Use of Wood in Buildings and Bridges

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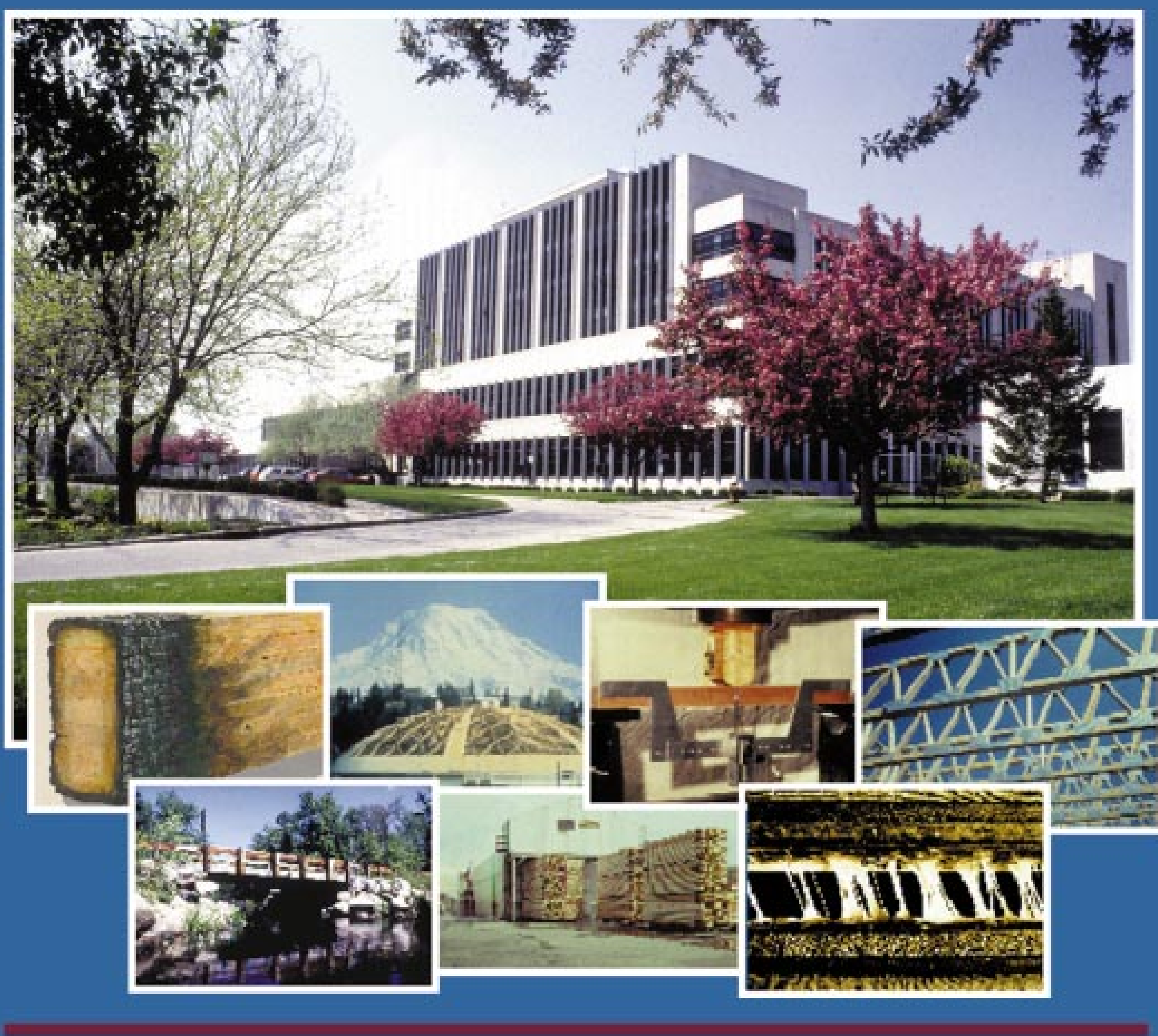
Wood Handbook

Wood as an Engineering Material



Abstract

Summarizes information on wood as an engineering material. Presents properties of wood and wood-based products of particular concern to the architect and engineer. Includes discussion of designing with wood and wood-based products along with some pertinent uses.

