1

CONSIDERATIONS FOR USE OF STEEL

The work of designing steel structures requires considerable understanding of the basic nature of steel as a material and of the products and processes from which steel structures are formed. This chapter treats some of the major concerns of this nature.

1.1 PROPERTIES OF STEEL

The strength, hardness, corrosion resistance, and some other properties of steel can be varied through a considerable range by changes in the production processes. Literally hundreds of different steels are produced, although only a few standard products are used for the majority of the elements of building structures. Working and forming processes such as rolling, drawing, machining, and forging may also alter some properties. However, certain properties such as density (unit weight), stiffness (modulus of elasticity), thermal expansion, and fire resistance tend to remain constant for all steels.

For various applications, other properties will be significant. Hardness affects the ease with which cutting, drilling, planing, and other working can be done. For welded connections the property of weldability of the base material must be considered. Resistance to rusting is normally low, but it can be enhanced by various materials added to the steel, producing various types of special steels, such as stainless steel and the so-called "rusting steels" that rust at a very slow rate.

These various properties of steel must be considered when working with the material and when designing for its use. However, it is the unique structural nature of steel with which we are most concerned in this book.

Structural Properties of Steel

Basic structural properties, such as strength, stiffness, ductility, and brittleness, can be interpreted from laboratory load tests on specimens of the material. Figure 1.1 displays characteristic forms of curves that are obtained by plotting stress and strain values from such tests. An important property of many structural steels is the plastic deformation (yield) phenomenon. This is demonstrated by curve 1 in Figure 1.1. For steels with this character, there are two different stress values of significance: the yield limit and the ultimate failure limit.

Generally, the higher the yield limit, the less the degree of ductility. The extent of ductility is measured as the ratio of the plastic deformation between first yield and strain hardening (see Figure 1.1) to the elastic deformation at the point of yield. Curve 1 in Figure 1.1 is representative of ordinary structural steel (ASTM A36), and curve 2 indicates the typical effect as the yield strength is raised a significant amount. Eventually, the significance of the yield phenomenon becomes virtually negligible when the yield strength approaches as much as three times the yield of ordinary steel (36 ksi for ASTM A36 steel).

Some of the highest-strength steels are produced only in thin sheet or drawn wire forms. Bridge strand is made from wire with strength as high as 300,000 psi. At this level, yield is almost nonexistent and the wires approach the brittle nature of glass rods.

For economical use of the expensive material, steel structures are generally composed of elements with relatively thin parts. This results in many situations in which the ultimate limiting strength of elements in bending, compression, and shear is determined by buckling, rather than by the stress limits of the material. Because buckling is a function of stiffness (modulus of elasticity) of the material, and because this property

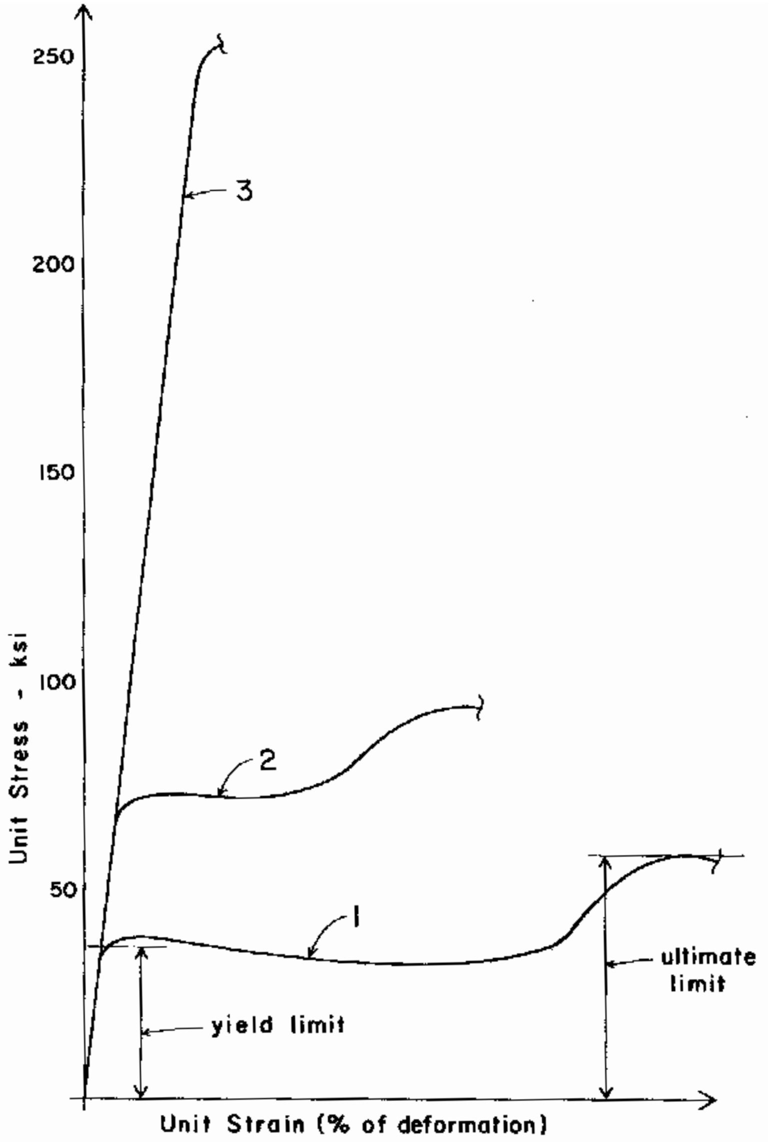

Figure 1.1 Stress/strain response: (1) ordinary structural steel; (2) high-strength steel for rolled shapes; (3) super-strength steel (usually in wire form).

remains the same for all steels, there is limited opportunity to make effective use of higher-strength steels in many situations. The grades of steel most commonly used are to some extent ones that have the optimal effective strength for most typical tasks.

Because many structural elements are produced as some manufacturer's product line, choices of basic materials are often mostly out of the hands of individual building designers. The proper steel for the task—on the basis of many properties—is determined as part of the product design, although a range of grades may be obtained for some products.

Steel that meets the requirements of the American Society for Testing and Materials (ASTM) Specification A36 is the grade of structural steel most commonly used to produce rolled steel elements for building construction. It must have an ultimate tensile strength of 58 to 80 ksi and a minimum yield point of 36 ksi. It may be used for bolted, riveted, or welded fabrication. This is the steel used for much of the work in this book, and it will be referred to simply as A36 steel.

Prior to 1963 a steel designated ASTM A7 was the basic product for structural purposes. It had a yield point of 33 ksi and was used primarily for riveted fabrication. With the increasing demand for bolted and welded construction, A7 steel became less useful, and in a short time, A36 steel was the material of choice for the majority of structural products.

For structural steel the AISC Specification expresses the allowable unit stresses used for ASD work in terms of some percent of the yield stress F_y or the ultimate stress F_u. Of course, LRFD work does not use allowable stresses, but rather the basic limiting stresses (yield and ultimate) of the material. Some modification for specific usage situations (tension, bending, shear, etc.) is made by use of different reduction factors (called resistance factors, as explained in Chapter 5).

Steel used for other purposes than the production of rolled products generally conforms to standards developed for the specific product. This is especially true for steel connectors, wire, cast and forged elements, and very high-strength steels produced in sheet, bar, and rod form for fabricated products. The properties and design stresses for some of these product applications are discussed in other sections of this book. Standards used typically conform to those established by industry-wide organizations, such as the Steel Joist Institute (SJI) and the Steel Deck Institute (SDI). In some cases, larger fabricated products make use of ordinary rolled products, produced from A36 steel or other grades of steel from which hot-rolled products can be obtained.

