*) Encasement in reinforced concrete. (*b*) Enclosure in metal lath and plaster. (*c*) Enclosure in multiple layers of gypsum board. (*d*) Spray-on fireproofing. (*e*) Loose insulating fill inside a sheet metal enclosure. (*f*) Water-filled box column made of a wide-flange shape with added steel plates.

surface, *spray-applied fire-resistive materials (SFRM)*, commonly referred to as spray-applied fireproofing, have become the most prevalent type. These generally consist of either a fiber and a binder or a cementitious mixture, and are sprayed over the steel to the required thickness (Figure 11.76). These products are available in weights of about 12 to 40 pounds per cubic foot (190 640 kg/m^3). The lighter materials are fragile and must be covered with finish materials. The denser materials are generally more durable. All spray-applied materials act primarily by insulating the steel from high temperatures for long periods of time. They are usually the least expensive form of steel fireproofing. Spray-applied fireproofing is most commonly applied in the

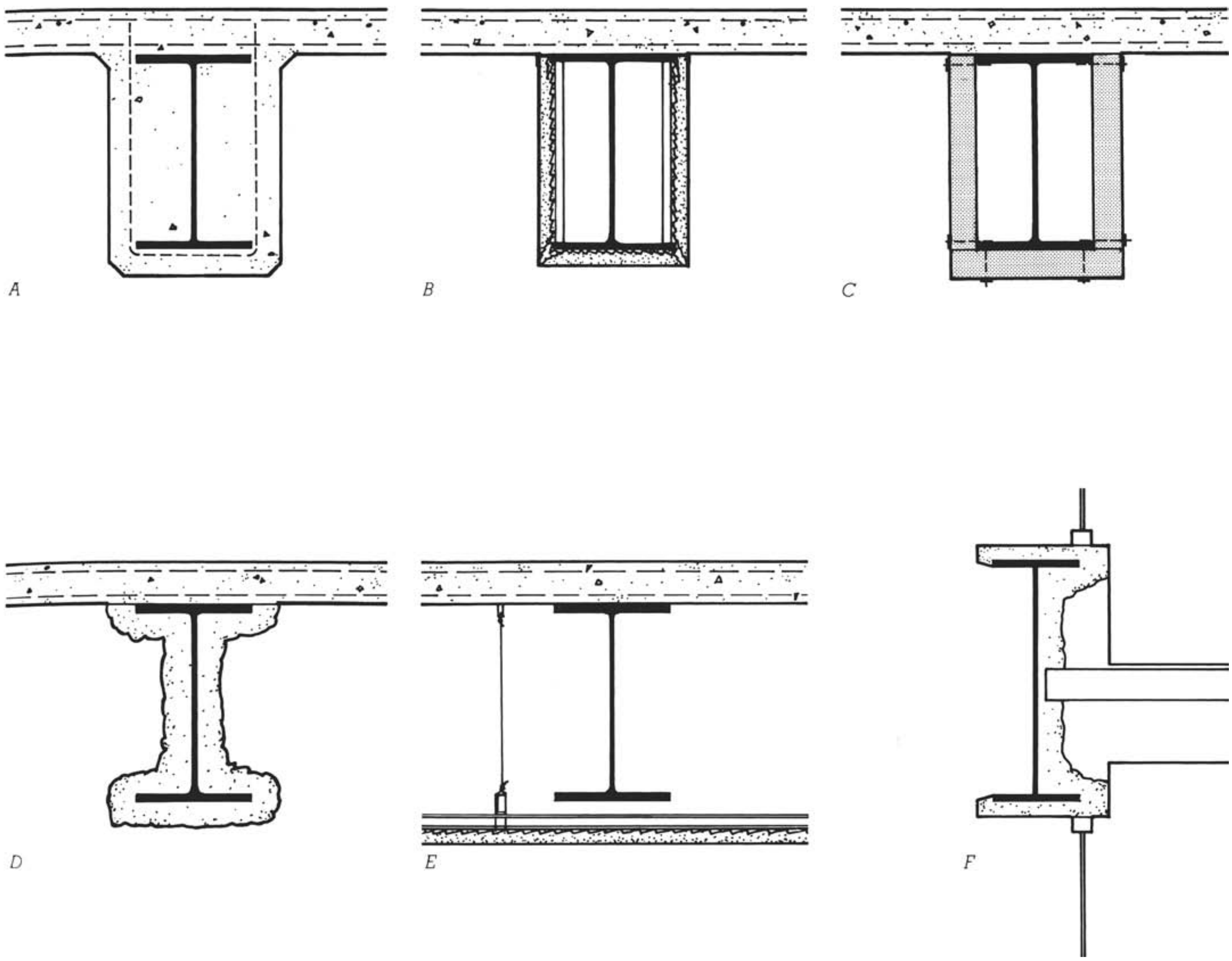


FIGURE 11.71
Some methods for fireproofing steel beams and girders. (*a*) Encasement in reinforced concrete. (*b*) Enclosure in metal lath and plaster. (*c*) Rigid slab fireproofing. (*d*) Spray-on fireproofing. (*e*) Suspended plaster ceiling. (*f*) Flame-shielded exterior spandrel girder with spray-on fireproofing inside.

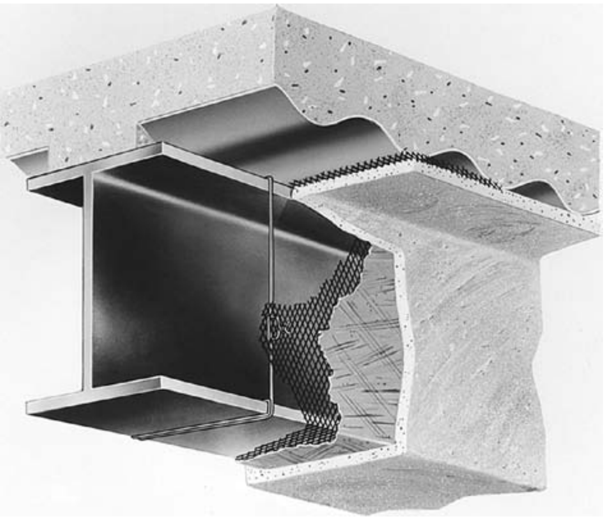


Figure 11.72
Lath-and-plaster fireproofing around a steel beam.
(Courtesy of United States Gypsum Company)

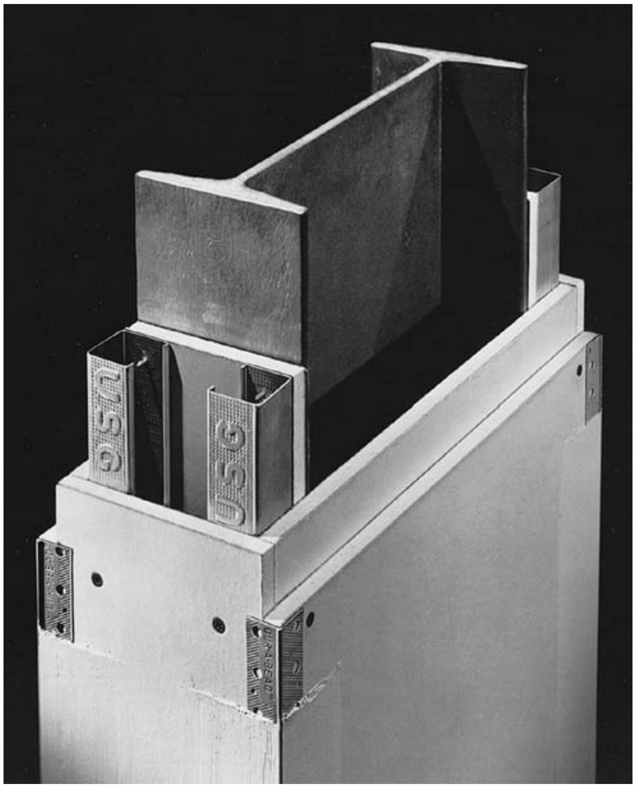


Figure 11.73
Gypsum board fireproofing around a steel column. The gypsum board layers are screwed to the four cold-formed steel C-channels at the corners of the column, and finished with steel corner bead and drywall compound on the corners. *(Courtesy of United States Gypsum Company)*

