Chapter 14 first describes structural wood elements, particularly linear elements: trusses, curved members, and stressed-skin panels are also discussed. The chapter then considers light-frame buildings, which constitute the majority of timber-framed buildings. The discussion of heavy-timber buildings includes glulam systems, arch structures, and domes. The final section on special considerations covers connections, lumber grades, and shrinkage.

14.1. HISTORY

From the earliest days of human history, people found shelter from the elements in natural caves. As our ancestors developed and began to provide their own shelter—where they wanted and needed it—and not only when nature had provided it—wood was usually the most available material. Nomadic cultures used sapling-size supports for coverings of hide or cloth because of easy assembly, disassembly, and transport. As civilizations developed, their needs grew to include shelter not only for people and animals, but also for storage of materials and foodstuffs, for various manufacturing or converting processes, for retail stores, and the like. Thus, larger and larger structures were needed, both for family use and commerce and industry.

In North America, two types of construction prevailed for dwellings in the days of the early settlers (Ref. 14.1). One type, prominent on the East Coast, was the New England timber frame house, which was based on the English timber frame house. The second type, more suited to the frontier, used logs that were placed horizontally. The log house has often been thought of as an American development, although it was introduced by Scandinavians in the early 17th Century. The size of log houses was limited by the length of the logs, and the structures were generally built as separate modules as needed, with the modules sometimes connected by a roofed area without walls.

With the appearance of sawmills in the early 19th Century, sawn lumber became available in quantities sufficient to meet the demands of the growing population. From this evolved the light-frame construction that currently forms the basis for the greatest proportion of American homes and for a significant proportion of low-rise retail, agricultural, commercial, and light-industrial buildings. In the nonresidential sector, mill-type or heavy timber construction was commonly found in industrial or warehouse facilities. As originally built, heavy timber construction used members of large cross section, which provided good resistance to fire, and structures were designed with attention to details such as avoiding concealed spaces and limiting the number of openings in walls to ensure adequate fire resistance. This type of construction is still recognized in many building codes.

Both light-frame and heavy timber constructions have adapted to the use of modern materials and techniques. For example, where floor, wall, and roof sheathing for light-frame construction was once commonly made from wood boards, sheathing now is commonly made from panel products such as plywood, structural flakeboards, particleboards of various types, or fiberboards. All of these are faster to install than boards and provide improved structural resistance to wind and earthquake loadings. Furthermore, prefabricated floor and wall panels along with prefabricated roof and floor trusses are replacing piece-by-piece on-site construction. Factory-made and hauled to the site, a structure can be enclosed within a short time using panelized systems.

In the case of larger structures, the development of glued-
laminated timbers (glulam) has greatly widened the horizons. No longer are the spans in a post-and-beam structure limited by the lengths of available timbers. Rather, spans may be of almost any length, and beams 100 feet (30 m) or longer and several feet (meters) in depth are relatively commonplace.

Building systems use many types of structural wood elements. The following section describes joists, rafters, and studs; beams and girders; posts and columns; trusses; curved members; and stressed-skin and sandwich panels. The section also describes the design of such elements.

14.2. STRUCTURAL WOOD ELEMENTS

Wood structural elements are required to resist loads in a wide variety of structures. Dimension lumber (usually nominal 2 in. (50 mm) in thickness) commonly provides the structural framework for light-frame buildings, particularly individual homes, but also small apartment and office buildings, and small retail or warehouse structures. In larger structures, structural timbers may provide the structural framework, including posts and girders, with wood decking for the floor. The roof over a large area (a particularly long span) may be supported by deep glued-laminated girders.

Over the years many technological developments have led to improvements in structural wood elements. These developments and their applicability to the architecture are briefly described in the following sections. The materials have been discussed in Chapter 4.

Joists, Rafters, and Studs

Joists and rafters of dimension lumber have traditionally been the primary elements for resisting bending loads in floors and roofs of light-frame structures. Typically, building codes specify different design loads for various areas of light-frame buildings, so grades and sizes for floor and ceiling joists vary with the requirements and cannot be generalized. Most lumber joists are nominal 2 by 8 in. (50 by 200 mm), nominal 2 by 10 in. (50 by 250 mm), or nominal 2 by 12 in. (50 by 300 mm). Grade, species, and size are related to allowable spans in tables prepared by lumber-producing organizations, with oversight from regulatory bodies (Ref. 14.2).

Wood-plywood or other composite members in either I or box sections can be made in sizes suitable for use as joists. The I-joist arrangement (Fig. 14.2.1) is the most common and is best adapted to a high-speed, automated manufacturing process. The flanges in such members may be sawn lumber or laminated veneer lumber (LVL). The webs are generally either plywood or structural flakeboard, and they are commonly glued into slots machined in the flanges.

Another option for floor joists is the flat truss (Fig. 14.2.2), which is most frequently made with metal plate connections between wood truss members. This type of truss is more fully discussed in a later section. A variation of this type of truss employs wood chords and two types of metal webs; a light-duty type with wood flanges and stamped steel webs with integral truss plates, and a heavy-duty type with wood flanges and tubular steel webs flattened at the ends and pinned into the flanges.

Roof systems are commonly made with triangular trusses of any of the wide variety of forms shown in Fig. 14.2.2. These are most commonly made with metal truss plates, although nail-glued plywood gusset plates are also used to a limited extent.

Where rafter systems are used, suitable spans vary with lumber grade and size, with roof slope, and of course, with anticipated loadings. Span tables for rafters are available (Ref. 14.2). The present trend is to replace the wide dimension lumber used for joists and rafters with I-joists and trusses. One advantage of prefabricated I-joists and trusses (both floor and roof) is that they can be designed for spans longer than those feasible with lumber alone, eliminating the need for central beams and load-bearing partitions.