1.2 TYPES OF STEEL PRODUCTS

Steel itself is shapeless, coming basically in the form of a molten material or a softened lump. The structural products produced derive their basic forms from the general potentialities and limitations of the industrial processes of forming and fabricating. Standard raw stock elements—deriving from the various production processes—are the following:

1. *Rolled shapes.* These are formed by squeezing the heat-softened steel repeatedly through a set of rollers that shape it into a linear element with a constant cross section. Simple forms of round rods and flat bars, strips, plates, and sheets are formed, as well as more complex shapes of I, H, T, L, U, C, and Z. Special shapes, such as rails or sheet piling, can also be formed in this manner.
2. *Wire.* This is formed by pulling (called drawing) the steel through a small opening.
3. *Extrusion.* This is similar to drawing, although the sections produced are other than simple round shapes. This process is not much used for steel products of the sizes used for buildings.
4. *Casting.* This is done by pouring the molten steel into a form (mold). Casting is limited to objects of a three-dimensional form and is also not common for building construction elements.
5. *Forging.* This consists of pounding the softened steel into a mold until it takes the shape of the mold. This is preferred to casting because of the effects of the working on the properties of the finished material.

The raw stock steel elements produced by the basic forming processes may be reworked by various means, such as the following:

1. *Cutting.* Shearing, sawing, punching, or flame cutting can be used to trim and shape specific forms.
2. *Machining.* This may consist of drilling, planing, grinding, routing, or turning on a lathe.
3. *Bending.* Rods, sheets, plates, or other linear elements may be bent if made from steel with a ductile character.
4. *Stamping.* This is similar to forging; in this case, sheet steel is punched into a mold that forms it into some three-dimensional shape, such as a hemisphere.

5. *Rerolling.* This consists of reworking a linear element into a curved form (arched) or of forming a sheet or flat strip into a formed cross section.

Finally, raw stock or reformed elements can be assembled by various means into objects of multiple parts, such as a manufactured truss or a prefabricated wall panel. Basic means of assemblage include the following:

1. *Fitting.* Threaded parts may be screwed together or various interlocking techniques may be used, such as the tongue-and-groove joint or the bayonet twist lock.
2. *Friction.* Clamping, wedging, or squeezing with high-tensile bolts may be used to resist the sliding of parts in surface contact.
3. *Pinning.* Overlapping flat elements may have matching holes through which a pin-type device (bolt, rivet, or actual pin) is placed to prevent slipping of the parts at the contact face.
4. *Nailing, screwing.* Thin elements—mostly with some preformed holes—may be attached by nails or screws.
5. *Welding.* Gas or electric arc welding may be used to produce a bonded connection, achieved partly by melting the contacting elements together at the contact point.
6. *Adhesive bonding.* This usually consists of some form of chemical bonding that results in some fusion of the materials of the connected parts.

We are dealing here with industrial processes, which at any given time relate to the state of development of the technology, the availability of facilities, the existence of the necessary craft, and competition with other materials and products.

Rolled Structural Shapes

The products of the steel rolling mills used as beams, columns, and other structural members are called *sections* or *shapes,* and their designations are related to the profiles of their cross sections. American standard I-beams (Figure 1.2*a*) were the first beam sections rolled in the United States and are currently produced in sizes of 3 to 24 in. in depth. The W shapes (Figure 1.2*b*—originally called wide-flange shapes) are a modification of the I cross section and are characterized by parallel flange surfaces as contrasted with the tapered inside flange surfaces of standard

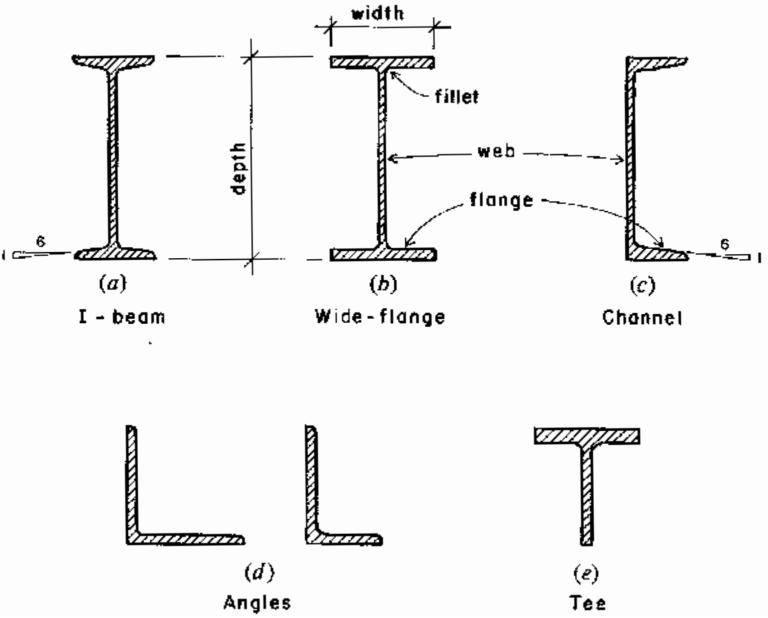

Figure 1.2 Shapes of typical hot-rolled products.

I-beams; they are available in depths of 4 to 44 in. In addition to the standard I and W sections, the structural steel shapes most commonly used in building construction are channels, angles, tees, plates, and bars. The tables in Appendix A list the dimensions, weights, and various properties of some of these shapes. Complete tables of structural shapes are given in the AISC Manual (Ref. 3).

W Shapes. In general, W shapes have greater flange widths and relatively thinner webs than standard I-beams; and, as noted above, the inner faces of the flanges are parallel to the outer faces. These sections are identified by the alphabetical symbol W, followed by the *nominal* depth in inches and the weight in pounds per linear foot. Thus, the designation W 12 × 26 indicates a wide-flange shape of nominal-12-in. depth, weighing 26 lb per linear foot.

The actual depths of W shapes vary within the nominal depth groupings. From Table A.3 in Appendix A, note that a W 12 × 26 has an actual depth of 12.22 in., whereas the depth of a W 12 × 30 is 12.34 in. This is a result of the rolling process during manufacture in which the cross-sectional areas of W shapes are increased by spreading the rollers both vertically and horizontally. The additional material is thereby added to the cross section by increasing flange and web thickness as well as flange width (Figure 1.2*b*). The resulting higher percentage of material in the flanges makes wide-flange shapes more efficient structurally than standard I-beams. A wide variety of weights is available within each nominal depth group.

In addition to shapes with profiles similar to the W 12 × 26, which has a flange width of 6.490 in., many W shapes are rolled with flange widths approximately equal to their depths. The resulting H configurations of these cross sections are much more suitable for use as columns than the I profiles. From Table A.3, note that the following shapes, among others, fall into this category: W 14 × 120, W 12 × 65, and W 10 × 49. It is recommended that the reader compare these shapes with others listed in their respective nominal depth groups in order to become familiar with the variety of geometrical relationships.

Standard I-Beams (S Shapes). American standard I-beams are identified by the alphabetical symbol S, the designations S 12 × 35 indicating a standard shape 12 in. deep weighing 35 lb per linear foot. Unlike W sections, standard I-beams in a given depth group have uniform depths, and shapes of greater cross-sectional area are made by spreading the rolls in one direction only. Thus, the depth remains constant, whereas the width of flange and thickness of web are increased.

All standard I-beams have a slope on the inside faces of the flanges of 16 percent or 1 in 6. In general, standard S shapes are not so efficient structurally as W shapes and consequently are not so widely used. Also the variety available is not so large as that for W shapes. Characteristics that may favor the use of S shapes in any particular situation are constant depth, narrow flanges, and thicker webs.

Standard Channels. The profile of an American standard channel is shown in Figure 1.2*c*. These shapes are identified by the alphabetical symbol C. The designation C 10 × 20 indicates a standard channel 10 in. deep and weighing 20 lb per linear foot. Table A.4 shows that this section has an area of 5.88 in.^{2}, a flange width of 2.739 in., and a web thickness of 0.379 in. Like the standard I-beams, the depth of a particular group remains constant and the cross-sectional area is increased by spreading the rolls to increase flange width and web thickness. Because of their tendency to buckle when used independently as beams or columns, channels require lateral support or bracing. They are generally used as elements of built-up sections such as columns and lintels. However, the absence of a flange on one side makes channels particularly suitable for framing around floor openings.