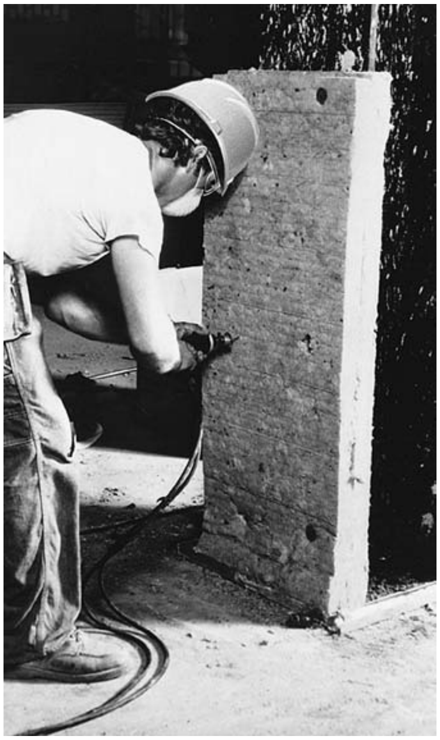


Figure 11.74
Attaching slab fireproofing made of mineral fiber to a steel column, using welded attachments. *(Courtesy of United States Gypsum Company)*

Figure 11.75
Slab fireproofing on a steel beam.
(Courtesy of United States Gypsum Company)

field after the steel has been erected and the connections between members are completed. It can also be applied in the fabrication shop, where controlled environmental conditions and easier access to the steel members can result in faster and more consistent-quality application.

When terrorists flew airliners into Manhattan's World Trade Center towers in 2001, the fireproofing on steel structural components of the buildings was dislodged by the impact of the airplanes. This left these structures vulnerable to the heat of the fires that followed the crashes and is believed to be a primary cause of the eventual collapse of both buildings. In response to this failure, the International Building Code now requires higher bond strengths for spray-applied fireproofing used in buildings with occupied floors greater than 75 feet (23 m) above the level of firefighter access.

The newest generation of fireproofing techniques for steel offers new possibilities to the designer. *Intumescent mastics* and *intumescent paints* are thin coatings that allow steel structural elements to remain exposed to view in situations of low to moderate fire risk. They expand when exposed to fire to form a thick, stable char that insulates the steel from the heat of the fire for varying lengths of time, depending on the thickness of the coating. Most intumescent coatings are available in an assortment of colors. They can also serve as a base coat under ordinary paints if another color is desired.

A rather specialized technique, applicable only to steel box or tube columns exposed on the exterior of buildings, is to fill the columns with water and antifreeze (Figure 11.70*f*). Heat applied to a region of a column by a fire is dissipated throughout the column by convection in the liquid filling.

Mathematical and computer-based techniques have been developed for calculating temperatures that will be reached by steel members in various situations during a fire. These allow the designer to experiment with a variety of ways of protecting the members, including metal flame shields that allow the component to be left exposed on the exterior of a building (Figure 11.71*f*).

FIGURE 11.76

Applying spray-on fireproofing to a steel beam, using a gauge to measure the depth. *(Courtesy of W. R. Grace & Co.)*

Longer Spans in Steel

Standard wide-flange beams are suitable for the range of structural spans normally encountered in offices, schools, hospitals, apartment buildings hotels, retail stores, warehouses, and other buildings in which columns may be brought to earth at intervals without obstructing the activities that take place within. For many other types of buildings athletic buildings, certain types of industrial buildings, aircraft hangars, auditoriums, theaters, religious buildings, transportation terminals longer spans are required than can be accomplished with wide-flange beams. A rich assortment of longer-span structural devices is available in steel for these uses.

Improved Beams

One general class of longer-span devices might be called improved beams. The *castellated beam* (Figures 11.77 and 11.78) is produced by flame cutting the web of a wide-flange section along a zigzag path, then reassembling the beam by welding its two halves point to point, thus increasing its depth without increasing its weight. This greatly augments the spanning potential of the beam, provided that the superimposed loads are not exceptionally heavy.

For long-span beams tailored to any loading condition, *plate girders* are custom designed and fabricated. Steel plates and angles are assembled by bolting or welding in such a way as to put the steel exactly where it is needed: The flanges are often made thicker in the middle of the span where bending forces are higher, more web stiffeners are provided near the ends where web stresses are high, and areas around the supports are specially reinforced. Almost any depth can be manufactured as needed, and very long spans are possible, even under heavy loads (Figure 11.79). These members are often tapered, having greater depth where the bending moment is largest.

Rigid steel frames are efficiently produced by welding together steel wide-flange sections or plate girders. They may be set up in a row to roof a rectangular space (Figure 11.80) or arrayed around a vertical axis to cover a circular area. Their structural action lies midway between that of a rectilinear frame and that of an arch. Like an arch, they may sometimes require steel tie rods at the base to resist lateral thrust, in which case these rods are usually concealed within the floor slab.

Castellated beams, plate girders, and rigid steel frames share the characteristic that because they are long, slender elements, they frequently must be braced laterally by purlins, girts, decking, or diagonal bracing to prevent them from buckling.

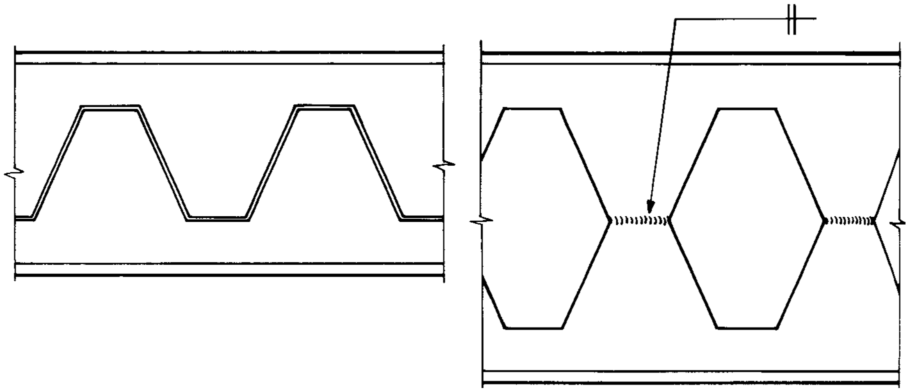


Figure 11.77
Manufacture of a castellated beam.