Keywords: wood structure, physical properties (wood), mechanical properties (wood), lumber, wood-based composites, plywood, panel products, design, fastenings, wood moisture, drying, gluing, fire resistance, finishing, decay, sandwich construction, preservation, and wood-based products

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The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

On the cover: (Left to right, top to bottom)

1. Research at the Forest Products Laboratory, Madison, Wisconsin, contributes to maximizing benefits of the Nation's timber resource.
2. Testing the behavior of wood in fire helps enhance fire safety.
3. The all-wood, 162-m (530-ft) clear-span Tacoma Dome exemplifies the structural and esthetic potential of wood construction (photo courtesy of Western Wood Structures, Inc., Tualatin, Oregon).
4. Bending tests are commonly used to determine the engineering properties of wood.
5. Engineered wood trusses exemplify research that has led to more efficient use of wood.
6. The Teal River stress-laminated deck bridge is located in Sawyer County, Wisconsin.
7. Kiln drying of wood is an important procedure during lumber manufacturing.
8. Legging adhesive (photo courtesy of Air Products and Chemicals, Inc., Allentown Pennsylvania). Adhesive bonding is a critical component in the performance of many wood products.

Pesticide Precautionary Statement

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Chapter 16

Use of Wood in Buildings and Bridges

Russell C. Moody and Anton TenWolde

Contents

In North America, most housing and commercial structures built prior to the 20th century used wood as the major structural material. The abundant wood resource formed the basic structure for most houses, commercial buildings, bridges, and utility poles. Today, houses and many light commercial and industrial buildings are made using modern wood structural materials. Recently, there has been increased interest in using wood for various types of transportation structures, including bridges.

In this chapter, the features of various types of building systems are described. Emphasis is placed on how these systems have adapted to the use of modern materials and techniques. For example, where floor, wall, and roof sheathing for light-frame construction were once commonly made from wood boards, sheathing is now commonly made from structural panel products, such as plywood and structural flakeboard. Compared with boards, these panel products are quicker to install and provide improved structural resistance to wind and earthquake loadings. Furthermore, prefabricated floor and wall panels along with prefabricated roof and floor trusses or I-joists are replacing piece-by-piece on-site construction with dimension lumber. A structure can be enclosed within a short time on site using factory-made panelized systems.

Glulam and other panelized wood systems are being used increasingly for both highway and railroad bridges. A brief description of the uses of wood in these types of structures is included.

Light-Frame Buildings

Historically, two general types of light-frame construction have been used—balloon and platform framing. Balloon framing, which was used in the early part of the 20th century, consists of full-height wall framing members for two-story construction. Additional information on balloon framing is available from older construction manuals. In the latter part of the 20th century, platform framing has dominated the housing market and is widely used in commercial and light industrial applications. Platform framing features the construction of each floor on top of the one beneath. Platform framing construction differs from that of 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. A detailed description of the platform-type of construction is given in *Wood Frame House Construction* (Sherwood and Stroh 1989); additional information is given in the *Wood Frame Construction Manual for One- and Two-Family Dwellings, 1995 SBC High Wind Edition* (AF&PA 1995).

Foundations

Light-frame buildings with basements are typically supported on cast-in-place concrete walls or concrete block walls supported by footings. This type of construction with a basement is common in northern climates. Another practice is to have concrete block foundations extend a short distance above ground to support a floor system over a "crawl space." In southern and western climates, some buildings have no foundation; the walls are supported by a concrete slab, thus having no basement or crawl space.

Treated wood is also used for basement foundation walls. Basically, such foundations consist of wood-frame wall sections with studs and plywood sheathing supported on treated wood plates, all of which are preservatively treated to a specified level of protection. To distribute the load, the plates are laid on a layer of crushed stone or gravel. Walls, which must be designed to resist the lateral loads of the backfill, are built using the same techniques as conventional walls. The exterior surface of the foundation wall below grade is draped with a continuous moisture barrier to prevent direct water contact with the wall panels. The backfill must be designed to permit easy drainage and provide drainage from the lowest level of the foundation.