Angles. Structural angles are rolled sections in the shape of the letter L. Table A.5 gives dimensions, weights, and other properties of equal and unequal leg angles. Both legs of an angle have the same thickness.

Angles are designated by the alphabetical symbol L, followed by the dimensions of the legs and their thickness. Thus, the designation L 4 × 4 × ½ indicates an equal leg angle with 4-in. legs, ½ in. thick. From Table A.5, note that this section weighs 12.8 lb per linear foot and has a cross-sectional area of 3.75 in.^{2}. Similarly, the designation L 5 × 3½ × ½ indicates an unequal leg angle with one 5-in. and one 3½-in. leg, both ½ in. thick. Table A.5 shows that this angle weighs 13.6 lb per linear foot and has an area of 4 in.^{2}. To change the weight and area of an angle of a given leg length, the thickness of each leg is increased the same amount. Thus, if the leg thickness of the L 5 × 3½ × ½ is decreased to ⅜ in., Table A.5 shows that the resulting L 5 × 3½ × ⅜ has a weight of 10.4 lb per linear foot and an area of 3.05 in.^{2}. It should be noted that this method of spreading the rolls changes the leg lengths slightly.

Single angles are often used as lintels, and pairs of angles are often used as members of light steel trusses. Angles were formerly used as elements of built-up sections such as plate girders and heavy columns, but the advent of the heavier W shapes has largely eliminated their usefulness for this purpose. Short lengths of angles are commonly used as connecting members for beams and columns.

Structural Tees. A structural tee is made by splitting the web of a W shape (Figure 1.2*e*) or a standard I-beam (S shape). The cut, normally made along the center of the web, produces tees with a stem depth equal to half the depth of the original section. Structural tees cut from W shapes are identified by the symbol WT; those cut from standard S shapes by ST. The designation WT 6 × 53 indicates a structural tee with a 6-in. depth and a weight of 53 lb per linear foot. This shape is produced by splitting a W 12 × 106 shape. Similarly, ST 9 × 35 designates a structural tee 9 in. deep weighing 35 lb per linear foot and cut from an S 18 × 70.

Plates and Bars. Plates and bars are made in many different sizes and are available in many different structural steel specifications. Flat steel for structural uses is generally classified as follows:

Bars.	6 in. or less in width, and 0.203 in. or more in thickness.
Plates.	More than 8 in. in width, and 0.230 in. or more in thickness.
	More than 48 in. in width, and 0.180 in. or more in thickness.
Sheet.	Generally any flat material less than 0.180 in. in thickness.

Bars are available in varying widths and in virtually any required thickness and length. The usual practice is to specify bars in increments of ¼ in. for widths and ⅛ in. in thickness.

For plates the preferred increments for width and thickness are the following:

Widths.	Vary by even inches, although smaller increments are obtainable.
Thickness.	1⁄32-in. increments up to ½ in.
	1⁄16-in. increments of more than ½ to 2 in.
	⅛-in. increments of more than 2 to 6 in.
	3-in. increments of more than 6 in.

The standard dimensional sequence when describing steel plate is

Thickness × Width × Length

Example: PL 1½ × 10 × 16

All dimensions are given in inches, fractions of an inch, or decimals of an inch.

Column base plates and beam bearing plates may be obtained in the widths and thicknesses noted. For the design of beam bearing plates and column base plates see Sections 3.14 and 4.7, respectively.

Designations for Structural Steel Elements. As noted earlier, wide-flange shapes are identified by the symbol W and American standard beam shapes by S. It was also pointed out the W shapes have essentially parallel flange surfaces, whereas S shapes have a slope of approximately 16 percent on the inner flange faces. A third designation, M shapes, covers miscellaneous shapes that cannot be classified as W or S;

TABLE 1.1 Standard Designations for Structural Steel Elements

Elements	Designation
American standard I-beams, S-shapes	S 12 × 35
Wide flanges, W shapes	W 12 × 27
Miscellaneous shapes, M shapes	M 8 × 18.5
American standard channels, C shapes	C 10 × 20
Miscellaneous channels, MC shapes	MC 12 × 40
Bearing piles, HP-shapes	HP 14 × 117
Angles, L shapes	L 5 × 3 × ½
Structural tees, WT, ST, MT	WT 9 × 38
Plates	PL 1½ × 10 × 16
Structural tubing	HSS 10 × 6 × ½
Pipe, standard weight	Pipe 4 Std
Pipe, extra strong	Pipe 4 X-strong
Pipe, double extra strong	Pipe 4 XX-strong

these shapes have various slopes on their inner flange surfaces and many of them are of only limited availability. Similarly, some rolled channels cannot be classified as C shapes. These are designated by the symbol MC.

Table 1.1 lists the standard designations used for rolled shapes, formed rectangular tubing, and round pipe.

Cold-Formed Steel Products

Many structural elements are formed from sheet steel. Elements formed by the rolling process must be heat-softened, whereas those produced from sheet steel are ordinarily made without heating the steel; thus, the common description for these elements is *cold-formed.* Because they are typically formed from very thin sheets, they are also referred to as *light-gage* steel products.

Figure 1.3 illustrates the cross sections of some of these products. Large corrugated or fluted sheets are in wide use for all paneling and for structural decks for roofs and floors. Use of these elements for floor decking is discussed in Chapter 3. These products are made by a number of manufacturers, and information regarding their structural properties may be obtained directly from the manufacturer. General information on structural decks may also be obtained from the Steel Deck Institute (see Ref. 5).

Cold-formed shapes range from the simple L, C, U, and so on to the special forms produced for various construction systems. Structures for some buildings may be almost entirely composed of cold-formed prod-

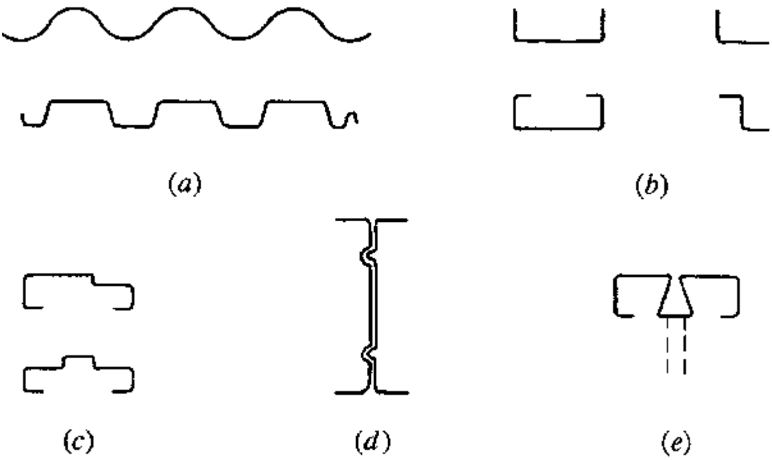

Figure 1.3 Cross-sectional shapes of common cold-formed products.

ucts. Several manufacturers produce patented systems of these components for the formation of predesigned, packaged building structures.

Fabricated Structural Components

A number of special products are formed of both hot-rolled and cold-formed elements for use as structural members in buildings. Open-web steel joists consist of prefabricated, light steel trusses. For short spans and light loads, a common design is that shown in Figure 1.4*a* in which the web consists of a single, continuous bent steel rod and the chords of steel rods or cold-formed elements. For larger spans or heavier loads, the forms more closely resemble those for ordinary light steel trusses; single angles, double angles, and structural tees constitute the truss members. Open-web joists for floor framing are discussed in Section 3.9.

Another type of fabricated joist is shown in Figure 1.4*b*. This member is formed from standard rolled shapes by cutting the web in a zigzag fashion. The resulting product has a greatly reduced weight-to-depth ratio when compared with the lightest of the rolled shapes.