Figure 11.78
Castellated beams and girders frame into a wide-flange column.
(Courtesy of Castelite Steel Products, Midlothian, Texas)

Figure 11.79
Erecting a welded steel plate girder. Notice how the girder is custom made with cutouts for the passage of pipes and ductwork. The section being erected is 115 feet (35 m) long, 13 feet (4 m) deep, and weighs 192,000 pounds (87,000 kg). *(Courtesy of Bethlehem Steel Corporation)*

Figure 11.80
The steel rigid frames of this industrial building carry steel purlins that will support the roof deck and girts to support the wall cladding. The depth of each frame varies with the magnitude of the bending forces and is greatest at the eave connections, where these forces are at a maximum. *(Courtesy of Metal Building Manufacturers Association)*

Trusses

Steel trusses (Figures 11.81 11.84) are triangulated arrangements of steel members that are generally deeper and lighter than improved beams and can span correspondingly longer distances. They can be designed to carry light or heavy loads. Earlier in this chapter, one class of steel trusses, open-web joists and joist girders, was presented. These are standardized light members for light loadings that are capable of fairly long spans, and they are usually less expensive than custom-made trusses. Custom-made roof trusses for light loadings are most often made up of steel tee or paired-angle top and bottom *chords* with paired-angle internal members. The angles within each pair are spaced just far enough

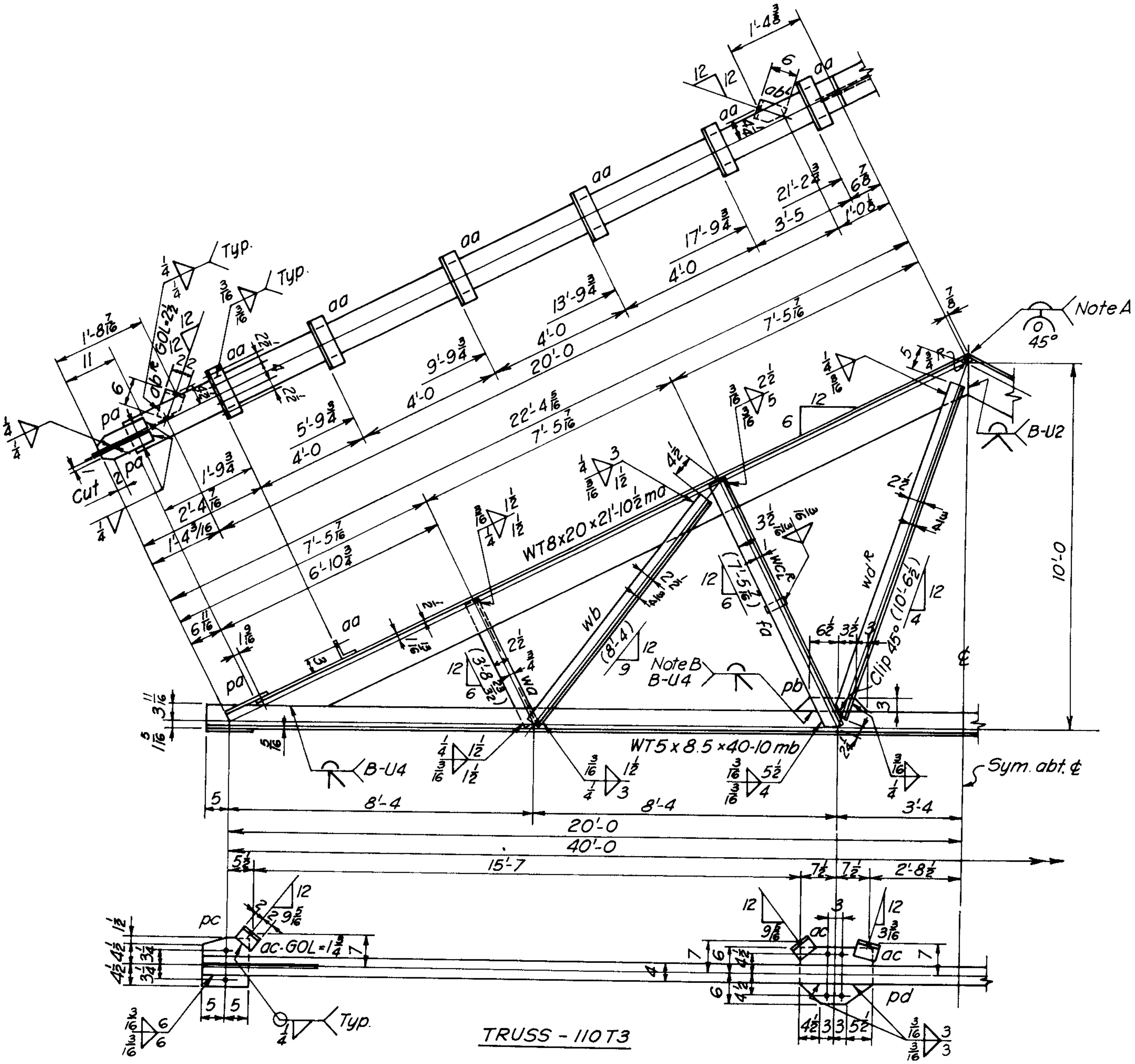


Figure 11.81

A fabricator's shop drawing of a welded steel roof truss made of tees and paired-angle diagonals. *(From* Detailing for Steel Construction, *Chicago, AISC, 1983. By permission of American Institute of Steel Construction)* apart to leave space between for the steel gusset plate connectors that join them to the other members of the truss. They may be either welded or bolted to the gusset plates. Trusses for heavier loadings, such as the transfer trusses that are used in some building frames to transmit column loads from floors above across a wide meeting room or lobby in a building, can be made of wide-flange or tubular shapes.

A steel *space truss* (more popularly called a *space frame*) is a truss made three dimensional (Figures 11.85 and 11.86). It carries its load by bending along both of its axes, much like a two-way concrete slab (Chapter 13). It must be supported by columns that are spaced more or less equally in both directions.

FIGURE 11.82

Bolted steel roof trusses over a shopping mall support steel purlins that carry the corrugated steel roof deck. *(Permission of American Institute of Steel Construction)*

FIGURE 11.83
Ironworkers seat the end of a heavy roof truss made of wide-flange sections. *(Permission of American Institute of Steel Construction)*

FIGURE 11.84
Tubular steel trusses support the roof of a convention center. *(Permission of American Institute of Steel Construction)*

Figure 11.85
Assembling a space truss. *(Courtesy of Unistrut Space-Frame Systems, GTE Products Corp.)*

Arches

Steel *arches*, produced by bending standard wide-flange shapes or by joining plates and angles, can be made into cylindrical roof vaults or circular domes of considerable span (Figure 11.87). For greater spans still, the arches may be built of steel trusswork. Lateral thrusts are produced at the base of an arch and must be resisted by the foundations or by a tie rod. At the time of this writing, the longest single-span roof structure in the world is reported to be a retractable football stadium roof, currently under construction in Arlington, Texas, supported on a pair of steel box trusses, spanning 1225 ft (373 m). The trusses are each 35 feet (11 m) deep and weigh 3255 tons (2955 metric tons).