Studs are the main framing members in exterior walls of light-frame structures. They are most commonly nominal 2 by 4 in. (50 by 100 mm), although nominal 2 by 5-in. (50- by 125-mm) and nominal 2 by 6-in. (50- by 150-mm) studs may be used to provide space for greater amounts of insulation, and in larger structures, to accommodate greater loads than are normal in typical houses. Stud spacing may range from 12 to 24 in. (300 to 600 mm) depending upon loading; common spacing is 16 in. (400 mm). Although 3 variety of species may be used, stud grades are generally used. No. 2 or better lumber, sized to match the studs, is commonly used for the top and bottom
plates to which the studs are attached. A double top plate is often used for additional stiffness.

Interior load-bearing partitions are framed in the same way and with the same lumber grades as exterior walls. Depending upon the building code, studs for non-load-bearing partitions may be 2 by 3 in. (50 by 75 mm) in size and spaced up to 24 in. (600 mm) apart using single top and bottom plates.

Beams and Girders

In light-frame construction, perhaps the most common central beam in the foundation system is a built-up beam consisting of several 2-in. (50-mm) planks (commonly three) set on edge and nailed together. The limited lengths of the sawn lumber used in the beam necessitate posts at frequent intervals to support such a beam. The butt joints between abutting pieces must be staggered between adjacent layers so that they are separated by 16 in. (400 mm). The beam is supported by posts positioned within 12 in. (300 mm) of the butt joints. Alternatively, a steel or glulam beam is used.

Mill-type or heavy timber construction has been widely used for warehouse and manufacturing structures, particularly in the Eastern United States. As previously noted, this type of construction is recognized as fire resistant because of the use of heavy (large cross section) timbers for beams, girders, and other structural elements.

To qualify as heavy timber construction, beams and girders of solid-sawn timber must be not less than 6 by 10 in. (150 by 250 mm) in cross section, and columns must be not less than 8 by 8 in. (200 by 200 mm) in cross section.

Stress-graded timbers classified as beams and stringers, as discussed in Chapter 4, are desirable for beams and girders in mill-type construction. These grades are described and allowable design stresses are provided in grading rule books of the associations that produce timbers in this classification.

For spans too long for ordinarily available lengths of sawn timbers, glulam members, whose lengths are relatively unlimited, may be manufactured for specific situations (that is, made to order). Such beams are straight or curved to meet job requirements. Stock glulam members,
commonly straight beams. are available through distributors nationwide (Ref. 14.3). For situations where stock beams are not suitable, beams may be made in a number of forms to fit special situations. To meet architectural and other requirements, the beams may be made in the forms shown in Fig. 14.2.3, including single- or double-tapered straight beams, double-tapered curved beams, and double-tapered pitched and curved beams.

In some situations, headroom or other limitations may dictate the use of continuous beams to take advantage of the reduced bending moments in such beams. If the greater length of a continuous beam creates problems, a cantilevered-suspended system may be indicated, as shown in Fig. 14.2.4.

Composite beams of various types with mechanical fasteners may be used (Fig. 14.2.5). Some slip between layers must take place before mechanical fasteners come into play, so that the efficiency of such beams in both strength and stiffness suffers somewhat. Despite reduced efficiency, such beams may serve well in such applications as door and window headers and garage door headers. Headers at floor openings in light-frame construction where joists are interrupted are commonly made of lengths of joist-size lumber face nailed together and set with the wide dimension of the components vertical.

**Posts and Columns**

Posts supporting central beams in residences or other light-frame structures are commonly made of solid-sawn lumber or pipe columns. In heavier construction (like mill-type construction), they are commonly solid sawn or glulam. In some instances, such columns may be built up from a number of pieces of dimension lumber (Fig. 14.2.6). As with built-up beams, built-up columns lose some efficiency because the components are connected with mechanical fasteners. In the case of types (a) and (b) of Fig. 14.2.6, the strength may be estimated by applying certain multipliers to the strength of a comparable solid column. These multipliers range from about 0.65 to about 0.82: details are given on p. 328 of Ref. 14.4.

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**Fig. 14.2.3.** Forms of glued-laminated (glulam) timber beams.

**Fig. 14.2.4.** A structural system of cantilevered and supported beams is efficient in multi-span structures (Ref. 14.40). (By permission of the American Institute of Timber Construction.)
The poles in a pole-supported building carry compressive loads, as do foundation and marine piles. The lower portions of such members may be subjected to sizable axial forces. All of these represent tapered-column forms; the poles and piles are naturally tapered. In structures supported by Tudor arches, the vertical legs of the arches are tapered by design requirements with respect to both shear and bending forces. Architectural considerations may lead to single- or double-tapered columns. Special methods of analysis are required for tapered columns (Ref. 14.4).

Spaced columns are sometimes used when solid members of adequately sized lumber are not available or to facilitate the column-to-beam connection: that is, the beam forms one end-block of the spaced column. The spaced column

![Configurations of columns built up from lumber components.](image-url)
consists of two (rarely more) individual column members separated by spacer blocks. The individual members are connected to the end blocks by timber connecton or, somewhat rarely, by bolts or nails. A center spacer block is usually held in place by a bolt. Slippage between the end blocks and the individual members is restrained by the connectors more effectively than would be the case for bolts or nails. Thus, the elements of the column act together rather than individually. Regardless of the type of mechanical connector, spaced columns generally require more board feet of lumber than does a solid column of the same capacity. Compression members in timber trusses often act as spaced columns.

Design procedures for glulam columns are the same as for solid columns except that the lower variability in stiffness for glulam offers some design advantages. Glulam members intended to support axial loads should be specified differently from beams; often, the glulam combinations intended for axial loading can be used efficiently (see Ref. 14.5).

Trusses

Developments of the 20th Century have widened the application of wood trusses. Split-ring and shear-plate connectors have improved trusses in long-span, wide-spaced, heavy-load applications such as industrial buildings and military facilities.