Other fabricated steel products range from those used to produce whole building systems to individual elements for construction of windows, doors, curtain wall systems, and the framing for interior partition walls. Many components and systems are produced as proprietary items by a single manufacturer, although some are developed under controls of

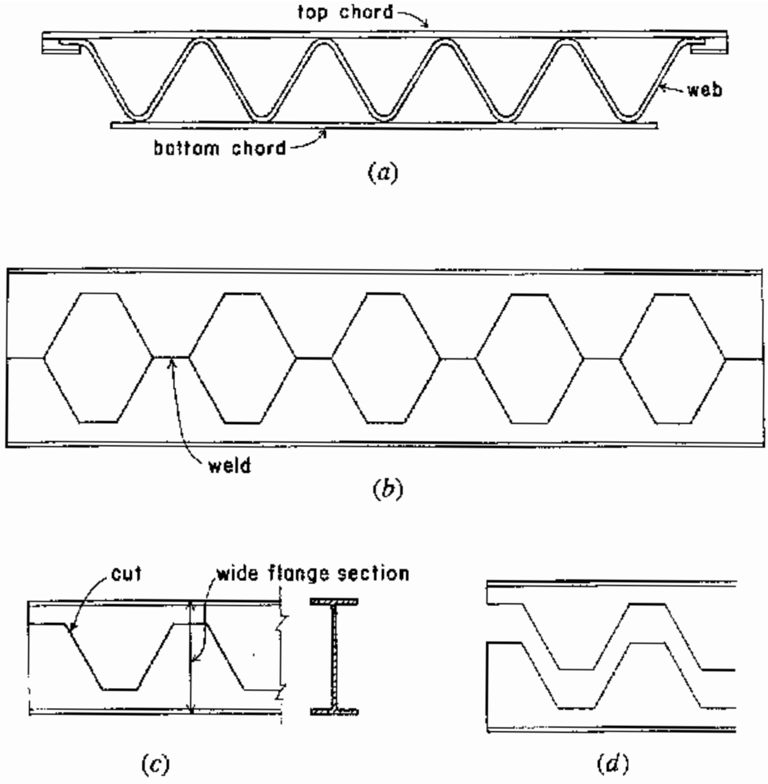

Figure 1.4 Fabricated products formed from steel elements.

industry-wide standards, such as those published by the Steel Joist Institute and Steel Deck Institute.

1.3 DEVELOPMENT OF STRUCTURAL SYSTEMS

Structural systems that compose entire roof, floor, or wall constructions—or even entire buildings—are typically assembled from many individual elements. These individual elements may be of some variety, as in the case of the typical floor using rolled steel shapes for beams and a formed sheet steel deck. Selection of individual elements is often done with some data from structural investigations but is also often largely a matter of practical development of the form of the construction.

It is common for a building to incorporate more than a single material for its entire structural system. Various combinations are possible, such as a wood deck on steel beams, or masonry bearing walls for a steel spanning floor or roof structure. This book deals primarily with structures of steel, but some of these mixed-material situations are very common and are discussed in various parts of the book.

1.4 CONNECTION METHODS

Connection of structural steel members that consist of rolled elements is typically achieved by direct welding or by steel rivets or bolts. Riveting for building structures has become generally obsolete in favor of high-strength bolts. The design of bolted connections and simple welded connections are discussed in Chapter 8. In general, welding is preferred for shop fabrication and bolting for field connections.

Thin elements of cold-formed steel may be attached by welding, by bolting, or by sheet metal screws. Thin deck and wall paneling elements are sometimes attached to one another by simple interlocking at their abutting edges; the interlocked parts are sometimes folded or crimped to give further security to the connection.

Adhesives or sealants may be used to seal joints or to bond thin sheet materials in laminated fabrications. Some elements used in connections may be attached to connected parts by adhesion to facilitate the work of fabrication and erection, but adhesive connection is not used for major structural joints.

A major structural design problem is that of the connections of columns and beams in heavy frames for multistory buildings. For rigid frame action to resist lateral loads, these connections are achieved with very large welds, generally developed to transfer the full strength of the connected members. Design of these connections is beyond the scope of this book, although lighter framing connections of various form are discussed in Chapter 8.

1.5 DATA FOR STEEL PRODUCTS

Information in general regarding steel products used for building structures must be obtained from steel industry publications. The AISC is the primary source of design information regarding structural rolled products, which are the principal elements used for major structural components: columns, beams, large trusses, and so on. Several other industry-wide organizations also publish documents that provide information about particular products, such as manufactured trusses (open-web joists), cold-formed sections, and formed sheet steel decks. Many of these organizations and their publications are described in the appropriate chapters and sections of this book.

Individual manufacturers of steel products usually conform to some industry-wide standards in the design and fabrication of their particular products. Still, there is often some room for variation of products; it is therefore advised that the manufacturers' own publications be used for specific data and details of the actual products. As in other similar situations in building design, the designer should strive to design and specify components of the building construction so that only those controls that are critical are predetermined, leaving flexibility in the choice of a particular manufactured product.

Some of the tabulated data presented in this book has been reproduced or abstracted from industry publications. In many cases the data presented here are abbreviated and limited to uses pertinent to the work displayed in the text example computations and necessary for the exercise problems. The reference sources cited should be consulted for more complete information, particularly because change occurs frequently due to growth of the technology, advances in research, and modification of codes and industry standards.

1.6 USAGE CONSIDERATIONS FOR STEEL STRUCTURES

Steel is a relatively expensive, industrialized product. Use of steel for structures must generally be made with very careful consideration of the limitations of the material, attention to high efficiency in the volume of material used, and design with clear understanding of the practical aspects of production and erection of steel products. In this chapter, we present discussions of a number of aspects regarding intelligent use of steel for structural applications.

Stress and Strain

Steel is one of the strongest materials used for building structures, but it has limitations for various forms of stress development. Unlike wood, stress response tends to be nondirectional, and unlike concrete or masonry, stress resistance is high for all the basic stresses: tension, compression, and shear. Some specific stress limits for steel are the following:

1. Stress beyond the yield point will produce permanent deformations, which may be tolerable in the small dimensions of a joint but may create major problems within the general form of structural elements. Even though ultimate strength may be high, the much lower yield stress must be used for a limit of acceptable behavior in most situations.
2. Ordinary steel is formed by molten casting, resulting in a crystalline structure of the material. Certain forms of stress failure may be precipitated by fracture along crystalline fault lines, especially those related to dynamic, repetitive force actions. This is more of a problem in machinery, but dynamically loaded structures may need consideration for this effect.
3. Various actions, such as cold-forming, machining, or welding, may change the character of the material, resulting in hardening, loss of ductility, or locked-in stresses within the material. The processes of fabrication and erection must be carefully studied to be sure these do not produce undesirable conditions to complicate stress behavior under service load situations.

In some cases the anticipated stress-strain responses may cause certain actions to occur that affect the overall structural resistance of a steel structure. An example of this is the formation of plastic hinges in rigid frames or in frames with eccentric bracing. The adjusted behavior of the structure in load response that occurs when a plastic hinge yields is a major element in visualization and computation of the structure's response. Some considerations for this action are discussed in Chapters 3 and 4.

Because of its strength, steel tends to carry a disproportionately high share of the load when sharing loads with other materials, such as wood or concrete. This is a major factor in design of composite structural elements, such as flitched beams of steel and wood and composite deck systems of steel and concrete (see Section 6.2). It is also a major consideration in the design of reinforced concrete and masonry.

Although stress resistance is subject to variation, strain resistance—as measured by the direct stress modulus of elasticity—is not. This makes for a shifting relationship when stress capability is raised to produce higher grades of steel. Although load resistance—as measured by stress capacity—may be increased, resistance to deformations is not. Thus, deflection or buckling—both affected by the stiffness of the material—may become relatively more critical for structures made with higher grades of steel.

Stability

Unlike the solid forms common with timber and concrete, elements of steel are often composed of relatively thin parts. In addition, framed assemblages often consist of fairly slender linear components. All of this thin and slender character results in a condition in which buckling collapse, rather than crushing or tension cracking, is a common limiting failure behavior. This situation requires that designers pay special attention to the potential for various types of buckling failure. These forms of failure are treated in the various chapters in this book that treat individual types of structural elements and systems.