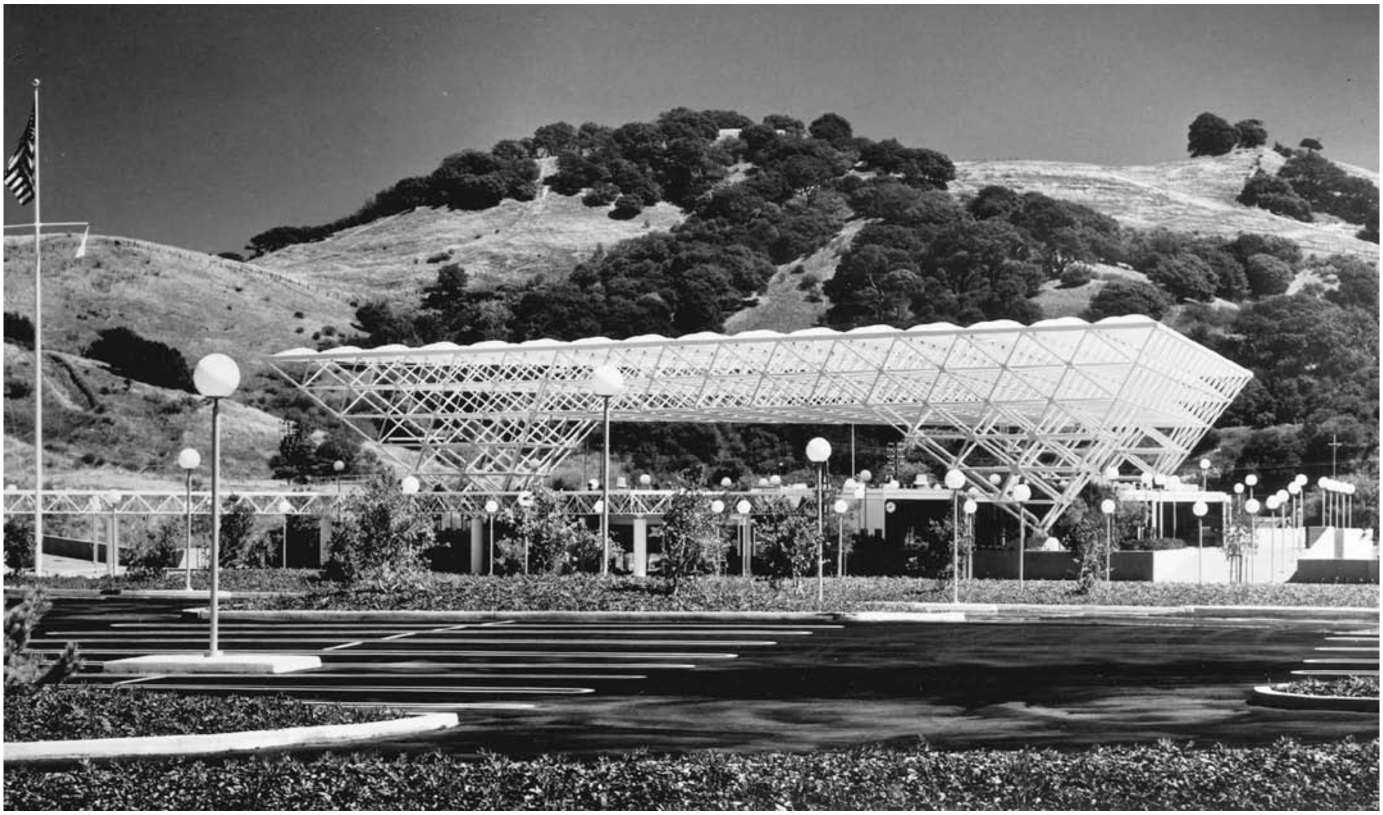
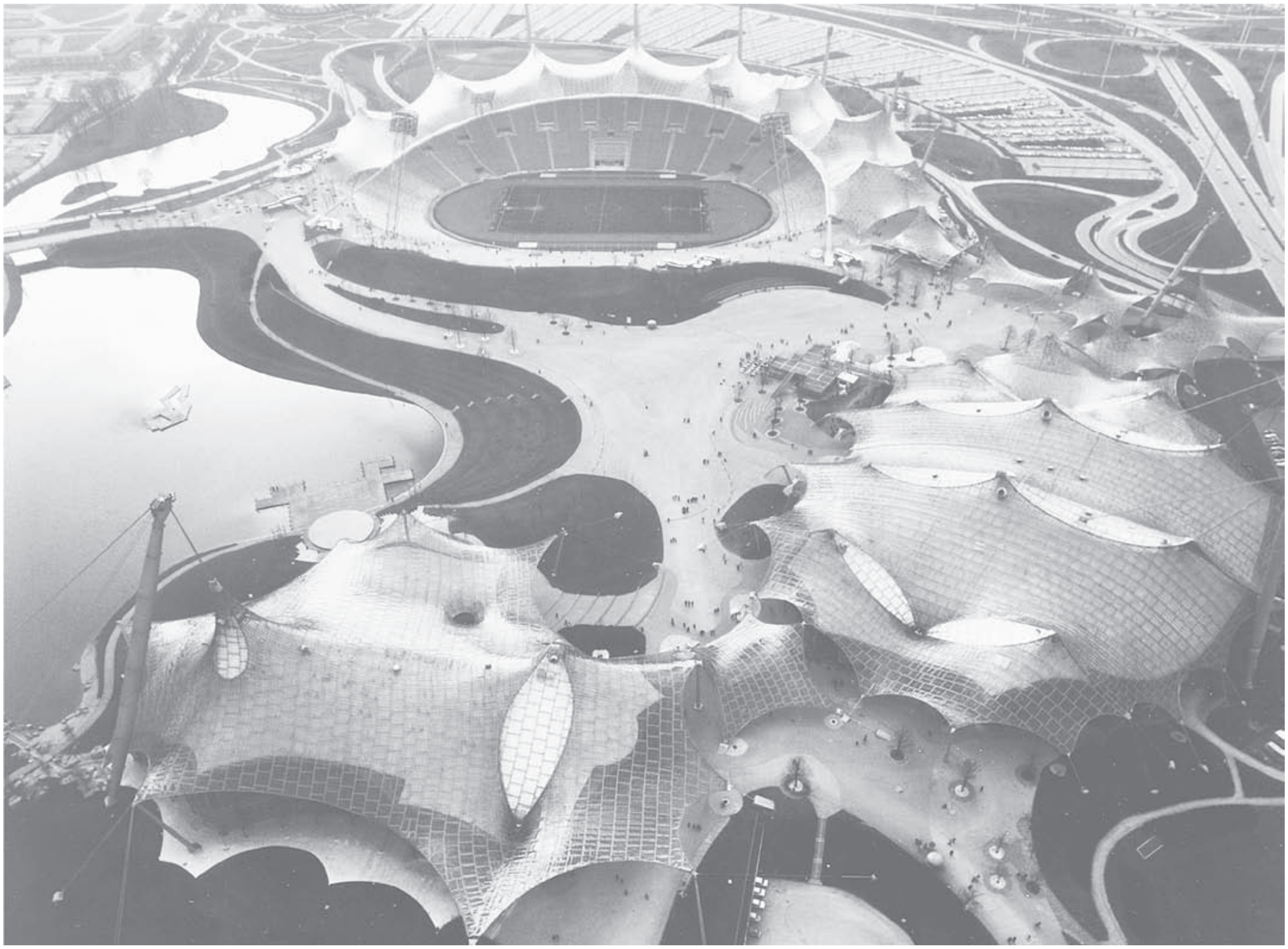


Figure 11.86
A space truss carries the roof of a ferry terminal. *(Architects: Braccia/DeBrer/Heglund. Structural engineer: Kaiser Engineers. Photo by Barbeau Engh. Permission of American Institute of Steel Construction)*

Figure 11.87
Erecting the steel dome at Disney World.
(© Walt Disney Productions. Permission of American Institute of Steel Construction)

Figures 11.88 and 11.89
The Olympic Stadium roof in Munich, Germany, is made of steel cables and transparent acrylic plastic panels. For scale, notice the worker seen through the roof at the upper left of Figure 11.89.
(Architects: Frei Otto, Ewald Bubner, and Benisch and Partner. Courtesy of Institute for Lightweight Structures, Stuttgart)

(continued)



Tensile Structures

High-tensile-strength wires of cold-drawn steel, made into cables, are the material for a fascinating variety of tentlike roofs that can span very long distances (Figures 11.88 and 11.89). With *anticlastic* (saddle-shaped) *curvature*, *cable stays*, or other means of restraining the cable net, hanging roofs are fully rigid against wind uplift and flutter. For smaller spans, fabrics can do most of the work, supported by steel cables along the edges and at points of maximum stress, as presented in the accompanying sidebar.

FIGURES 11.88 AND 11.89
(continued)

> **The spider web is a good inspiration for steel construction.**
>
> **Frank Lloyd Wright, "In the Cause of Architecture: The Logic of the Plan,"** ***Architectural Record*** **(January 1928).**

FABRIC STRUCTURES

Fabric structures are not new: People have constructed tents since the earliest days of human civilization. During the last several decades, however, new, durable fabrics and computerized methods for finding form and forces have helped to create a new construction type: a permanent, rigid, stable fabric structure that will last for 20 years or more.