The nail-glued plywood gusset plate connector has facilitated the greater use of light wood trusses or trussed rafters for residential, agricultural, and other light-frame structures. Another type of connector, the toothed metal-plate connector, has teeth stamped at right angles to the plane of the metal sheet; when the teeth are pressed into the wood of the truss members, they serve to transmit shear, axial, and moment forces from one member to another. This type of connector dominates the light truss market today.

Wood trusses are available in a wide variety of forms (Fig. 14.2.2) commonly used in residential construction as well as commercial-industrial and agricultural structures. They are manufactured by fabricators nationwide and are available through lumber yards and building material suppliers. The designs are generally provided by plate manufacturers or structural designers who specialize in trusses. Building codes generally require that trusses be made to designs approved by licensed structural engineers.

Trusses are designed for light or heavy applications. One light-duty truss consists of dimension lumber chords and stamped steel webs; integral toothed metal plates hold the webs and chords together. A heavy-duty metal web truss is made from high grade lumber. LVL or glulam chords with tubular metal web members flattened at the ends and pinned to the chords. Heavy-duty trusses are also manufactured with 4-in. (100-mm)-thick lumber or glulam chords and heavy metal truss plates (Fig. 14.2.7).

Competition from metal-plate trusses, laminated beams.

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Fig. 14.2.7. Lone-span trusses made with toothed metal-plate connectors and double nominal 4- by 6-in. (100- by 150-mm) lumber chords and webs.
bar joists, and metal-web trusses has radically reduced the use of heavy wood trusses. Heavy trusses are still used to give a rustic appearance to a building. These trusses are primarily parallel-chord and full triangular types. Bowstring trusses are found in many buildings erected in the Ant half of the century.

**Curved Members**

Glue-laminating techniques remove the limitations on member size and form caused by the cross-section size and length of structural timbers.

Pitched and tapered beams were described under the heading Beams and Girders. Two-hinged arches are seldom used except for short spans; transporting such arches over long distances is troublesome because of limited clearances at railway or highway crossings. Three-hinged arches (hinges at supports and at a point within the arch, usually at the peak) are likely to be easier to transport than the two-hinged arch. Most commonly, three-hinged arches are some variation of the forms shown in Fig. 14.2.8. Arches of especially long span or of a form that is difficult to ship may be made in several segments and then connected in the field with moment-resisting joints.

**Stressed-Skin and Sandwich Panels**

Units consisting of plywood or structural flakeboard "skins" glued to wood stringers are often called stressed-skin panels (Fig. 14.2.9). These panels provide efficient structural units for floor, roof, and wall components of buildings. They can be designed to provide the necessary stiffness, bending strength, and shear strength for use in building construction. The panel skins provide resistance to bending and the wood stringers provide resistance to shear.

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**Fig. 14.2.8.** Two-hinged and three-hinged glulam arches. Other more complex shapes may also be fabricated (Ref. 14.3). (By permission of the American Institute of Timber Construction.)
Sandwich panels are also of layered construction: the faces provide bending resistance and the core shear resistance. Fig. 14.2.10 shows the application of one of many possible sandwich constructions. Because the core provides nearly continuous support for the faces, as contrasted with stressed-skin panels, the faces may be thinner than those of stressed-skin panels and a greater variety of materials may be used. Facings include plywood, veneer, plywood overlaid with a resin-treated paper, fiberboard, structural flakeboard, particleboard, glass-fiber-reinforced plastic, veneer bonded to metal, or metal (aluminum, enameled steel, stainless steel, magnesium, or titanium).

Sandwich cores have been made from many light-weight materials: balsa wood, rubber foam, resin-impregnated paper, reinforced plastic, perforated chipboard, expanded plastic, foamed glass, light-weight concrete, clay products, and formed sheets of cloth, metal, or paper. Cores made of formed sheet materials are often called honeycomb cores. Cores are made in a wide range in densities by varying the sheet material, sheet thickness, and cell size and shape.

Fig. 14.2.9. Cross Section of a stressed skin panel.

Fig. 14.2.10. Sandwich panels with plywood facings and paper honeycomb core. (a) Closeup view of construction, (b) panel used in an experimental structure.
Special properties can be imparted to the panels by careful selection of facing and core. An impermeable facing can act as a moisture barrier, and an abrasion-resistant facing can serve as the top facing of a floor panel. Plywood or plastic facings can produce a decorative effect. Both sandwich and stressed-skin panels may serve as structural elements in construction. Because such panels are relatively light weight, they can be economical in some nonstructural applications such as curtain walls.

### Design of Wood Structural Elements

Wood has some special characteristics that differentiate it from other structural materials. For example, wood is hygroscopic, taking on moisture from the atmosphere or giving it off. Because important properties vary with moisture content, wood elements must be protected from excessive exposure to moisture change. Wood is also isotropic in nature and thus has different properties in the three major directions. Since strength properties perpendicular to grain are characteristically only a fraction of those parallel to grain, elements must be designed to avoid or to minimize stresses perpendicular to grain.

Years of experience with many types of timber structures, large and small, together with continuing research have resulted in design procedures that take into account the unique characteristics of wood. A number of publications devoted to the design of wood structures are available to the structural designer who is not already experienced in wood design. These include design handbooks, specifications, and textbooks (Table 14.1).

### 14.3. LIGHT-FRAME BUILDINGS

In the 1980s, light-frame construction has dominated the housing market and is widely used in agricultural, commercial, and light industrial applications. In many respects, contemporary light-frame construction differs from this type of building 50 years ago in the use of new and innovative materials, panel products for floor and roof sheathing, and prefabricated components and modules as opposed to stick-built or on-site construction. Additional

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*Some associations that publish specifications for wood structural elements also have publications on wood design.*
information on construction of residential buildings using platform-type construction is given in Refs. 14.35 and 14.36.