Another type of stability problem results from the usual type of assemblage connections used with steel structures. These connections have generally the character of very little moment-resistance, often qualifying essentially as pinned connections, rather than fixed connections. In truth the typical connection is one that is partially fixed, with some limited moment-transmitting capacity. In any event, the problem is that most assemblages do not derive much stability from the connections. Attention must therefore be paid to what *does* stabilize the assembled structure.

The problem of stability just described often relates to the resistance of lateral loads—that is, horizontal forces by comparison to the vertical forces of gravity. However, the problem may be a general one of giving the structure some degree of three-dimensional stability. The general means of achieving this are as follows:

1. Modify the usual connections to more fully resist moments, producing what is described as *rigid frame* action.
2. Arrange the frame so that the overall assemblage works for stability without rigid joints, as with triangulation that produces truss action.
3. Add extra bracing elements (guys, struts, X-bracing, flying buttresses, etc.) for the specific added purpose of achieving stability.
4. Borrow stability from other parts of the building construction; for example, masonry walls.

The point here is that this problem requires some extra consideration beyond that given to ordinary resistance of gravity loads. Specific situations of this type are discussed in the various chapters of the book.

Deformation Limits and Controls

The most critical limit for a structure for purposes of establishing safety is usually the magnitude of load it can resist, as measured in terms of strength. However, as discussed in the preceding section, failure may be precipitated by a loss of stability, before stress levels achieve limiting magnitudes. True safety must therefore be established by consideration for both strength and stability.

Although it does not often relate to safety, a practical limitation that must also be considered is that of the amount of *deformation*—literally, shape change—that can be tolerated. Stress resistance cannot be developed without some accompanying strain, so deformation is inevitable for any structure.

For structural members, the most critical deformations are usually those caused by bending, due simply to their larger dimension. A column may be heavily loaded but shorten by a virtually imperceptible amount, whereas even a short-span beam will deflect noticeably when loaded. The most common deformation problem is thus the vertical deflection of beams.

Practical deflection limitations derive mostly from consideration of effects on the general building construction. Cracking of tiled floors or plastered ceilings may provide such limitations. However, many other situations also limit the tolerable movement of the structure. Although the real need for control of deformation may easily be understood, the practical means for establishing design criteria is elusive, and much professional judgement is involved. These problems are treated in some depth in the chapters that deal with spanning structures.

Another type of deformation problem occurs within structural connections. Here also development of stress is unavoidably accompanied by strain and deformation. This may add to stability problems or simply increase overall movement of an assembled structure. Some of these issues are discussed in Chapter 8.

Rust

Exposed to air and moisture, most steels will rust at the surface of the steel mass. Rusting will generally continue at some rate until the entire steel mass is eventually rusted away. Response to this problem may involve one or more of the following actions:

1. Do nothing, if there is essentially no exposure, as when the steel element is encased in cast concrete or other encasing construction.
2. Paint the steel surface with rust-inhibiting material.
3. Coat the surface with nonrusting metal, such as zinc or aluminum.
4. Use a steel that contains ingredients in the basic material that prevent or retard the rusting action (see discussion in Section 1.1 on corrosion-resistant steels).

Rusting is generally of greater concern when exposure conditions are more severe. It is also of greatest concern for the thinner elements, especially those formed of thin sheet steel, such as formed roof decks.

In some cases it may be necessary to leave the steel in an essentially bare condition, such as when field (on-site) welding is to be done or when steel items are to be encased in concrete. These are standard practices in building construction, but they can be difficult to deal with when appearance is important due to the final exposed condition of the structure.

When structures are exposed to conditions likely to cause serious rusting, designers tend to avoid use of excessively thin parts. This reduces vulnerability of the structure to failure by loss of material in cross sections, in the event that rust prevention methods are less than totally successful.

Deterioration of steel can also be caused by exposure to various corrosive chemicals, such as acid rain, seacoast salt air, or air heavily polluted with various industrial wastes. Special protection or simply avoiding exposure as much as possible may be required for such conditions. Where not just appearance but actual structural safety is at risk, these matters require serious attention by the structural designer.

Fire

As with all materials, the stress and strain response of steel varies with its temperature. The rapid loss of strength (and stiffness, which may be more important when buckling is critical) at high temperatures, coupled with rapid heat gain due to the high conductivity of the material and the common use of thin parts, makes steel structures highly susceptible to fire. On the other hand, the material is noncombustible and less critical for some considerations compared with constructions with thin elements of wood.

The chief strategy for improving fire safety with steel structures is to prevent the fire (and the rapid heat buildup) from getting to the steel by providing some coating or encasement with fire-resistant, insulative materials. Ordinary means for this include use of concrete, masonry, plaster, mineral fiber, or gypsum plasterboard elements. The general problem and some specific design situations are presented in Chapter 10.

Concrete is often used with steel framing as a fill on top of formed steel deck or as a structural concrete slab bearing directly on steel beams. In some situations the concrete may also be used to encase steel columns or beams, although building code acceptance of other means for achieving necessary fire ratings have largely eliminated this practice. One easy form of this construction occurs with the steel beam-plus-concrete slab construction shown in Figure 1.5. A problem for concern in design of such a system, however, is the considerable added weight of the construction due to the concrete encasement.

System Assemblage Considerations

As whole systems, steel structures consist of many individual parts. Assemblage of the complete structure—that is, simply bringing together all of the parts and connecting them—is a major design concern. Designers must deal with the work of design for each of the individual parts in many cases, but they must also consider the assemblage of the complete structure. Following are two major aspects of the development of the assemblage:

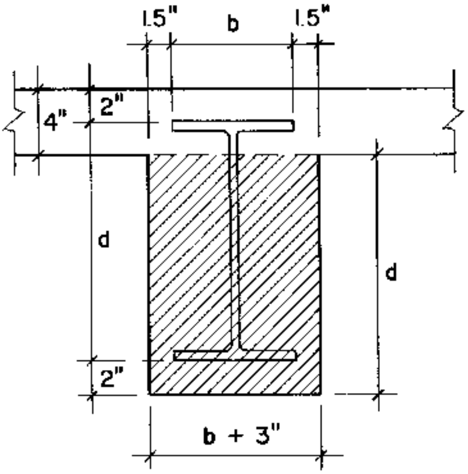

Figure 1.5 Steel beam encased in concrete for fire protection. Shaded portion indicates concrete in excess of that required for the supported concrete slab.

1. Planning of the structural arrangement. This consists of decisions for the overall form of the structure and for dimensions of spans, story heights, sizes of openings, and so on. A frequent decision involves choice of repetitive modules, such as the spacing for sets of beams and columns.
2. Mating of the parts. Decks must be attached to beams, beams attached to columns, columns attached to footings, and so on. This involves geometric considerations for the shape of individual parts and the development of individual connections for necessary transfer of loads.

Assemblage is mostly achieved with standard methods of connection. These relate to the form of the connected elements and to the type of loads being transferred among them. The amount of connecting work required for a typical steel structure is considerable, so methods used should be practical and economical—and above all, familiar to the construction assemblage crew.

A critical factor has to do with the assemblage that is performed as fabrication in the factory (called the *shop*) and that is performed at the job site (called the *field*). To some degree different methods are employed at these locations, relating to working conditions. Part of the designer's task is to visualize where the assemblage occurs, because it may well affect choices for individual members and for connecting methods.

Assemblage problems are discussed for individual types of structural elements (beams, decks, columns, etc.) in the various chapters of this book. Overall problems of structural assemblages are treated in Section 1.7 and in the discussions for the building case examples in Chapter 10.

Cost of Construction

Steel is relatively expensive, on a volume basis. The real dollar cost of concern, however, is the final *installed cost,* that is, the total cost for the erected structure. Economy concerns begin with attempts to use the least volume of the material, but this is applicable only within the design of a single type of item. Rolled structural shapes do not cost the same per pound as fabricated open web joists. Furthermore, each item must be transported to the site and erected, using various auxiliary devices to complete the structure, such as connecting elements for structural components and bridging for joists.