Because a foundation wall needs to be permanent, the preservative treatment of the plywood and framing as well as the fasteners used for connections are very important. A special foundation (FDN) treatment has been established for the plywood and framing, with strict requirements for depth of chemical penetration and amount of chemical retention. Corrosion-resistant fasteners (for example, stainless steel) are recommended for all preservatively treated wood. Additional information and materials and construction procedures are given in *Permanent Wood Foundation Basic Requirements* (AF&PA 1987).

Floors

For houses with basements, the central supporting structure may consist of wood posts on suitable footings that carry a built-up girder, which is frequently composed of planks the same width as the joists (standard 38 by 184 mm to 38 by 286 mm (nominal 2 by 8 in. to 2 by 12 in.)), face-nailed together, and set on edge. Because planks are seldom sufficiently long enough 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. The girder may also be a glulam beam or steel I-beam, often supported on adjustable steel pipe columns. Similar details may be applied to a house over a crawl space. The floor framing in residential structures typically consists of wood joists on 400- or 600-mm (16- or 24-in.) centers supported by the foundation walls and the center girder (Fig. 16–1).

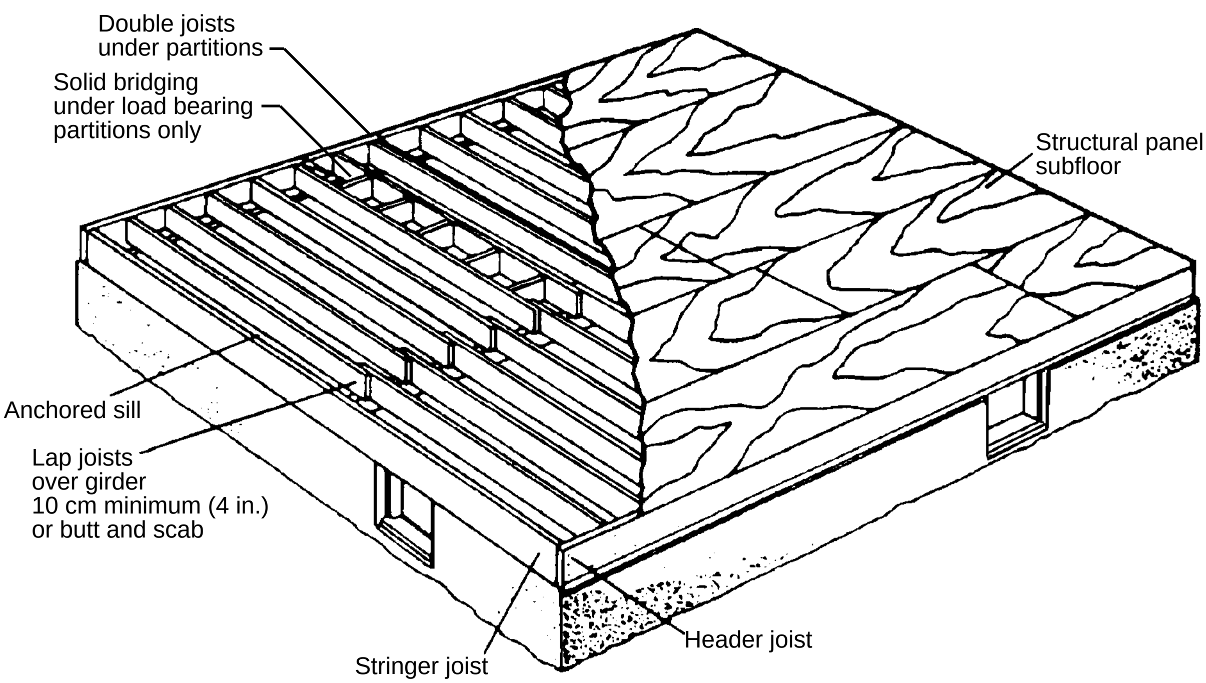

Figure 16–1. Typical floor details for platform construction with joists spliced on center beam.

Joist size depends on the anticipated loading, spacing between joists, distance between supports (span), species, and grade of lumber. Commonly used joists are standard 38- by 184-mm or 38- by 235-mm (nominal 2- by 8-in. or 2- by 10-in.) lumber, prefabricated wood I-joists, or parallel chord trusses. Lumber joists typically span from 3.6 to 4.8 m (12 to 16 ft). Span tables are available from the American Forest & Paper Association (AF&PA 1993). Span capabilities of the prefabricated wood I-joists or parallel chord trusses are recommended by the manufacturer.