Foundations

The light-frame building is typically supported on cast-in-place concrete walls or by concrete block walls supported by footings. This type of construction with a basement is common in northern climates. Some buildings, commonly in southern climates, have no foundation as such: the frame is supported by a concrete slab, so there is no basement or crawl space. The central supporting structure for a house with a basement may consist of wood posts on suitable footings that carry a built-up beam, which is frequently composed of planks the same width as the joists (2 by 8 in. to 2 by 12 in. (50 by 200 mm to 50 by 300 mm)). face-nailed together and set on edge. Because planks are seldom sufficiently long to span the full length of the beam, butt joints are required in the layers. The joints are staggered in the individual layers near the column supports (see Section 14.2. Beams and Girders). The girder may also be a steel H-section, perhaps supported on steel pipe columns. Similar details may be used in a house over a crawl space. In some instances, a glulam girder may be used rather than a built-up beam.

A fairly recent innovation is the use of treated wood for basement foundation walls. Basically, such foundations consist of prefabricated wood-frame wall sections of treated studs and treated plywood sheathing supported on treated wood plates (Fig. 14.3.1). The plates are laid on a layer of crushed stone or gravel to distribute the loads on the plates. The exterior surface of the foundation wall below grade is draped with a continuous sheet of 6-mil (0.15-mm) polyethylene to prevent direct water contact with the surface of the prefabricated panels. Because a foundation wall needs to be permanent, the preservative treatment of the plywood and framing is highly important. Therefore, a special foundation (FDN) treatment has been established with strict requirements for the treatment results, both as to depth of chemical penetration and amount of chemical

Fig. 14.3.1. Basement footing and foundation wall built with pressure-treated wood.
Floors

The floor framing in residential structures typically consists of wood joists on 16- or 24-in. (400- or 600-mm) centers supported by the foundation walls and the center girder (Fig. 14.3.2). The joists may bear directly on top of the girder and on top of the foundation walls or, more commonly, on a sill plate that is anchored to the walls. This arrangement carries the potential for problems if the lumber in the beam and the joists has not been adequately dried before installation in the building: if the joists and girder dry in service, the greater depth of wood (joist plus girder) can result in greater shrinkage at the center of the building than at the perimeter, where shrinkage occurs in the joists alone or the joists and sill plate, resulting in a sloping floor. To reduce this possibility, the joists may be framed into the sides of the center beam so that the tops of the joists are just below the top of the girder to allow for possible beam shrinkage. The joists may be supported on ledger strips or on joist hangers attached to the sides of the beam. Joists may be butted into the side of a steel beam with support provided by a wood ledger attached to the beam.

Joist size depends on the anticipated loading, spacing between joists, distance between supports (span), and species and grade of lumber. Joists are usually spaced 16 or 24 in. (400 or 600 mm) apart. Span tables are available for allowable spans for loadings and spacings (Ref. 14.2), and other tables list allowable stresses and moduli of elasticity assigned to various stress grades (Ref. 14.7). Conversely, when spans are set by other considerations, the span tables provide a basis for choosing grade, species, and size.

Floor openings, as at stairwells, fireplaces, and chimneys, may interrupt one or more joists. Preferably, such openings should be parallel to the length of the joists to reduce the number of joists that will be interrupted. At the interruption, a support (header) is placed between the uninterrupted joists and attached to them. A single header is usually adequate for openings up to about 4 ft (1.2 m) in width, but double headers are required for wider openings. Special care must be taken to provide adequate support at headers (by joist hangers, for example).

Cutting of framing members for installation of plumbing lines, heating ducts, and the like must be carefully done and should be avoided if possible. Cut members may require a reinforcing scab or a supplementary member may be needed. Areas of highly concentrated loads, such as under bathtubs, require doubling of joists or other measures to provide adequate support. One advantage of framing floors with parallel-chord trusses or prefabricated I-joists is the elimination of interior supports. An additional advantage is that plumbing, electrical, and heating ducts and piping may pass through the web area of these types of components.

Floor sheathing, or subfloor, is used over the floor framing to provide a working platform and a base for the finish flooring. Old homes have board sheathing but new homes generally use panel products. Common sheathing materials include plywood and structural flakeboard, which may be obtained in a number of types to meet sheathing requirements. Exterior-type panels with water-resistant adhesive are desirable for locations where moisture may be a problem, as in floors near plumbing fixtures or in situations where the subfloor may be exposed to the weather for some time during construction.

Plywood should be installed with the grain direction of the face plies at right angles to the joists. Structural flakeboard also often has a preferred direction of installation. Nailing patterns are either prescribed by code or recommended by the manufacturers. About 1/8 in. (3 mm) of space should be left between edges and ends of abutting panels to provide for dimensional changes associated with moisture content changes.

The literature of the American Plywood Association (APA) should be consulted for selection and installation of the types of structural panels suitable for subfloors (Ref. 14.38).

Exterior Walls

The exterior walls of light-frame Structures are generally load bearing: they support upper floors and roof. An exception are the gable ends of one-story buildings. Basically, wall framing consists of vertical studs and horizontal members, including top and bottom plates and headers (or lintels) over window and door openings. The studs are generally nominal 2- by 4-in. (50- by 100-mm) members spaced between 12 and 24 in. (300 and 600 mm) on center depending on the loads the wall is to carry and the need for support of wall-covering materials. Sometimes, 2- by 5-in. (50- by 125-mm) or 2- by 6-in. (50- by 150-mm) studs are used when required by the loading or if the walls will be filled with more than 3 1/4 in. (90 mm) of insulation. Headers are usually 2 by 6 in. (50 by 150 mm), nailed together face to face with spacers, which brings the headers flush with the faces of the studs. Wall framing is erected over the platform formed by the first-floor joists and subfloor. In most cases, a whole wall is framed in a horizontal position on the subfloor and then tilted into place. If a wall is too long to make this procedure practical, sections of wall may be formed horizontally and tilted up, then joined to adjacent sections.