Types of Fabric Structures

Fabric structures are either tensile or pneumatic (Figure A). A *tensile fabric structure* is a membrane supported by masts or other rigid structural elements such as frames or arches. The membrane usually consists of a woven textile fabric and is generally reinforced with steel cables along the main lines of stress. The fabric and cables transmit external loads to the rigid supports and ground anchors by means of tensile forces.

Pneumatic structures depend on air pressure for their stability and their capacity to carry snow and wind loads. The most common type of pneumatic structure is the *air-supported structure*, in which an airtight fabric, usually reinforced with steel cables, is held up by pressurizing the air in the inhabited space below it. The fabric and cables in an air-supported structure are stressed in tension.

Fabrics for Permanent Structures

Nearly all fabric structures are made of woven cloth that has been coated with a synthetic material. The cloth provides structural strength to resist the tensile forces in the structure, and the coating makes the fabric airtight and water resistant. The most widely used fabric is polyester cloth that has been laminated or coated with polyvinyl chloride (vinyl, PVC). Two other frequently used, longer-lasting fabrics are based on glass fiber cloth: One is coated with polytetrafluorethylene (PTFE, the most common brand of which is known as Teflon); the other is coated with silicone. The polyester/PVC fabric is the most economical of the three, but it does not meet U.S. building code requirements for a noncombustible material and is used predominantly for smaller structures. The glass/PTFE and glass/silicone fabrics are classified as noncombustible. Though it is more expensive, the glass/PTFE fabric remains clean longer than the other two. All three fabrics are highly resistant to such forces of deterioration as ultraviolet light, oxidation, and fungi.

Fabrics may be white, colored, or imprinted with patterns or graphics. A fabric may be totally opaque, obstructing all passage of light, or it may be translucent, allowing a controlled percentage of light to pass through.

Though a single layer of fabric has little resistance to the flow of heat, a properly designed fabric structure can achieve substantial energy savings over conventional enclosures through selective use of translucency and reflectivity. Translucency can be used to provide natural illumination, gather solar heat in the winter, and cool the space at night in the summer. A highly reflective fabric can reduce solar heat gain and conserve artificial illumination. With the addition of a second layer, a fabric liner that is suspended about a foot (300 mm) below the structural fabric, the thermal resistance of the structure can be improved. An acoustic inner liner can help to control internal sound reflection, which is especially important in air-supported structures, which tend to focus sound. Tensile structures, because of their anticlastic curvature, tend to disperse sound rather than focus it.

FIGURE A
Simple tensile and pneumatic (air-supported) fabric structures. *(Sketch by Edward Allen)*

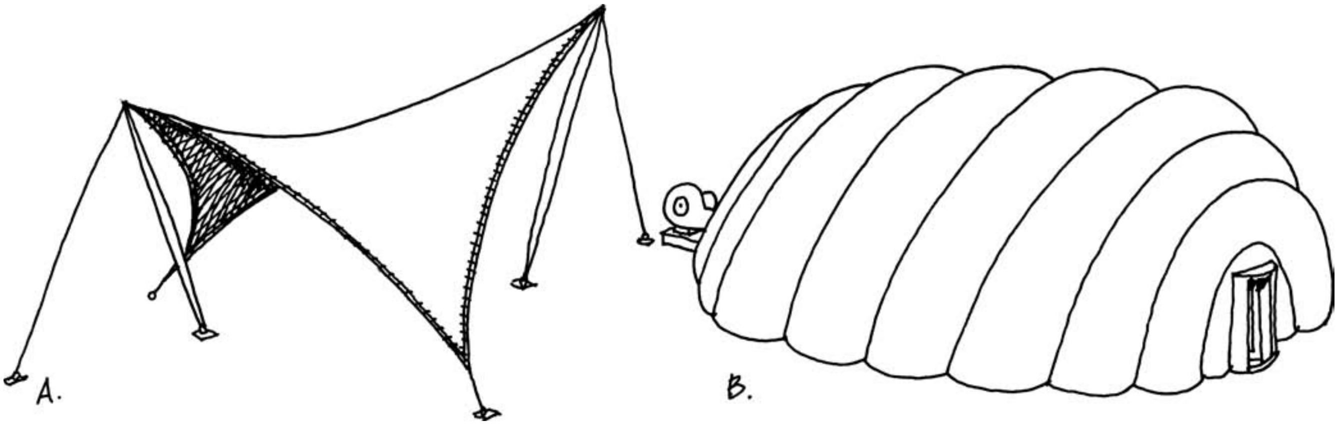


Figure B
The world's largest roof structure covers the Haj Terminal in Jeddah, Saudi Arabia, a colossal airport facility that is used to facilitate the travel of vast numbers of Muslim faithful during a short period of annual pilgrimage. The roof is made up of radial shapes. *(Architects: Skidmore, Owings & Merrill. Roof designer and structural engineer: Geiger Berger Associates. Photographs for Figures B–G are furnished by the courtesy of the photographer, Horst Berger.)*

Figure C
The fabric of the Haj Terminal is PTFE-coated glass fiber cloth.

Figure D
The roof canopy of the San Diego Convention Center is supported at the perimeter on the concrete frame of the building below.

Figure E
The San Diego Convention Center's roof is raised at the middle on rigid steel struts that rest on cables supported by the concrete frame. *(Architects: Arthur Erickson Associates. Roof designer and structural engineer: Horst Berger Partners)*

FABRIC STRUCTURES *(CONTINUED)*

FIGURE F

The form of the Denver International Airport roof combines saddle and radial shapes to echo the forms of the surrounding mountains. *(Architects: C. W. Fentriss, J. H. Bradburn & Associates. Roof designer and structural engineer: Severud Associates, Horst Berger, Principal Consultant)*

FIGURE G

Like the petals of a giant flower, tensile structures arranged in a huge circle shade the grandstand of King Fahd Stadium in Riyadh, Saudi Arabia. The masts are 190 feet (58 m) high. *(Architects: Ian Fraser, John Roberts & Partners. Roof designer and structural engineer: Geiger Berger Associates)*

Tensile Structures

Tensile structures are stabilized by anticlastic curvature and *prestress*. Anticlastic curvature means that the fabric is curved simultaneously in two opposite directions. Two basic geometries may be used to create anticlastic curvature: One is the saddle shape (Figures D, E, and G), the other the radial tent (Figures B and C). It is from combinations and variations of these geometries, as in Figure F, that all tensile structures are shaped.

Prestress is the introduction of permanent tension into the fabric in two opposing directions. Without anticlastic curvature and prestress, the fabric would flutter in the wind and destroy itself within a short time. The amount of curvature and the amount of prestressing force must both be sufficient to maintain stability under expected wind and snow conditions. If the curvature is too flat or if the prestressing tension is too low, excessive deflection or flutter will occur.

The design of a tensile structure usually begins by experimenting with simple physical models. These often are made of pantyhose material or stretch fabric, either of which is easily stretched and manipulated. After a general shape has been established with the model, a computer is used to find the exact equilibrium shape, determine the stresses in the fabric and supporting members under wind and snow loadings, and generate cutting patterns for the fabric. The design process is referred to as *form finding*, because a tensile structure cannot be made to take any arbitrary shape. Just as a hanging chain will always take a form that places its links in equilibrium with one another, a tensile structure must take a form that maintains proportionate amounts of tension in all parts of the fabric under all expected loading conditions. The designer's task is to find such a form.