Floor openings for stairways, fireplaces, and chimneys may interrupt one or more joists. Preferably, such openings are 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 1.2 m (4 ft) in width, but double headers are required for wider openings. Special care must be taken to provide adequate support at headers (using joist hangers, for example).

Cutting of framing members to install items such as plumbing lines and heating ducts should be minimized. 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 that their longer span capabilities may eliminate the need for interior supports. An additional advantage is that the web areas of these components are designed for easy passing of plumbing, electrical, and heating ducts.

Floor sheathing, or subflooring, is used over the floor framing to provide a working platform and a base for the finish flooring. Older homes have board sheathing but newer homes generally use panel products. Common sheathing materials include plywood and structural flakeboard, which are available in a number of types to meet various sheathing requirements. Exterior-type panels with water-resistant adhesive are desirable in locations where moisture may be a problem, such as floors near plumbing fixtures or 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 has a preferred direction of installation. Nailing patterns are either prescribed by code or recommended by the manufacturer. About 3 mm (1/8 in.) of space should be left between the edges and ends of abutting panels to provide for dimensional changes associated with moisture content.

Literature from APA–The Engineered Wood Association includes information on the selection and installation of the types of structural panels suitable for subfloors (APA 1996).

Exterior Walls

Exterior walls of light-frame structures are generally load bearing; they support upper floors and the roof. An exception is the gable ends of a one- or two-story building. 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 standard 38- by 89 mm, 38- by 114-mm, or 38- by 140-mm (nominal 2- by 4-in., 2- by 5-in., or 2- by 6-in.) members spaced between 300 and 600 mm (12 and 24 in.) on center. Selection of the stud size depends on the load the wall will carry, the need for support of wall-covering materials, and the need for insulation thickness in the walls. Headers over openings up to 1.2 m (4 ft) are often 38 by 140 mm (2 by 6 in.), nailed together face to face with spacers to bring the headers flush with the faces of the studs. Special headers that match the wall thickness are also available in the form of either prefabricated I-joists or structural composite lumber. Wall framing is erected over the platform formed by the first-floor joists and subfloor. In most cases, an entire wall is framed in a horizontal position on the subfloor, then tilted into place. If a wall is too long to make this procedure practical, sections of the wall can 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 the interior finish (Fig. 16–2). 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 or floor joists 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 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 that should be anchored to the foundation. If a second story is 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 the first floor.

Sheathing for exterior walls is commonly some type of panel product. Here again, 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 resistance to lateral loads. Intermediate-density board is used where structural support is needed. Numerous foam-type panels can also be used to impart greater thermal resistance to the walls.

In cases where the sheathing cannot provide the required racking resistance, diagonal bracing must be used. Many foam sheathings cannot provide adequate racking resistance,