Corner studs are usually prefabricated in such a configuration as to provide a nailing edge for interior finish (Fig. 14.3.3). Studs are sometimes doubled at the points of intersection with an interior partition to provide backup support for the interior wall finish. Alternatively, a horizontal block is placed midheight between exterior studs to support the
partition wall. In such a case, backup clips on the partition stud are needed to accommodate the interior finish.

Upper plates are usually doubled, especially when rafters will bear on the top plate between studs. The second top plate is added in such a way that it overlaps the first plate at corners and at interior wall intersections. This provides a tie and additional rigidity to the walls. In areas subject to high winds or earthquakes, ties should be provided between
the wall, floor framing, and sill plate, which is anchored to the foundation. If a second story is to be added to the structure, the edge floor joist is nailed to the top wall plate, and subfloor and wall framing are added in the same way as for the first floor.

Sheathing for exterior walls is commonly some type of panel product. Here again, as for subfloors, plywood or structural flakeboard may be used. Fiberboard that has been treated to impart some degree of water resistance is another option. Several types of fiberboard are available. Regular-density board sometimes requires additional bracing to provide necessary racking resistance. Intermediate-density board is used where structural support is needed. Numerous foam-type panels are also used to impart greater thermal resistance to the walls. However, because many foam sheathings cannot provide tacking resistance, diagonal braces must be placed at the corners, or structural panels must be applied over the first 4 ft (1.2 m) of the wall from the corner. In cases where the sheathing cannot provide the required racking resistance, diagonal bracing must be used. When light-weight insulating foam sheathings are used, bracing is commonly provided by let-in 1- by 4-in. (25- by 100-mm) lumber or by steel strapping.

Ceiling and Roof

Prefabricated roof trusses are used to form the ceiling and sloped roof of over 80 percent of current light-frame buildings. The remainder are framed with ceiling joists and rafter systems. Trusses reduce on-site labor and can span greater distances without intermediate support, thus eliminating the need for interior load-carrying partitions. This provides greater flexibility in the layout of interior walls.

In the past, sloping rafters were common. Such rafters are supported on the top plate of the wall and attached to a ridge board at the roof peak. However, because the rafters slope, they tend to push out the tops of the walls. This is
prevented by nailing the rafters to the ceiling joists and nailing the ceiling joists to the top wall plates (Fig. 14.3.4a).

A valley or hip is formed where two roof sections meet perpendicular to each other. A valley rafter is used to support short-length jack rafters that are nailed to the valley rafter and to the ridge board (Fig. 14.3.4b). In some cases, the roof does not extend to a gable end but is sloped from some point down to the end wall to form a “hip” roof. A hip rafter supports the jack rafters, and the other ends of the jack rafters are attached to the top plates (Fig. 14.3.4c). In general, the same materials used for wall sheathing and subfloors are used for roof sheathing.

Sources of Additional Information
Additional information on the use of wood in housing and other light-frame construction is available from several organizations:
American Plywood Association
7011 South 19th Street
Tacoma, WA 98466

Canadian Wood Council
55 Metcalfe Street
15th Floor, Suite 1550
Ottawa, Ontario
Canada K1P 6L5

Fig. 14.3.4. Typical framing details for a fafter-type roof (a) showing framing details at a valley (b) and a hip corner (c).
14.4. HEAVY TIMBER BUILDINGS

Log and Timber Frame Houses

Interest is growing in log houses—from small, simple houses for vacation use to large, permanent residences. Fig. 14.4.1 illustrates a modern residential log structure. Several firms in the United States furnish designs and materials for log houses. In general, walls, roofs, and floor systems are built from logs rather than framed with dimension lumber.

The companies tend to categorize log types into two systems. In the round log system, the logs are machined to a smooth, fully rounded surface, and they are generally all the same diameter. In the other system, the logs are machined to specific shapes, generally not fully round. The exterior surfaces of the logs are generally rounded, whereas the interior surfaces may be either flat or rounded. The interface between logs is machined to form an interlocking joint.

Consensus standards have been developed to conform log houses to building code requirements (Ref. 14.41). Builders and designers need to realize that logs may reach the building site at moisture content levels higher than ideal; the effects of moisture change and the consequences of associated shrinkage should be considered.

Fig. 14.4.1. Modern log homes are available in a variety of designs.
The popularity of “timber frame” structures is also increasing. This type of construction was used in early American houses, barns, and factory buildings (Fig. 14.4.2). The frame is made of large solid-sawn timbers connected to one another by hand-fabricated joints such as mortise and tenon. Construction of such a frame involves rather sophisticated joinery, as illustrated in Fig. 14.4.2.

Because the timber frame is characteristically quite rigid, wall bracing or structural sheathing are not needed to resist racking. Frequently, a prefabricated, composite, 4- by 8-ft (1.2- by 7.4-m) sheathing panel is applied directly to the frame. This panel may consist of an inside layer of 1/2-in. (12-mm) gypsum, a core layer of rigid foam insulation, and an outside layer of exterior plywood. Finish siding is applied over the composite panel. In some cases, a layer of 1-in. (15-mm), tongue-and-groove, solid-wood boards is applied to the frame, and a rigid, foam-exterior, plywood composite panel is then applied over the boards to form the building exterior. Local fire regulations should be consulted about the suitability of foam insulation for such a use, since some types of foams emit hazardous fumes in a fire.

Because the framing members are cut in large cross sections, seasoning them before installation is difficult, if not impossible. Thus, the builder (and the owner) should recognize the dimensional changes that may occur as the members dry in place. The structure must be designed to accommodate these dimensional changes as well as seasoning checks, which are almost inevitable.