Cost concerns for structures as a whole, and for the total building construction, are discussed in Chapter 9. In other parts of the book, when design of single structural components are discussed, the usual approach is to generally seek to use the lightest-weight (least volume of material) elements that will satisfy the design criteria.

1.7 CHOICE AND PLANNING OF STEEL STRUCTURAL SYSTEMS

Elements of steel may be used to provide a variety of horizontal spanning floor or roof structures. The two primary spanning systems treated in this book are the rolled steel beam and the light, prefabricated truss. In this chapter we deal with some of the general issues involved in development of spanning systems. Design of beams and decks is treated in Chapter 3, and design of trusses is treated in Chapter 7. The special cases of rigid frames and bents are discussed in Chapter 5.

Deck–Beam–Girder Systems

A framing system extensively used for buildings with large roof or floor areas is that in which columns are arranged in orderly rows for the support of a rectangular grid of steel beams or trusses. The actual roof or floor surface is then generated by a solid deck of wood, steel, or concrete, which spans in multiple, continuous spans over a parallel set of supports. Planning for such a system must begin with consideration of the general architectural design of the building, but should also respond to logical considerations for the development of the structure.

Consider the system shown in the partial framing plan in Figure 1.6*a*. In developing the layout for the system and choosing its components, considerations such as the following must be made:

1. *Deck span.* The type of deck as well as its specific variation (thickness of plywood, gage of steel sheet, etc.) will relate to the deck span.
2. *Joist spacing.* This determines the deck span and the magnitude of load on the joist. The type of joist selected may limit the spacing, based on the joist capacity. The type and spacing of joists must be coordinated with the selection of the deck.
3. *Beam span.* For systems with some plan regularity, the joist spacing should be some full-number division of the beam span.

4. *Column spacing.* The spacing of the columns determines the spans for the beams and joists, and is thus related to the planning modules for all the other components.

For a system such as that shown in Figure 1.6*a,* the basic planning begins with the location of the system supports, usually columns or bearing walls. The character of the spanning system is closely related to the magnitude of the spans it must achieve. Decks are mostly quite short in span, requiring relatively close spacing of the elements that provide their direct support. Joists and beams may be small or large, depending mostly on their spans. The larger they are, the less likely they will be very closely spaced. Thus, very long-span systems may have several levels of components, ranging in size down from the elements that achieve the longest span to the elements that directly support the deck.

Concerns for the design of individual components of the deck–beam–girder system are discussed in Chapter 3. General discussion of design in the context of whole building system development is presented in the building system design examples in Chapter 10.

Figure 1.6*b* shows a plan and elevation of a system that uses trusses for the major span. If the trusses are very large and the purlin spans quite long, the purlins may have to be quite widely spaced. A constraint on the purlin locations is usually that they coincide with the joints in the top of the truss, so as to avoid high shear and bending in the truss top chord. If purlins are widely spaced, it may be advisable to use joists between the purlins to provide support for the deck. On the other hand, if the truss spacing is a modest distance, it may be possible to use a long-span deck with no purlins. The basic nature of the system can thus be seen to change with different magnitudes of spans deriving from the locations of supports. In any event, the truss span and panel module, the column spacing, the purlin span and spacing, the joist span and spacing, and the deck span are interrelated and the selection of the components is a highly interactive exercise.

For systems with multiple elements, some consideration must be given to the various intersections and connections of the components. For the framing plan shown in Figure 1.6*a,* there is a five-member intersection at the column, involving the column, the two beams, and the two joists (plus an upper column, if the building is multistory). Depending on the materials and forms of the members, the forms of connections, and the types of force transfer at the joint, this may be a routine matter of construction or a real mess. Some relief of the traffic congestion may be

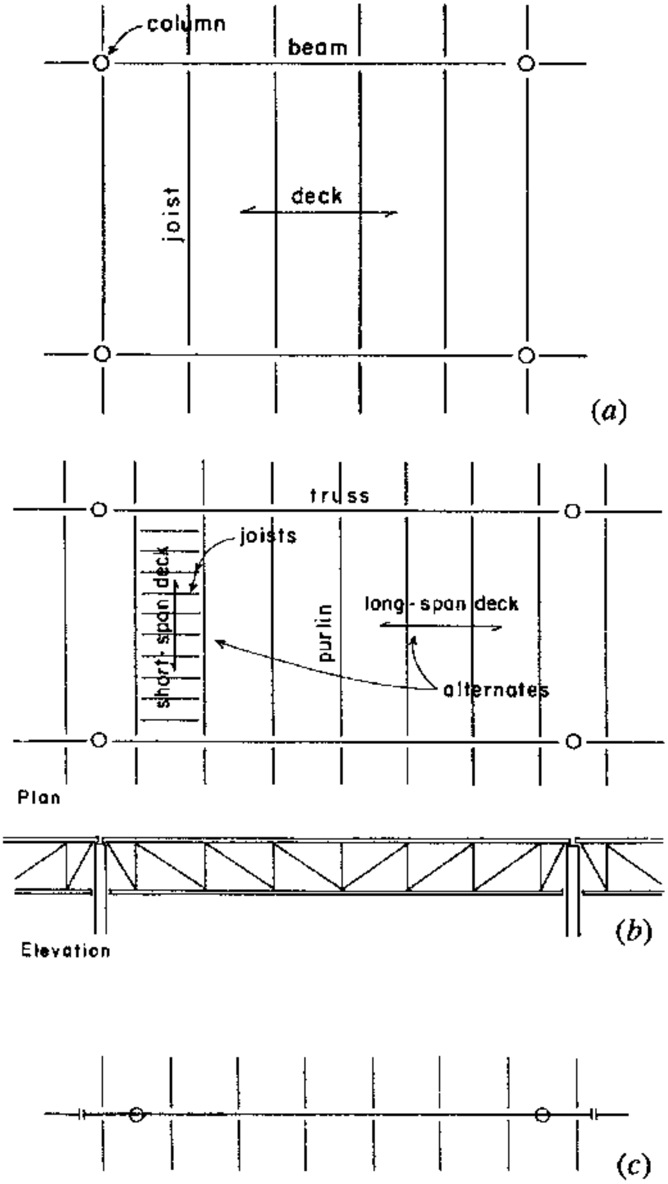

Figure 1.6 Planning considerations for beam framing.

achieved by the plan layout shown in Figure 1.6*c,* in which the module of the joist spacing is offset at the columns, leaving only the column and beam connections at the column location. A further reduction possible is that shown in Figure 1.6*c,* where the beam is made continuous through the column, with the beam splice occurring off the column. In the plan in Figure 1.6*c,* the connections are all only two-member relationships: column to beam, beam to beam, and beam to joist.

Bridging, blocking, and cross-bracing for trusses must also be planned with care. These members may interfere with continuous piping or ducting or may create complex connection problems similar to those just discussed. Use of required bracing elements for multiple purposes should be considered. Blocking required for plywood nailing may also function as edge nailing for ceiling panels and as lateral bracing for slender joists or rafters. The cross-bracing required to brace tall trusses may be used to support ceilings, ducts, building equipment, catwalks, and so on.

In the end, structural planning must be carefully coordinated with the general planning of the building and with its various subsystems. True optimization of the structure may need to yield to other, more pragmatic concerns.

Cantilevered Edges

A problem that occurs frequently is allowing for the extension of the horizontal structure beyond the plane of the building's exterior walls, providing a cantilevered edge. This most often occurs with an overhanging roof, but it can also be required for balconies or exterior walkways for a floor. Figure 1.7*a* shows one possibility for achieving this, by simply extending the ends of joists or rafters that are perpendicular to the wall. With steel framing, this type of cantilever is most easily achieved if the extended roof framing members perpendicular to the wall simply rest on top of the supporting beam or bearing wall at the wall plane. With an exterior column system, an alternate is shown in Figure 1.7*b,* in which the column line members are extended to support a member at the cantilevered edge, which in turn supports simple span members between the column lines. Loading, member size and type, and the magnitude of the cantilever would all affect the choice of one of these schemes over the other.