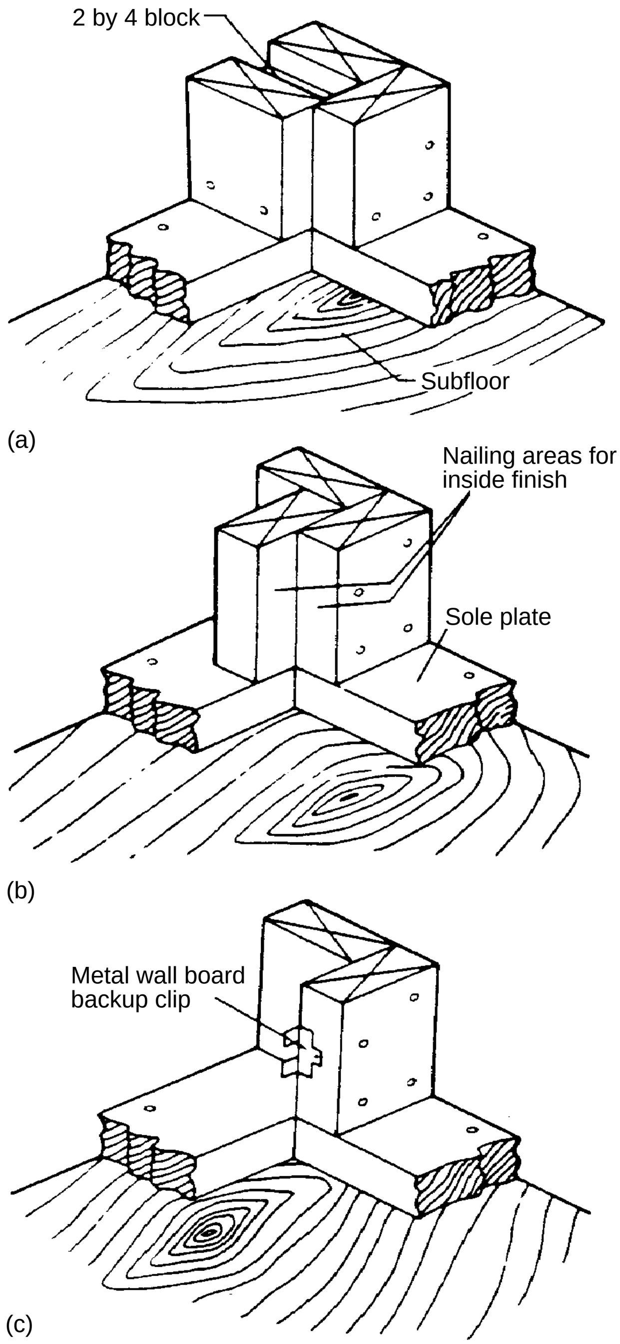

Figure 16–2. Corner details for wood stud walls that provide support for interior sheathing: (a) traditional three-stud corner with blocking; (b) three-stud corner without blocking; (c) two-stud corner with wallboard backup clips.

so either diagonal braces must be placed at the corners or structural panels must be applied over the first 1.2 m (4 ft) of the wall from the corner. When light-weight insulating foam sheathings are used, bracing is commonly provided by standard 19- by 89-mm (nominal 1- by 4-in.) lumber or steel strapping.

Ceiling and Roof

Roof systems are generally made of either the joists-and-rafter systems or with trusses. Engineered 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. Prefabricated roof trusses are used to form the ceiling and sloped roof of more than two-thirds of current light-frame buildings. For residential buildings, the trusses are generally made using standard 38- by 89-mm (nominal 2- by 4-in.) lumber and metal plate connectors with teeth that are pressed into the pieces that form the joints (TPI 1995).

Joists and rafter systems are found in most buildings constructed prior to 1950. Rafters are generally 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. 16–3a).

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 the ridge board (Fig. 16–3b). 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. 16–3c). In general, the same materials used for wall sheathing and subflooring are used for roof sheathing.

Wood Decks

A popular method of expanding the living area of a home is to build a wood deck adjacent to one of the exterior walls. Decks are made of preservatively treated lumber, which is generally available from the local building supply dealer and, depending upon the complexity, may be built by the "do-it-yourselfer." To ensure long life, acceptable appearance, and structural safety, several important guidelines should be followed. Proper material selection is the first step. Then, proper construction techniques are necessary. Finally, proper maintenance practices are necessary. Detailed recommendations for all these areas are included in *Wood Decks: Materials, Construction, and Finishing* (McDonald and others 1996).

Post-Frame and Pole Buildings

In post-frame and pole buildings, round poles or rectangular posts serve both as the foundation and the principal vertical framing element. This type of construction was known as "pole buildings" but today, with the extensive use of posts, is commonly referred to as "post-frame" construction. For relatively low structures, light wall and roof framing are nailed to poles or posts set at fairly frequent centers, commonly 2.4 to 3.6 m (8 to 12 ft). This type of construction