**Pole and Post Frame Buildings**

Round poles, or square or rectangular posts, may serve as the foundation of a building and simultaneously as the principal framing element. This type of construction is known as the wood pole (or wood post) foundation-framing system. For relatively low structures, such as shown in Fig. 14.4.3, light wall and roof framing is nailed to poles or posts set at fairly frequent centers, commonly 8 to 12 ft (2.4 to 3.6 m). For larger buildings, the center-to-center separation of poles or posts may be greater. This type of construction was originally used for agricultural buildings, but the structural principle has been extended to both commercial buildings and residences.

Attachment of framing may be difficult if round poles are used. This problem may be eased by slabbing the outer face of the pole, and for corner poles, two faces may be slabbed at right angles. This permits better attachment of both light and heavy framing by nails or timber connectors. In some cases, the pole is left round, but it is inserted in the foundation hole so that the outer face of the pole is vertical. Poles may be notched to provide seats for beams.

Posts may be solid sawn, glulam, or built up by nail laminating. Built-up posts are advantageous because only the bases of the posts must be treated. The treated portion in the ground may have laminations of varying lengths that are matched with the lengths of untreated laminations in the upper part of the post. The design of these types of posts must consider the integrity of the splice between the treated and untreated lumber.

**Mill-Type Construction**

Mill-type construction has been widely used for warehouse and manufacturing structures, particularly in the Eastern United States. This type of construction uses timbers of large cross sections; columns are spaced in a grid according to the available lengths of beam and girder timbers. As previously noted, the size of the timbers makes this type of construction resistant to fire. The good insulating qualities of wood (and char, result in slow penetration of fire into the large members, and the members thus retain a large proportion of their original load-carrying capacity and stiffness for a relatively long period after the onset of fire exposure. Consequently, fire fighting is safe for longer periods in mill-type construction than in light-frame construction. Mill-type construction is recognized by some building codes as 1-h fire-resistant construction, with some limitations.

To be recognized as mill-type construction, the structural elements must not be less than specific sizes—columns cannot be less than a nominal 8 in. (200 mm) in dimension, and beams and girders cannot be less than 6 by 10 in. (150 by 30 mm) in cross section. Other limitations must be observed as well. For example, walls must be made of masonry, and concealed spaces must be avoided. Construction details are illustrated in Ref. 14.26. The structural frame has typically been constructed of solid-sawn timbers, which should be stress graded. These timbers can now be supplanted with glulam timbers, and longer spans are permitted.
Glulam Beam Systems

Various forms of glulam beams were described earlier in this chapter. A panelized roof system using glulam roof framing is widely used in the Southwestern United States. This system is based on supporting columns located at the corners of preestablished grids. The main glulam beams support glulam or sawn purlins, which in turn support preframed structural panels. The basic unit of the preframed system is a 4- by 8-ft (1.2- by 2.4-m) structural panel nailed to 2- by 4-in. (50- by 100-mm) or 2- by 6-in. (50- by 150-mm) stiffeners (subpurlins). The stiffeners run parallel to the 8-ft (2.4-m) dimension of the structural panel. One stiffener is located at the centerline of the panel: the other is located at an edge, with the plywood edge at the stiffener centerline. The stiffeners are precut to a length equal to the long dimension of the plywood less the thickness of the purlin, with a small allowance for the hanger.

In some cases, the purlins are erected with the hangers in place, the prefabricated panels are lifted and set into place in the hangers, and the adjoining basic panels are then attached to each other. In other cases, the basic panels are attached to one purlin on the ground. A whole panel is lifted into place to support the loose ends of the stiffeners. This system is fully described in Ref. 14.42.

Arch Structures

Arch structures are particularly suited to applications in which large, unobstructed areas are needed, such as churches, recreational buildings, and aircraft hangars. Although a number of basic arch forms are shown in Fig. 14.2.8, the variety of possible forms seems to be limited only by the imagination of the architect. Churches have used arches from the beginning of the manufacture of glulam in the United States (Ref. 14.6).

Domes

Radial-rib domes consist of curved members extending from the base ring (tension ring) to a compression ring at the top of the dome and ring members at various elevations between the tension ring and compression ring (Fig. 14.4.4). The ring members may be curved or straight. If they are curved to the same radius as the rib and have their centers at the center of the sphere, the dome will have a spherical surface. If the ring members are straight, the dome will have an umbrella look. Design of the radial-rib dome is fairly straightforward because it is statically determinate. Connections between the ribs and the ring members are critical because of the high compressive loads in the ring members. Erection is not overly complicated, but care must be taken to stabilize the dome, since it has a tendency to rotate about the central vertical axis.

Other dome patterns called Varax and Triax are also used. Their geometries are quite complex, and specialized computer programs are used for their design. The key to these domes are the steel hubs at the joints and supports. Most hubs are proprietary and are designed by either the manufacturer or its representative. The 530-ft (190-m) diameter Tacoma Dome, a Triax type, is shown under construction in Figure 14.4.5; its structural design is described in Ref. 14.43.

Sources of Additional Information

The following organizations have information on heavy timber structures:

American Institute of Timber Construction
11818 SE Mill Plain Blvd.
Suite 415
Vancouver, WA 98684
14.5 SPECIAL CONSIDERATIONS

As discussed in Chapter 4, wood has a number of special characteristics that distinguish it from other materials. In many cases, these characteristics affect the behavior of products made from wood. Thus, the success or failure of a project may rest to a greater or lesser degree on the care
with which that product is chosen or the way in which it is used in the overall project. This suggests the desirability of careful specification writing and design, together with attention to detail in the construction process. The following sections outline some precautions.

Connections

Connections between the load-carrying members of a building or other structure are essential to the proper functioning of that structure. Obviously, individual pans of a truss must be interconnected or the truss would not function as a single unit. What may not be quite so obvious is that structural units must be interconnected. This is especially true in areas subject to high winds, earthquakes, high water, or waves, where experience has shown that failure to provide adequate connections between roof systems and walls and between walls and foundation can result in disastrous damage to the structure. Such damage frequently can be prevented by careful attention to the details of connections between elements and units. Many fastener types, such as nails, screws, lag screws, dowels, drift pins, and bolts, have been available for many years. More recent fasteners include special nails, staples, split rings, shear plates, spike grids, toothed metal plates, clamping plates, framing anchors, joist and purlin hangers, and special fasteners. Some of these fasteners are illustrated in Figs. 14.5.1 and 14.5.2.