A special problem with the cantilevered edge occurs at a building outside corner, when both sides of the building have the cantilever condition, as shown in Figure 1.8*a.* With the framing system shown in Figure 1.7*a,* a possibility for the corner is that shown in Figure 1.8*b,* where the sup-

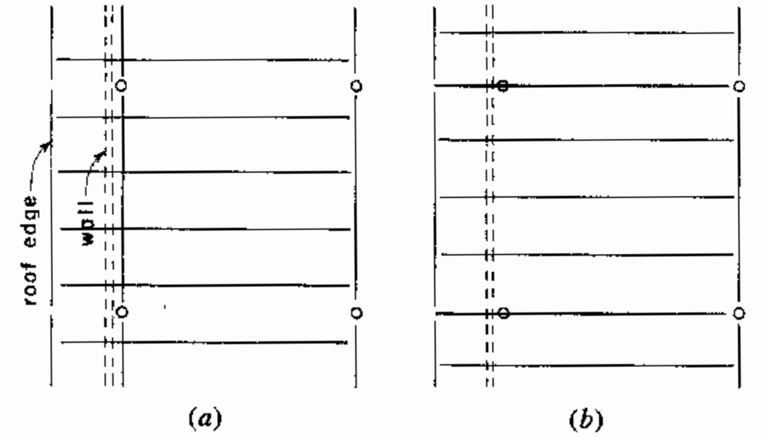

Figure 1.7 Framing at cantilevered edge.

ported beam is cantilevered to support edge member 1 and the joists are cantilevered to support edge member 2.

For the system shown in Figure 1.7*b,* a way of achieving the corner is depicted in Figure 1.8*c.* In this case the column-line member is cantilevered as usual to support edge member 1, which in turn cantilevers to the corner to support edge member 2.

A third possibility for the corner is the use of a diagonal member, as shown in Figure 1.8*d.* A feature of this solution is the reorientation of the framing system as the corner is turned. This layout is more often utilized in wood than in steel and is commonly used for sloping roofs when the diagonal member defines a ridge as the roof slopes to both edges. Note that there is a rather busy intersection at the interior column in the plan in Figure 1.8*d.*

Special Concerns

Various general planning concerns for structures are discussed in the examples in Chapter 10. The following are some particular issues that relate to design of steel framing systems.

Ceilings. Where ceilings exist, they are generally provided for in one of three ways: by direct attachment to the overhead structure (underside of the roof or floor above), by some independent structure that

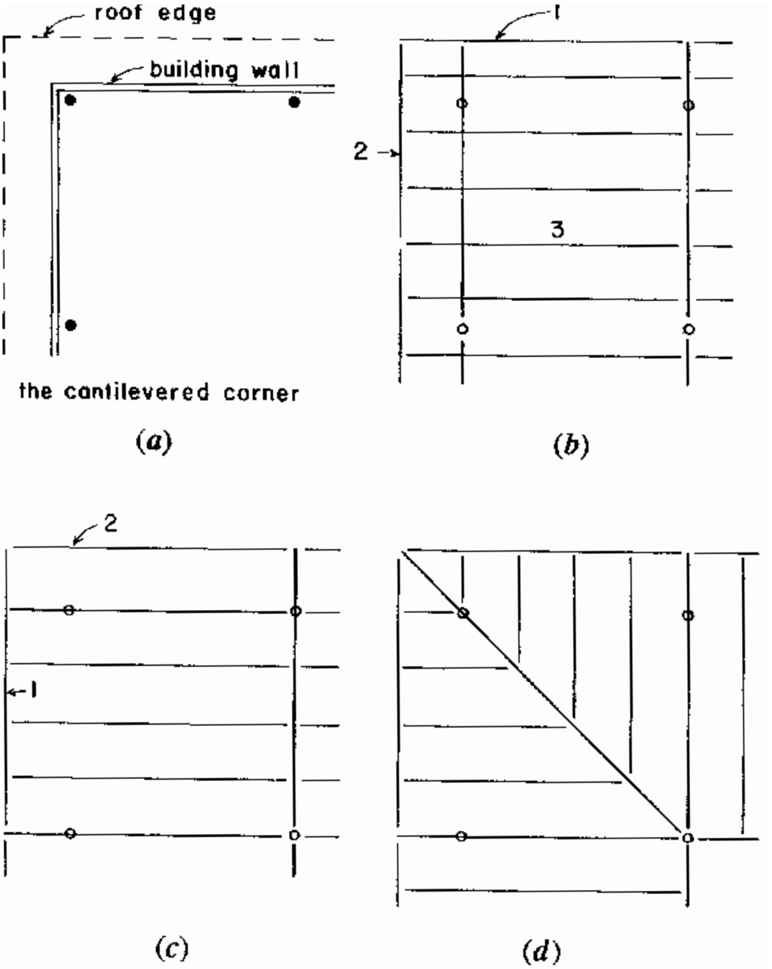

Figure 1.8 Framing at cantilevered corner.

achieves its own span, or by suspension from the overhead structure. Suspended ceilings are quite common, because the space created between the ceiling and the structure is often used for concealment of ducting and registers of the HVAC system, wiring and recessed fixtures of the lighting system, and various other items of building equipment. If a joist or rafter system is used with closely spaced members (4 ft center to center or less), the structure for the ceiling is usually suspended from these members. The other means for suspension is to use hangers attached to the deck, an advantage being the freeing of the modules of the spanning structure and the ceiling framing from each other. The suspended ceiling is also used when the form of the ceiling does not correspond to that of the overhead structure (for example, sloped rafters with a horizontal ceiling).

Roof Drainage. Providing for minimum slopes required for drainage of flat roofs is always a problem for a roof framing system. The most direct means is simply to tilt the framing to provide the slope patterns required. For a complex roof, this gets to be quite complicated with regard to the specification of the levels of the various framing members. The desired patterns of slopes and the locations of drains may not relate well to the layout of the roof framing members. Another possibility is to keep the framing flat but vary the thickness of the deck (applicable only to cast-in-place concrete decks) or to use tapered insulation fill on top of the deck. The latter technique simplifies the framing details but is usually capable of developing only a few inches of slope differential. If a flat ceiling is required and is to be attached directly to the roof structure, this must be considered in facilitating the drainage.

For some types of structural members—most notably the manufactured trusses—it is possible to slope the top of the member while keeping the bottom flat. This makes it possible to have a sloping roof surface and a flat ceiling, with both the roof deck and the ceiling surfacing directly attached to the truss chords.

Dynamic Behavior. Roof structures may usually be optimized for light weight without major restriction, resulting in a benefit of dead-load reduction for both the spanning structure and its supports. Lightweight floor structures, on the other hand, tend to be bouncy, which is generally not a desirable characteristic. Bounciness can also be a result of an excessive span-to-depth ratio for the spanning elements. Experience is the primary guide in this matter, but following are some general rules:

1. Restrict live-load deflections to a conservative ratio of the span (usually not greater than 1/360 of the span for any floor).
2. Limit span-to-depth ratios well below those of the maximum permitted. Suggestions: maximum of 20 for solid members, 15 for trussed joists.

3. Use a very stiff deck for its load-distributing function (to achieve the repetitive member effect, as described for wood joists).
4. Even if load distribution is not significant, do not use decks for the longest spans listed in design data references.

A major factor in reducing bounciness is the presence of the concrete fill on top of steel decks. This fill is now commonly also used on top of wood decks.