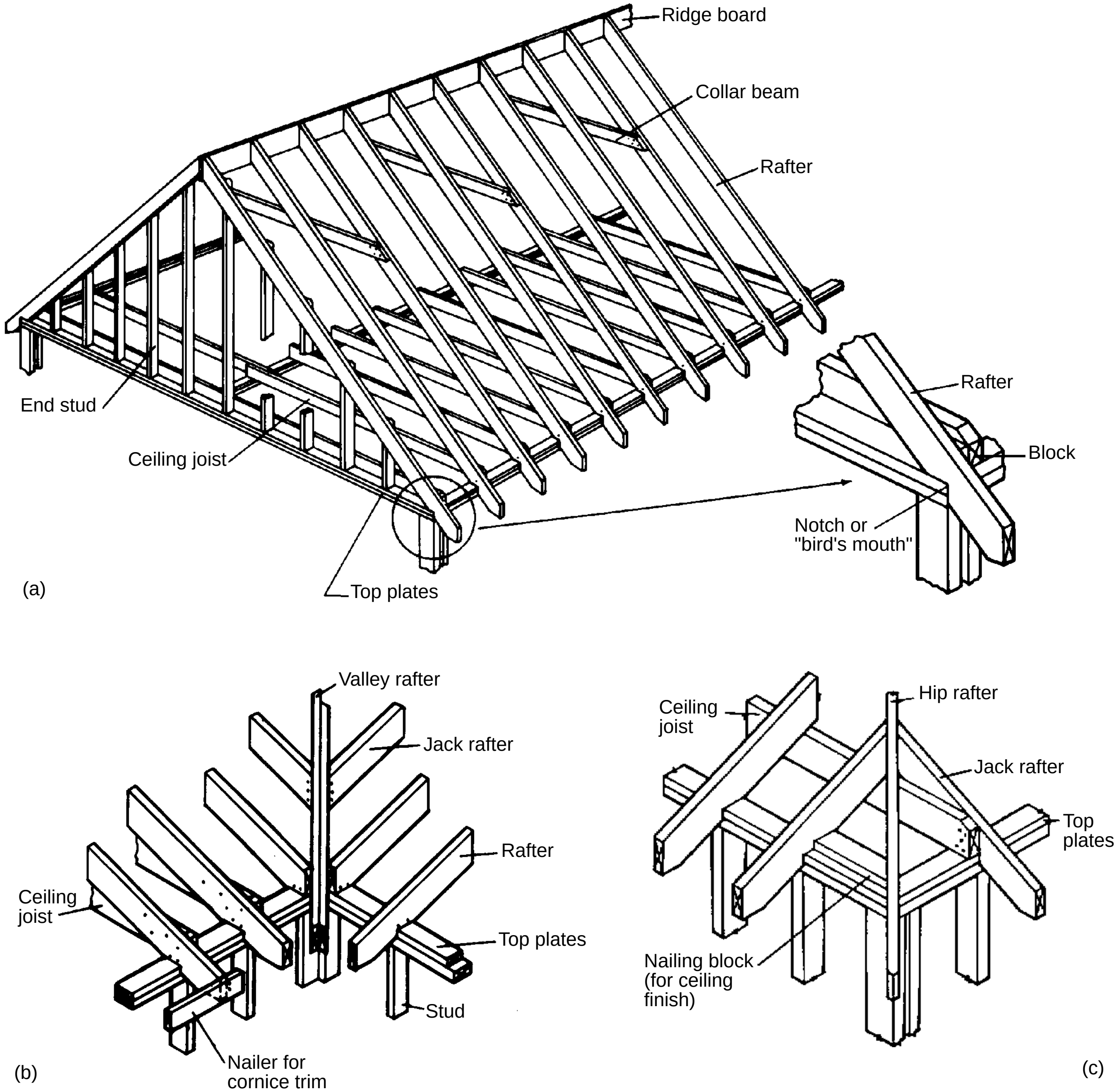

Figure 16–3. (a) A rafter-type roof with typical framing details for (b) a valley and (c) a hip corner.

was originally used with round poles for agricultural buildings, but the structural principle has been extended to commercial and residential buildings (Fig. 16–4).

Round poles present some problems for connecting framing members; these problems can be eased by slabbing the outer face of the pole. 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. When the pole is left round, the outer face may be notched to provide seats for beams.

Rectangular posts are the most commonly used and may be solid sawn, glulam, or built-up by nail laminating. Built-up posts are advantageous because only the base of the post must be preservatively 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. The wall system consists of horizontal girts often covered by light-gauge metal that provides some degree of racking resistance.