A good design for a tensile structure employs short *masts* to minimize buckling problems. The fabric generally cannot come to a peak at the mast, but must terminate in a cable ring that is attached to the mast in order to avoid high tensile stresses in the fabric. The perimeter edges of the fabric usually terminate along curving steel cables. To make a stable structure, these cables must have adequate curvature and must be anchored to foundations that offer firm resistance to uplift forces. The fabric may be attached to the cables by sleeves sewn into the edges of the fabric or clamps that grip the fabric and pull it toward the cable.

Air-Supported Structures

Air-supported structures are pressurized by the fans that are used to heat, cool, and ventilate the building. The required air pressures are so low that they are scarcely discernible by people entering or leaving the building, but they are high enough (5–10 pounds per square foot, or 0.25–0.50 kPa) to prevent ordinary swinging doors from opening. For this reason, revolving doors, whose operation is unaffected by internal pressure and that maintain a continual seal against loss of air, are usually used for access.

The fabric of an air-supported structure is prestressed by its internal air pressure to prevent flutter. For low-profile roof shapes, a cable net is employed to resist the high forces that result from the flat curvature. The fabric spans between the cables. The fabric and cables pull up on the foundations with a total force that is equal to the internal air pressure multiplied by the area of ground covered by the roof. The supporting elements and foundations must be designed to resist this force.

Wind causes suction forces to occur on many areas of an air-supported structure, which results in additional tension in the fabric and cables. The downward forces from wind or snow load on an air-supported structure must be resisted directly by the internal air pressure pushing outward against them. In geographic areas where snow loads are larger than acceptable internal pressures, snow must be removed from the roof. Failure to do so has led to unplanned deflations of several air-supported roofs.

In theory, air-supported structures are not limited in span. In practice, flutter and perimeter uplift forces restrict their span to a few hundred meters, but this is sufficient to house entire football stadiums. For safety, the outer edges of most air-supported roofs terminate at a level that is well above the floor level within. Thus, if the roof deflates because of fan failure, inadequate snow removal, or air leakage, the roof fabric will hang in suspension at a height well above the floor of the building (Figure H).

For further information, see Horst Berger, *Light Structures; Structures of Light*, Basel, Birkhäuser Verlag, 1996.

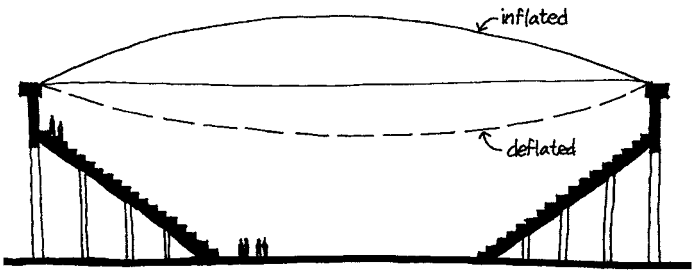


FIGURE H
Most air-supported structures are designed so that if air pressure fails, the membrane will hang at a safe level above the heads of the occupants. *(Sketch by Edward Allen)*

COMPOSITE COLUMNS

Columns that combine the strength of structural steel shapes and sitecast concrete have been used in buildings for many years. One type of composite column surrounds a steel wide-flange column with sitecast reinforced concrete. Another type consists of a steel pipe that is filled with concrete. In a third type, a wide-flange column is inserted within the pipe before the concrete is added to create a higher loadbearing capacity.

Several recent high-rise buildings use very large steel pipe columns filled with very-high-strength concrete to carry a major portion of both vertical and lateral loads. These columns enable reductions of as much as 50 percent in the overall quantity of steel required for the building (Figure 11.90). In one such building, a 720-foot (200-m) office tower, four 10-foot-diameter (3-m) pipe columns filled with 19,000-psi (131-MPa) concrete carry 40 percent of the gravity loads and a large proportion of the wind loads. There is no reinforcing or other steel inside the pipes except at certain connections that carry very heavy loads. The potential advantages of composite columns in tall buildings include reduced steel usage, greater rigidity of the building against wind forces, and simplified beam-column connections.

INDUSTRIALIZED SYSTEMS IN STEEL

Steel adapts well to industrialized systems of construction. The two most successful and most economical prefabrication systems in the United States are probably the manufactured home (often referred to as a mobile home) and the package industrial building. The manufactured home, built largely of wood, is made possible by a rigid undercarriage (chassis) welded together from rolled steel shapes. The package building is most commonly based on a structure of welded steel rigid frames supporting an enclosure of corrugated metal sheets. The manufactured home is

FIGURE 11.90

A core structure of eight large composite columns, each a concrete-filled pipe 7½ feet (2.3 m) in diameter, carries the majority of gravity and wind loads in this 44-story Seattle office building. The perimeter of the building is supported by smaller-diameter composite pipe columns. *(Courtesy of Skilling Ward Magnusson Barkshire, Inc., Seattle, Washington)*

CONSIDERATIONS OF SUSTAINABILITY IN STEEL FRAME CONSTRUCTION

Manufacture

The raw materials for steel are iron ore, coal, limestone, air, and water. The ore, coal, and limestone are minerals whose mining and quarrying cause disruption of land and loss of wildlife habitat, often coupled with pollution of streams and rivers. Coal, limestone, and low-grade iron ore are plentiful, but high-grade iron ore has been depleted in many areas of the earth.

The steel industry has worked hard to reduce pollution of air, water, and soil, but much work remains to be done.

Supplies of some alloying metals, such as manganese, chromium, and nickel, are becoming depleted.

The manufacture of a ton of steel from iron ore by the basic oxygen process consumes 3170 pounds (1440 kg) of ore, 300 pounds (140 kg) of limestone, 900 pounds (410 kg) of coke (made from coal), 80 pounds (36 kg) of oxygen, and 2575 pounds (1170 kg) of air. In the process, 4550 pounds (2070 kg) of gaseous emissions are given off, and 600 pounds (270 kg) of slag and 50 pounds (23) of dust are generated. Further emissions emanate from the process of converting coal to coke.

The embodied energy of steel produced from ore by the basic oxygen process is about 14,000 BTU per pound (33 MJ/kg). In modern facilities, scrap steel is typically added as an ingredient during this process, resulting in recycled materials content of 25 to 35 percent.

Today, most structural steel in North America is made from recycled scrap by the electric arc furnace process; its embodied energy is approximately 4000 BTU per pound (9.3 MJ/kg), less than one-third that of steel made from ore. The recycled materials content of steel made by this process is 90 percent or higher.

In North America, virtually all hot-rolled structural steel shapes are manufactured by the electric arc furnace process. Steel plate and sheet, used in the manufacture, for example, of light gauge steel members, decking, and hollow structural sections, may be produced by either the electric arc furnace or basic oxygen processes.

Ninety-five percent or more of all structural steel used in North American building construction is eventually recycled or reused, which is a very high rate. In a recent one-year period, 480 million tons (430 million metric tons) of scrap steel were consumed worldwide.

Scrap used in the production of structural steel in minimills usually comes from sources within approximately 300 miles (500 km) of the mill. When the steel produced in such mills is then used for the construction of buildings not too far from the mill, the steel is potentially eligible for credit as a regionally extracted, processed, and produced material. This is most likely for the most commonly used steel alloys that are produced in the greatest number of mills. However, some less commonly produced steel alloys are only available from a limited number of mills or, in some cases, are produced solely overseas, and are not eligible for such a credit except for projects located fortuitously close to the mills where these particular types of steel are produced.

Construction

Steel fabrication and erection are relatively clean, efficient processes, although the paints and oils used on steel members can cause air pollution.

Steel frames are lighter in weight than concrete frames that would do the same job. This means that a steel building generally has smaller foundations and requires less excavation work.

Some spray-on fireproofing materials can pollute the air with stray fibers.

In Service

Steel framing, if protected from water and fire, will last for many generations with little or no maintenance.

Steel exposed to weather needs to be repainted periodically unless it is galvanized, given a long-lasting polymer coating, or made of more expensive stainless steel.