Holes. Both floor and roof surfaces are commonly pierced by a number of passages for various items. Large openings are required for stairs and elevators, medium-sized ones for ducts and chimneys, and small ones for piping and wiring. The structure must be planned and detailed to accommodate these openings, which entails some of the following considerations:

1. *Location of openings.* Openings may often occur at locations not convenient for the framing. This may indicate some poor planning of the framing or may be essentially unavoidable. For structures that utilize column line rigid frame bents for lateral bracing, the integrity of the bents generally requires that openings be kept off of the column lines. For regularly spaced systems in general, the layout of the framing and locations of required openings should be coordinated to maintain a maximum regularity of the system. Openings should not interrupt the major elements of the system (large trusses or girders).
2. *Size of openings.* Large openings must have some framing around their perimeters, which are also likely to be locations of supported wall construction. Small openings (for single pipes, for example) may simply pierce the deck with no special provision. For sizes of openings between these extremes, the accommodation requirements depend on the form and size of the elements of the structure. For closely spaced joists, provision for openings of a size that fits between the joists is usually quite simple; when the size requires the interruption of one or more joists, it entails some more difficult measures, such as doubling the joists on each side of the opening.
3. *Openings near columns.* For efficiency in architectural planning, it is sometimes convenient to locate duct shafts or chases for piping or wiring next to a structural column. If this can be done without

interrupting a major spanning member, it may not present a problem. If the opening must be on the column line, it may require straddling of the opening with a double framing member of two spaced elements.

4. *Loss of effectiveness of diaphragms.* Presence of large openings must be considered with regard to effects on the functioning of the floor or roof system as a horizontal diaphragm for lateral bracing. It may be necessary to provide special framing or connections to develop collector functions, drag struts, or the subdivision of the diaphragm, as described in Section 10.4.

The Three-Dimensional Frame

Steel elements are frequently used to obtain what is essentially a two-dimensional structure, often constituting a single plane of a floor, a roof, or a wall. However, steel elements can also be arranged in three-dimensional systems, producing a skeleton structure for a tower or a multistory building. One of the early major uses of rolled shapes was for the early skyscrapers of the late nineteenth century.

Product development and usage applications often grow interactively. Such was the case for development of the W shapes (as mentioned, originally called wide-flange shapes). These shapes have relatively wide flanges, and most of the flange surface is flat rather than tapered. This geometry particularly facilitates the assemblage of frameworks that use a common joint configuration as shown in Figure 1.9. Here a multistory steel column is shown as continuous between two stories, with steel beams framing into it from three horizontal directions. The W-shape column (actually I- or H-shaped in cross section) is ideally formed to accommodate this framing. To achieve the joint shown in Figure 1.9, the column needs the following attributes:

1. The flanges must be wide enough to accept the framing connection of the beam on the flange side of the column.
2. The distance from flange to flange (or the *depth* of the W shape) must be large enough to accommodate the framing connection of the beams that frame into the column web.
3. For the connection detail as shown, any splice joints in the column must be located above or below the beam level.

This results in some common practices, such as the following.

Minimum Column Depth. Steel columns for multistory construction are usually a minimum of 10 in. in nominal depth. For heavier loads and larger beams depths may be 12 or 14 in.

Minimum Flange Width. Shapes used for columns are mostly those with flanges at least 6-in. wide. Wider flanges are also available, with an approximately square column shape being commonly produced for column use in the 10-, 12-, and 14-in. nominal shapes series.

Common Column Splice Location. This is usually about 3 ft above the tops of the beams, also a handy height for the steel erection crew.

Planning of three-dimensional frames involves many considerations, including those mentioned in the preceding section for two-dimensional systems. Obviously, it is generally desirable for columns in one story to be located over columns in the story below whenever possible. Another possible consideration involves the use of so-called framed bents. In the three-dimensional system, these may be constituted by the columns and beams in a single vertical plane. The nature and problems of such bents are discussed in Chapter 5.

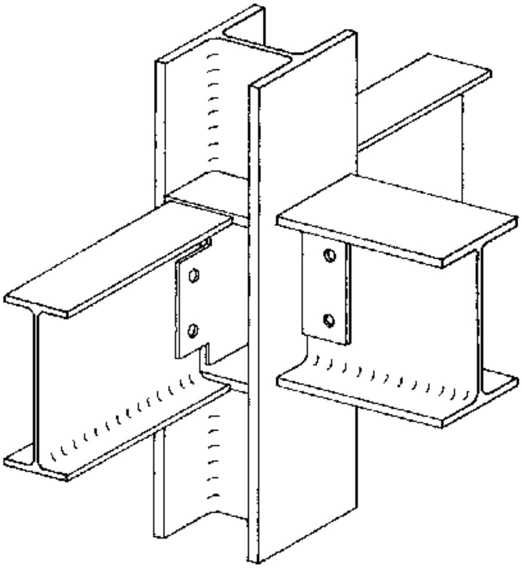

Figure 1.9 Connections for column/beam framing.

Truss Systems

Trussing can be used to produce some of the lightest of steel-framed structures. Two basic principles are involved. The first is the use of the basic planar stability of the three-sided triangle held rigid simply by resistance of change in the length of its sides. The second is the isolation of highly efficient concentrations of material with great distances of separation—a feat only possible with a relatively strong material. The specific usage and problems of steel trusses are discussed at length in Chapter 7.

In steel frameworks, trusses may be substituted for beams in some situations. This may be done to achieve spans more efficiently, especially when spans are great. However, the trussed joist of more modest dimensions is also frequently used in place of beams with solid webs. A benefit deriving from the absence of a solid web is the ease of passing of ducting, piping, or wiring through the system—a value that may well favor the selection of trusses over solid-web beams.

Another major use of trussing consists of adding diagonal members to a vertical planar arrangement of steel beams and columns to produce a *trussed bent.* This is a common means of producing three-dimensional stability for steel frameworks and is one of the major options for development of bracing for resistance to the horizontal force effects of wind or earthquakes.

Trussing is also highly adaptable to the generation of many forms other than rectilinear frameworks. Linear rolled shapes can be bent or curved, but arrangements of truss members can more easily be shaped to achieve just about any form.

Rigid Frames

Rigid frames are frameworks in which rigid (moment-resistive) connections are made between members. This is not the "normal" way of connecting linear steel elements for building structural frames or trusses, so the joints must be specially developed. In Figure 1.9, for example, the "normal" connection between the beams and the supporting column involves the use of some connecting device that is attached to the beam web and then to the column. This is used essentially to transfer only vertical load. To make this joint capable of transmitting bending moment to the column, the beam flanges must be connected to the column. If this is done, a rigid, or moment-resistive, joint will be produced.

One way of achieving the rigid joint is to weld the beam flanges directly to the column. For the beams on the flange side of the column, this is a direct connection, achieved with a butt weld at the end of the beam flange. Because bending moment in the column is most effectively developed by the column flanges, this is a reasonably direct transfer between the beam and the column.

However, the beam thus grabs only one of the column flanges, so the joint is typically enhanced by welding of filler plates (as shown in position in Figure 1.9) on the inside of the column at the level of the beam flanges. This helps transfer the bending across the whole column section.

The most effective column-beam rigid frame bent is obviously achieved by turning the W-shape columns in plan so that the column flanges are perpendicular to the plane of the planar framed bent. However, in some situations, it may be necessary to achieve bent action in both directions and thus to attach the beams that intersect the open side of the columns for moment transfer. This is not so easily achieved, although possibilities do exist.

Various problems of achieving framing connections are discussed in Chapter 8. General problems of rigid frames are discussed in Chapter 5. Some general planning problems for rigid frame bents in multistory construction are discussed in Section 10.3.

The rigid bent can also be used for simple planar structures. Examples of such structures are presented in Sections 10.1 and 10.5.

Mixed Systems

The all-steel structure is sometimes possible—and is surely ideal in the eyes of people in the steel business. However, the typical building utilizes a variety of materials, so that the mixed-material structure occurs frequently. Spanning roof or floor systems of steel may be supported by steel columns but are also frequently supported by structural walls of concrete or masonry. Steel frameworks are sometimes surfaced with formed sheet steel but are also surfaced with plywood panels, cast-in-place concrete decks, and precast concrete panels.

The planning of elements in a mixed-material system must relate to problems of all the materials and types of structural elements involved. Because this book is devoted essentially to steel structures, it is not possible to develop all possible combinations here. The case study examples in Chapter 10 involve mixed materials in various situations and discussions there deal with some planning concerns.