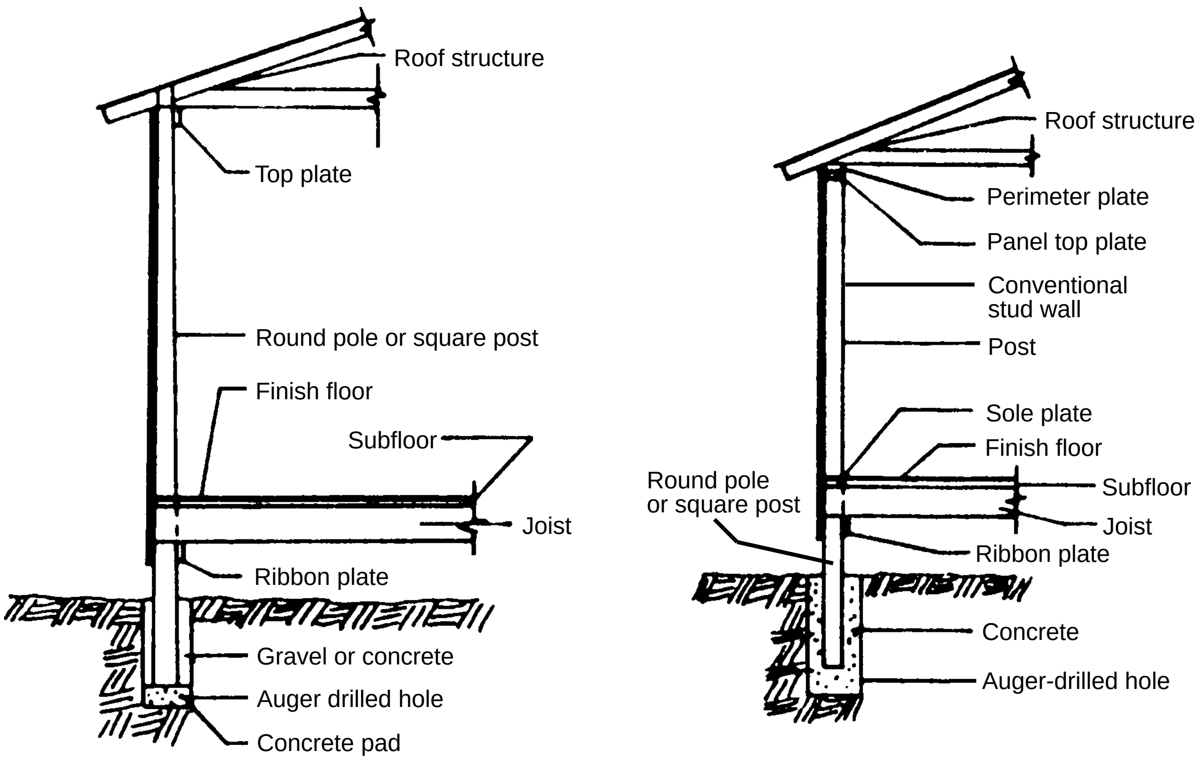

Figure 16–4. Pole and post-frame buildings: (left) pole or post forms both foundation and wall; (right) pole or post forms only the foundation for conventional platform-framed structure.

Roof trusses made with metal plate connectors are attached to each pole, or posts, and roof purlins are installed perpendicular to the trusses at spacings from 1.2 to 3.7 m (4 to 12 ft), with 2.4 m (8 ft) as a common spacing. For 2.4-m (8-ft) truss spacing, these purlins are often standard 38 by 89 mm (nominal 2 by 4 in.) spaced on 0.6-m (2-ft) centers and attached to either the top of the trusses or between the trusses using joists hangers. The roofing is often light-gauge metal that provides some diaphragm stiffness to the roof and transmits a portion of the lateral loading to the walls parallel to the direction of the load. Detailed information on the design of post-frame buildings is given in the *National Frame Builders Association* ([n.d.]) or Walker and Woeste (1992).