Steel framing members in building walls and roofs should be thermally broken or insulated in such a way that they do not conduct heat between indoors and outdoors.

When a steel building frame is demolished, its material is almost always recycled.

Steel seldom causes indoor air quality problems, although surface oils and protective coatings sometimes outgas and cause occupant discomfort.

founded on steel because of steel's matchless stiffness and strength. The package building depends on steel for these qualities, for the repeatable precision with which components can be produced, and for the ease with which the relatively light steel components can be transported and assembled. It is but a short step from the usual process of steel fabrication and erection to the serial production of repetitive building components.

STEEL AND THE BUILDING CODES

Steel frame construction appears in the typical building code tables in Figures 1.2 and 1.3 as six different construction types I, II, and III the exact classification depending on the degree of fireproofing treatment applied to the various members of the frame. With a high degree of fireproofing, especially on members supporting more than one floor, unlimited building heights and areas are permitted for most occupancy groups. With no fireproofing whatsoever of steel members, building heights and areas are severely limited, but many occupancy groups can easily meet these restrictions.

UNIQUENESS OF STEEL

Among the common structural materials for fire-resistant construction masonry, concrete, and steel steel alone has useful tensile strength, which, along with compressive strength, it possesses in great abundance (Figure 11.91). A relatively small amount of steel can do a structural job that would take a much greater amount of another material. Thus, steel, the most dense structural material, is also the one that produces the lightest structures and those that span the greatest distances.

The infrastructure needed to bring steel shapes to a building site the mines, the mills, the fabricators, and the scrap metal industry is vast and complex. An elaborate sequence of advance planning and preparatory activities is required for making a steel building frame. Once on the site, however, a steel

Material	Working Strength in Tension[a]	Working Strength in Compression[a]	Density	Modulus of Elasticity
Wood (framing lumber)	300 1000 psi 2.1 6.9 MPa	600 1700 psi 4.1 12 MPa	30 pcf 480 kg/m^3	1,000,000 1,900,000 psi 6900 13,000 MPa
Brick masonry (including mortar, unreinforced)	0	250 1300 psi 1.7 9.0 MPa	120 pcf 1900 kg/m^3	700,000 3,700,000 psi 4800 25,000 MPa
Structural steel	24,000 43,000 psi 170 300 MPa	24,000 43,000 psi 170 300 MPa	490 pcf 7800 kg/m^3	29,000,000 psi 200,000 MPa
Concrete (unreinforced)	0	1000 4000 psi 6.9 28 MPa	145 pcf 2300 kg/m^3	3,000,000 4,500,000 psi 21,000 31,000 MPa

[a] Allowable stress or approximate maximum stress under normal loading conditions.

FIGURE 11.91
Comparative physical properties for four common structural materials: wood, brick masonry, steel (shaded row), and concrete. Steel is many times stronger and stiffer than these other structural materials. The ranges of values of strength and stiffness reflect differences among structural steel alloys.

frame goes together quickly, and with relatively few tools, in an erection process that is rivaled for speed and all-weather reliability only by certain precast concrete systems. With proper design and planning, steel can frame almost any shape of building, including irregular angles and curves. Ultimately, of course, structural steel produces only a frame. Unlike masonry or concrete, it does not lend itself easily to forming a total building enclosure except in certain industrial applications. This is of little consequence, however, because steel mates easily with glass, masonry, and panel systems of enclosure and because steel does its own job, that of carrying loads high and wide with apparent ease, so very well.

FIGURE 11.92
This elegantly detailed house in southern California was an early example of the use of structural steel at the residential scale. *(Architect: Pierre Koenig, FAIA. Photo: Julius Shulman, Hon. AIA)*

Figure 11.93
Architect Peter Waldman utilized steel pipe columns, wide-flange beams, open-web steel joists, and corrugated steel roof decking for his own house in Charlottesville, Virginia. *(Photo by Maxwell McKenzie)*

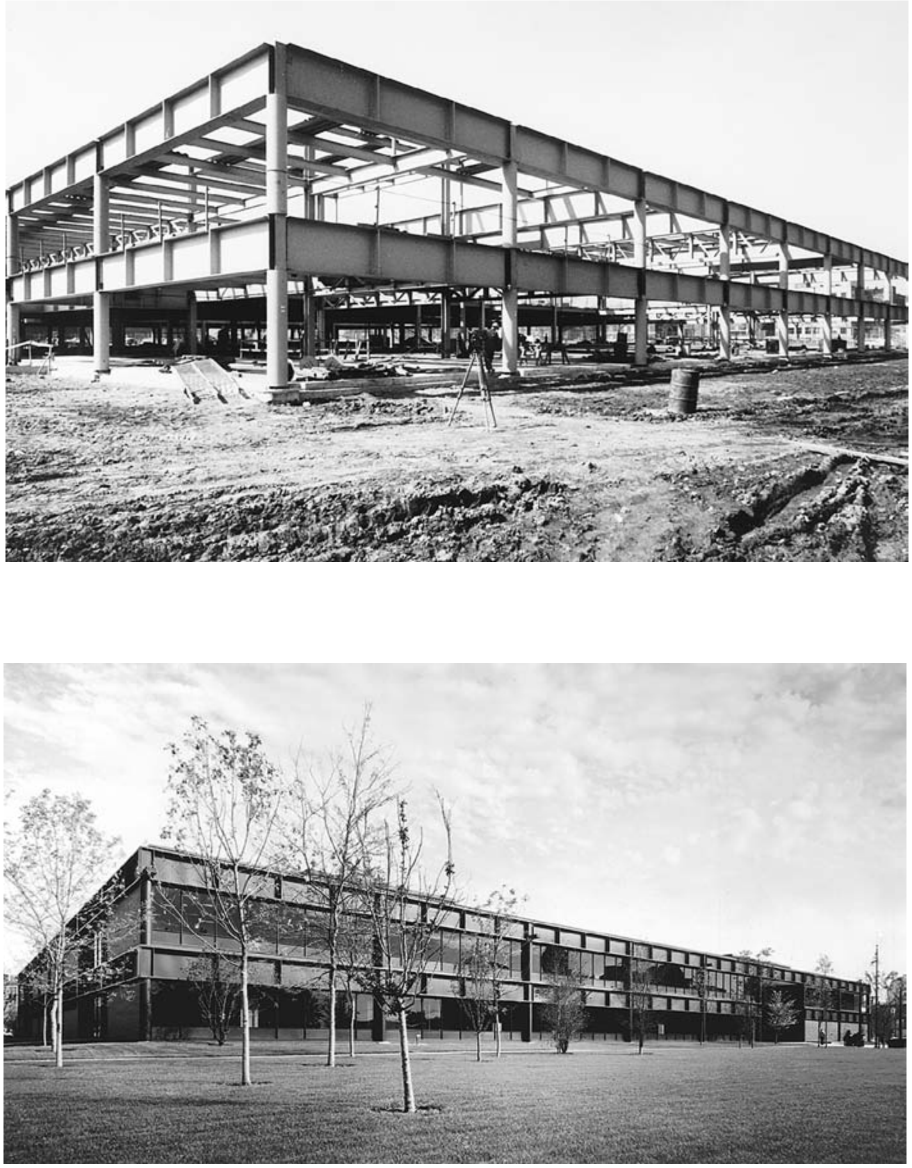


Figure 11.94
The Chicago Police Training Center expresses elegantly the logic and simplicity of a straightforward steel frame. *(Architect: Jerome R. Butler, Jr. Engineer: Louis Koncza. Permission of American Institute of Steel Construction)*


EXIT

Figure 11.95
Architect Suzane Reatig structured the roof of a Washington, D.C., church with trusses made of steel angles. The ribs of the roof decking add a strong texture to the ceiling. *(Photo by Robert Lautman)*