Nails are commonly used when loads are low, and they are the fastener of choice in most light-frame construction as well as for diaphragms and shear walls. Screws are not generally used to join structural members.

Lag screws, bolts, and timber connectors are used for loads of relatively large magnitude. They are used in heavy timber construction and may be used in light-frame construction when exceptional loads are anticipated.

Bolts are less efficient than split rings and shear plates, but they are adequate for many situations. Lag screws are used in place of bolts under special conditions, such as in a connection for a very thick member or when one face of a member is not accessible for installation of washers and nuts. Both bolts and lag screws may be used with split rings and shear plates.

Split rings and shear plates (Fig. 14.5.1) are used for joints in heavy timber construction. They may be used in light wood trusses designed for long spans or wide spacings.

Thin-gauge steel plate connectors (Fig. 14.5.2) are used to join structural elements in fastening subassemblies and to anchor a structure to its foundation. Joist and purlin hangers, beam seats, column caps, strap ties, framing anchors, and like fasteners are commonly available for these purposes.

Toothed metal plates are used extensively in light wood trusses for both roof and floor systems. Such systems are used in a very high percentage of residential structures as well as in some commercial and institutional buildings. The plates are commonly galvanized, but when used with either preservative-treated or fire-retardant-treated wood, stainless steel is recommended because of the corrosive nature of the treating salts. Design handbooks, such as those listed in Table 14.1, describe connection design in detail. In addition, AITC 104 (Ref. 14.44) gives details on connections particularly applicable to glulam.

Some special characteristics of wood can affect not only member design, but also connection design. This problem is covered in considerable detail in Wood: Engineering Design Concepts (Ref. 14.4, chapter on design of connections). Among the subjects treated are the effects of connection details that impose tensile stress perpendicular to grain: for instance, when a load is suspended near the bottom of a beam or shrinkage resulting from moisture change is restrained by widely separated fasteners. This book also describes details that result in accumulation of moisture in a wood member, such as encasing the end of a column in a concrete floor or supporting the end of an arch or a column in a concrete floor or a steel box. The problems that result from undesirable stresses accompanying the use of eccentric joints in trusses are also covered. Because more extensive coverage of this subject is not feasible here, references in this area are “must” reading for both architects and structural designers.
Grades of Lumber and Panel Products

In effect, the grading rules for lumber are descriptions of products for specific purposes. One set of grades is designed for structural uses of lumber, such as joists, truss members, or scaffold planks. Accordingly, the factors that affect strength and stiffness are properly limited or perhaps prohibited. Another set of grades describes lumber intended to be cut into smaller pieces for parts of doors, windows, and the like, setting limits on the size and quality of the pieces that can be produced by cutting between defects, such as large knots. Such grades in softwoods are called “shop” grades. However, even though a piece of shop grade lumber might be of the same species, general appear-
ance, and size as a piece graded for a joist and plank grade. This does not make it suitable for use as a joist. The size and location of large knots are not specified in the "shop" rules and consequently not limited in the piece. Use of such a piece for structural purposes, such as a joist, could result in disaster. Therefore, the selection of lumber grade should be guided by the end use of the wood.

Certain specifications refer to a grade name that is not an accepted grade—"commercial" grade, for example—and this "grade" is not described anywhere. This practice can only result in confusion. Thus, the architect should specify only a fully described and accepted grade of lumber that bears a grade mark, such as that shown in Fig. 14.5.3.

Some light-frame structures are built after an engineering analysis. In such instances, the lumber chosen for structural elements should be stress graded to provide assurance that the structural elements meet the strength and stiffness requirements established by the engineering analysis. In other instances, such as in some dwellings, the framing systems may copy those that had been used earlier and had worked well even though they were not based on engineering analysis. If no stress grades are available and new grades have to be chosen, guides to the selection of such grades are available. Span tables can be used for choosing grades and sizes of joists for specific spans or conversely, for choosing suitable spans for available materials. Span tables are based on allowable values of strength and assigned values of modulus of elasticity, coupled with anticipated loadings. Stress grades should be used to ensure that the requirements implicit in the span tables will be met by the structure (Ref. 14.7).

Plywood and other panel products made in accordance with the APA performance standard (Ref. 14.45) and PS 1-83 (Ref. 14.46) include some engineered grades and some appearance grades: both kinds of grades are made for exterior or interior use—that is, with or without waterproof adhesives. In addition, allowable design stresses are available for the engineered grades of plywood (Ref. 14.11). Engineered grades suitable for use as subfloor or roof sheathing, when marked under APA supervision, carry an identification index that indicates the free safe distance between supports (Fig. 14.5.4). For example, an identification index of 42/10 indicates that the plywood panel is suitable for use as roof sheathing when roof rafters or trusses are spaced as much as 42 in. (1.1 m) between centers: when used as subfloor, the support spacing may not be more than 20 in. (500 mm). An index of 24/0 indicates that supports for roof sheathing may be spaced as much as 24 in. (600 mm) on center, but that the panel may not be used as subfloor. Such indices provide a good guide to proper usage of plywood and other panel products.

Interior-type panels may have adhesive bonds with three levels of moisture resistance: interior, intermediate, and exterior. When bonded with an interior adhesive, the panel is intended for interior use only. When bonded with an intermediate adhesive, the panel is intended for use in protected construction and industrial applications where protection from weather may be delayed for short periods or conditions of high humidity or water leakage may prevail. When bonded with an exterior adhesive, the panel is intended for construction and industrial uses where construction delays or other conditions may expose the wood to moisture for long periods. Obviously, exterior adhesive is also necessary when the panels will be treated with preservatives.