Figure 11.96
The United Airlines Terminal at Chicago's O'Hare Airport is a high-tech wonderland of steel framing and fritted glass. *(Architect: Murphy-Jahn. Photo by Edward Allen)*

FIGURE 11.97
Chicago is famous for its role in the development of the steel frame skyscraper (see Figure 11.4). One of the tallest in the United States is the Sears Tower, seen in the foreground of this photograph. *(Architect and engineer: Skidmore, Owings and Merrill. Photo by Chicago Convention and Tourism Bureau, Inc. Permission of the American Institute of Steel Construction.)*

CSI/CSC

MasterFormat Sections for Steel Frame Construction

05 10 00	STRUCTURAL METAL FRAMING
05 12 00	Structural Steel Framing
05 16 00	Structural Cabling
05 20 00	METAL JOISTS
05 21 00	Steel Joist Framing
05 30 00	METAL DECKING
05 31 00	Steel Decking
05 35 00	Raceway Decking Assemblies
05 36 00	Composite Metal Decking
05 50 00	METAL FABRICATIONS
05 56 00	Metal Castings

SELECTED REFERENCES

1. American Institute of Steel Construction, Inc. *Steel Construction Manual*. Chicago, updated regularly.

This is the bible of the steel construction industry in the United States. It contains detailed tables of the dimensions and properties of all standard rolled steel sections, data on standard connections, and specifications and code information.

2. American Iron and Steel Institute. *Specification for Structural Steel Buildings*. Washington, DC, 2005.

This specification, included in the Steel Construction Manual, can also be viewed for free on the American Institute of Steel Construction's web site, www.aisc.org.

3. American Iron and Steel Institute. *Designing Fire Protection for Steel Beams* and *Designing Fire Protection for Steel Trusses*. Washington, DC, 1984 and 1991, respectively.

The problem of fireproofing steel building elements is discussed, and a range of fireproofing details is illustrated in these concise booklets.

4. Ambrose, James, and Patrick Tripeny. *Simplified Design of Steel Structures* (8th ed.). Hoboken, NJ, John Wiley & Sons, Inc., 2007.

This is an excellent introduction to the calculation of steel beams, columns, and connections.

5. Geoffrey L. Kulak, John W. Fisher, and John H. A. Struik. *Guide to Design Criteria for Bolted and Riveted Joints* (2nd ed.). Chicago, AISC, 2001.

This 300-plus page guide provides detailed engineering guidelines for the design of bolted and riveted steel connections. This guide can be viewed for free on the Research Council on Structural Connections web site, www.boltcouncil.org.

6. Steel Joist Institute. *Catalog of Standard Specifications and Load Tables for Steel Joists and Joist Girders*. Myrtle Beach, SC, updated regularly.

Load tables, sizes, and specifications for open-web joists are given in this booklet.

Web Sites

Steel Frame Construction

Author s supplementary web site: **www.ianosbackfill.com/11_steel_frame_construction**

The Material Steel

American Institute of Steel Construction (AISC): **www.aisc.org**
American Iron and Steel Institute: **www.steel.org**
Chaparral Steel: **www.chaparralsteel.com**
Jacob Stainless Steel Fittings and Wire: **www.jakobstainlesssteel.com**
Lincoln Electric Welding: **www.lincolnelectric.com**
Nucor Steel: **www.nucor.com**
Nucor Vulcraft Group: **www.vulcraft.com**
Research Council on Structural Connections web site: **www.boltcouncil.org**
Steel Joist Institute (SJI): **www.steeljoist.org**
Steel Recycling Institute: **www.recycle-steel.org**

Longer Spans in Steel

Birdair Tensioned Membrane and Lightweight Structures: **www.birdair.com**

Key Terms and Concepts

Bessemer process
open-hearth method
steel
mild steel
cast iron wrought iron
ferrous metal
iron ore
coke
basic oxygen process
electric arc furnace
beam blank, bloom
high-strength, low-alloy steel
weathering steel
stainless steel
structural mill, breakdown mill
hot saw
cooling bed
roller straightener
bar
plate
sheet
wide-flange shape
American Standard shape, I-beam
angle
gusset plate
channel
tee
plate
bar
sheet
quenching
tempering
cast steel
cold-worked steel, cold-formed steel
hollow structural section (HSS)
open-web steel joist (OWSJ)
joist girder
rivet
high-strength bolt
carbon steel bolt
bearing-type connection
sung-tight
slip-critical connection, friction connection
preloaded
faying surface
galling
impact wrench
turn-of-nut method
load indicator washer, direct tension indicator (DTI)
calibrated wrench method
tension-control bolt
shear wrench
lockpin and collar fastener, swedge bolt
electric arc welding
electrode
weld symbols
backup bar, backing bar
runoff bar
demand-critical weld
shear connection
shear
bending moment
framed connection
moment connection
full-penetration groove weld
stiffener plate
braced frame
diagonal bracing
eccentrically braced frame
Chevron bracing, inverted V bracing
cross bracing
shear wall
moment-resisting frame
rigid core
diaphragm action
rigid perimeter
Fully-Restrained moment connection, AISC Type 1 connection
Partially-Restrained moment connection, AISC Type 3), connection
Simple connection. AISC Type 2 connection
seated connection
shear tab
end plate connection

fabricator
shop drawing
coped flange
plasma cutting
laser cutting
camber
erector
ironworker
tier
baseplate
leveling plate
grout
luffing-boom crane
hammerhead boom crane
raising gang
plumbing up
tower crane
tagline
drift pin
topping out
metal decking
roof decking
cellular decking
puddle weld
composite metal decking
shear stud
subpurlin
girt
architecturally exposed structural steel (AESS)
fireproofing
spray-applied fire-resistive materials (SFRM)
intumescent mastic
intumescent paint
castellated beam
plate girder
rigid steel frame
steel truss
chord
space truss, space frame
arch
anticlastic curvature
cable stay
tensile fabric structure
pneumatic structure
air-supported structure
prestress
form finding
mast

REVIEW QUESTIONS

1. What is the difference between iron and steel? What is the difference between wrought iron and cast iron?

2. By weight, what is the major raw material used in the making of cast iron?

3. How are steel structural shapes produced? How are the weights and thicknesses of a shape changed?

4. How does the work of the fabricator differ from that of the erector?

5. Explain the designation W21 × 68.

6. How can you tell a shear connection from a moment connection? What is the role of each?

7. Why might a beam be coped?

8. What is the advantage of composite construction?

9. Explain the advantages and disadvantages of a steel building structure with respect to fire. How can the disadvantages be overcome?

10. List three different structural systems in steel that might be suitable for the roof of an athletic fieldhouse.

EXERCISES

1. For a simple multistory office building of your design:

   a. Draw a steel framing plan for a typical floor.

   b. Draw an elevation or section showing a suitable method of making the building stable against lateral forces wind and earthquake.

   c. Make a preliminary determination of the approximate sizes of the decking, beams, and girders, using the information in the box on page 417.

   d. Sketch details of the typical connections in the frame, using actual dimensions from the *Manual of Steel Construction* (reference 1) for the member size you have determined and work to scale.

2. Select a method of fireproofing, and sketch typical column and beam fireproofing details for the building in Exercise 1.

3. What fire-resistance ratings in hours are required for the following elements of a steel framed department store, three stories in height, unsprinklered, with 21,000 square feet of area per floor? (The necessary information is found in Figures 1.2 and 1.3.)

   a. Lower-floor columns

   b. Floor beams

   c. Roof beams

   d. Interior nonbearing walls and partitions

4. Find a steel building frame under construction. Observe the connections carefully and figure out why each is detailed as it is. If possible, arrange to talk with the structural engineer of the building to discuss the design of the frame.