Exterior-type plywood will retain its glue bond when repeatedly wetted and dried or otherwise subjected to weather or other conditions of comparable severity such as pressure preservative treatment.

Thus, the load and moisture resistance of plywood and panel products covers a wide range, and it should be considered when selecting a type of panel for specific uses.

Plywood produced under the American National Standards Institute (ANSI) HP 1983 (Ref. 14.47) is

![Fig. 14.5.3. Example of a lumber grade mark. All structural lumbers should bear a grade mark.](image)

![Fig. 14.5.4. Example of identification index for sheathing panels.](image)
basically intended for use as decorative wall panels; cut-to-site and stock panels for furniture, cabinets, containers, and specialty products; and marine applications.

Moisture Content and Shrinkage

The growing tree has large amounts of moisture. When wood is cut from the tree, it immediately begins to lose moisture to the surrounding atmosphere. Conversely, when wood that has been dried encounters a humid atmosphere or is wetted by water, it gains moisture. Thus, outside the tree, wood has the property of changing its moisture content in an attempt to achieve equilibrium with the surroundings (i.e., wood is hygroscopic). When wood is below the fiber saturation point (see Chapter 4), certain properties change with changing moisture content. Below this point, for example, strength and modulus of elasticity increase as moisture content decreases and decrease as moisture content increases. Thus, allowable design stresses are different for wood at low moisture content than at high. The structural designer must anticipate conditions in service and choose appropriate design specifications from which to calculate member sizes.

Reduction in moisture content after a wood member is placed in service may have undesirable effects. For example, green wood placed in service in a structure, even a relatively unprotected structure, will lose moisture with time, with the potential of warping, reduction of cross-sectional dimensions, splitting, and other defects.

As wood loses moisture below the fiber saturation point, it shrinks; conversely, wood swells with increases in moisture content. These effects are demonstrated in dresser drawers (or doors) that operate freely in winter but may be all but impossible to operate after a siege of high summer humidity. Shrinkage is least in the fiber direction (parallel to grain), more in the perpendicular-to-grain direction radial to the annual growth rings, and still more in the perpendicular-to-grain direction parallel to a tangent to the growth rings. Specific shrinkage coefficients for different species are given in the Wood Handbook (Ref. 14.29). A general rule of thumb is that wood will change about 1 percent in dimension perpendicular to the grain for each 4 percent change in moisture content below about 30 percent moisture content.

In lumber, the width of edge-grained lumber is parallel to the radial direction, whereas that of a flat-sawn board or plank is more or less parallel to the tangential direction. An edge-grained board will consequently have less shrinkage in width than will a flat-sawn board. In such applications as siding, the tendency for cupping is greatly reduced by using edge-grained wood: cupping is not only unsightly but may also result in splitting and pulling of the nails that attach the siding to the framing. Although edge-grained siding costs more than other types of siding, it can be expected to give better performance over time.

Directional Properties

Unlike many other materials, wood does not have the same properties, mechanical and otherwise, in all directions. The ratio of mechanical properties at right angles to the grain to those parallel to grain may range from perhaps 0.03 to 0.12 or, roughly, from 1/30 to 1/8. This strongly suggests that design details that permit large forces to be developed perpendicular to grain, especially in tension, are highly undesirable. For example, a hanger carrying a concentrated load and supported by a bolt a short distance above the bottom of a girder would not be good practice because of the likelihood of failure in tension perpendicular to grain. In many instances, compressive loads perpendicular to grain cannot be avoided, as where girders bear on the supports or where posts bear against caps, as in the bents of a trestle. Although catastrophic failure is not likely in such locations, excessive crushing perpendicular to grain may occur and result in such things as sloping floors in buildings. Consideration should be given to potential problems that might result from anisotropy. Properties other than strength and stiffness may also be anisotropic in nature. Shrinkage with changes in moisture content varies with respect to both fiber direction and annual ring orientation: the potential effects of shrinkage were discussed previously.

Erection and Bracing

Proper erection and bracing are essential for the satisfactory performance of timber structures. Many engineered wood products have low lateral stiffness and must be handled carefully to prevent damage. Without proper lateral bracing, many long-span engineered wood products such as trusses, I-beams, and glulam timbers are unstable during erection or under a fraction of their design load. For example, the top chord of many trusses will buckle unless properly restrained.

Wood members of any kind should not be lifted with steel cables in direct contact with their edges. Special blocking or fabric slings should be used to protect the edges from indentations, which can disproportionately weaken the members. Trusses must be carefully handled during erection, and often a spreader bar or strongback must be used to prevent damage.

Once in place, temporary bracing is often required for many engineered wood products until the permanent sheathing is attached. This temporary bracing should be a pan of the building design, but may be the responsibility of the construction contractor. The first member erected must be securely braced because the common practice is to brace the other members to the first member. Bracing of the top chord of trusses is more important because the top chord is particularly susceptible to lateral buckling. This bracing is often placed at the ridge line and at intervals of
8 to 10 ft (2 to 3 m) along the span. To permit the addition of sheathing or permanent bracing with the temporary bracing intact, the temporary bracing is often installed on the underside of the top chord.

Handling and erection of trusses are discussed in detail in Ref. 14.49.

The design of many engineered wood products requires that the compression side of bending members be laterally supported either continuously or at specific intervals. The designer must ensure that the bracing system provides stability for the building under service loads. In many instances, panel-type sheathing is attached to the compression side of bending members and provides the needed lateral support. If sheathing is attached to purlins, these purlins can be designed to assure stability. Suggested bracing for wood truss systems is given in Ref. 14.50. Sometimes, compression web members of trusses also require additional diagonal bracing. All permanent bracing should be installed as soon as practical after the structure is erected because some parts of a structure are subjected to heavy loads during construction.

REFERENCES


SUGGESTIONS FOR FURTHER READING