Log Buildings

Interest is growing in log houses—from small, simple houses for vacation use to large, permanent residences (Fig. 16–5). Many U.S. firms specialize in the design and material for log houses. Log homes nearly always feature wall systems built from natural or manufactured logs rather than from dimension lumber. Roof and floor systems may be also be built with logs or conventional framing. Log home companies tend to categorize log types into two systems: round and shaped. 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 shaped system, the logs are machined to specific shapes, generally not fully round. The exterior surfaces of the logs are generally rounded, but the interior surfaces may be either flat or round. The interface between logs is machined to form an interlocking joint.

Consensus standards have been developed for log grading and the assignment of allowable properties, and these standards are being adopted by building codes (ASTM 1996). Builders and designers need to realize that logs can reach the building site at moisture content levels greater than ideal. The effects of seasoning and the consequences of associated shrinkage and checking must be considered. Additional information on log homes is available from The Log Home Council, National Association of Home Builders, Washington, DC.

Heavy Timber Buildings

Timber Frame

Timber frame houses were common in early America and are enjoying some renewed popularity today. Most barns and factory buildings dating prior to the middle of the 20th century were heavy timber frame. The traditional timber frame is made of large sawn timbers (larger than 114 by 114 mm (5 by 5 in.)) 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 Figure 16–6.

Figure 16–5. Modern log homes are available in a variety of designs.

In today's timber frame home, a prefabricated, composite sheathing panel (1.2 by 2.4 m (4 by 8 ft)) is frequently applied directly to the frame. This panel may consist of an inside layer of 13-mm (1/2-in.) gypsum, a core layer of rigid foam insulation, and an outside layer of exterior plywood or structural flakeboard. Finish siding is applied over the composite panel. In some cases, a layer of standard 19-mm (nominal l-in.) 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 acceptance of various foam insulations.

Framing members are cut in large cross sections; therefore, 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.

Mill Type

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 with columns spaced in a grid according to the available lengths of beam and girder timbers. The size of the timbers makes this type of construction resistant to fire. The good insulating qualities of wood as well as the char that develops during fire result in slow penetration of fire into the large members. Thus, the members retain a large proportion of their original load-carrying capacity and stiffness for a relatively lengthy period after the onset of fire. Mill-type construction is recognized by some building codes as a 1-h fire-resistant construction, with some limitations.

To be recognized as mill-type construction, the structural elements must meet specific sizes—columns cannot be less than standard 184 mm (nominal 8 in.) in dimension and beams and girders cannot be less than standard 140 by 235 mm (nominal 6 by 10 in.) in cross section. Other limitations must be observed as well. For example, walls must be made of masonry, and concealed spaces must be avoided. 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.

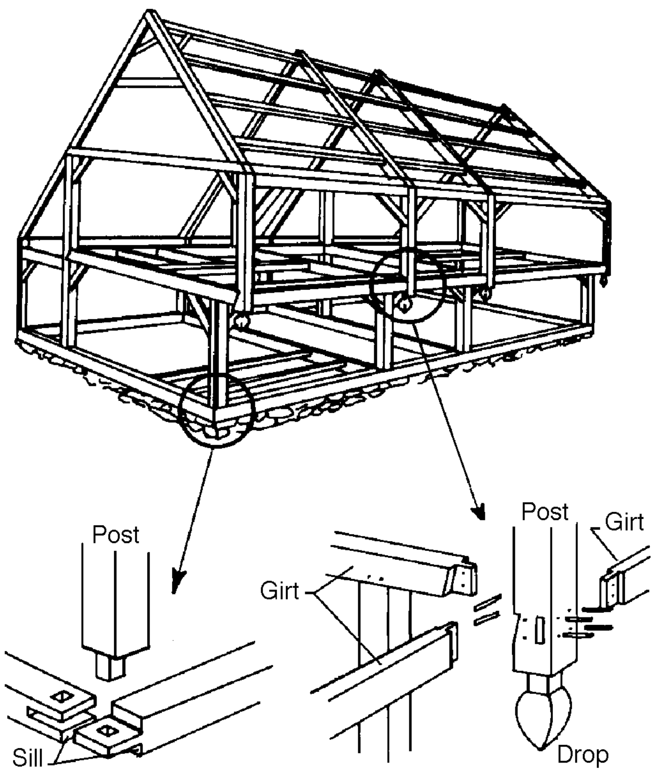

Figure 16–6. Timber frame structure with typical joint details.

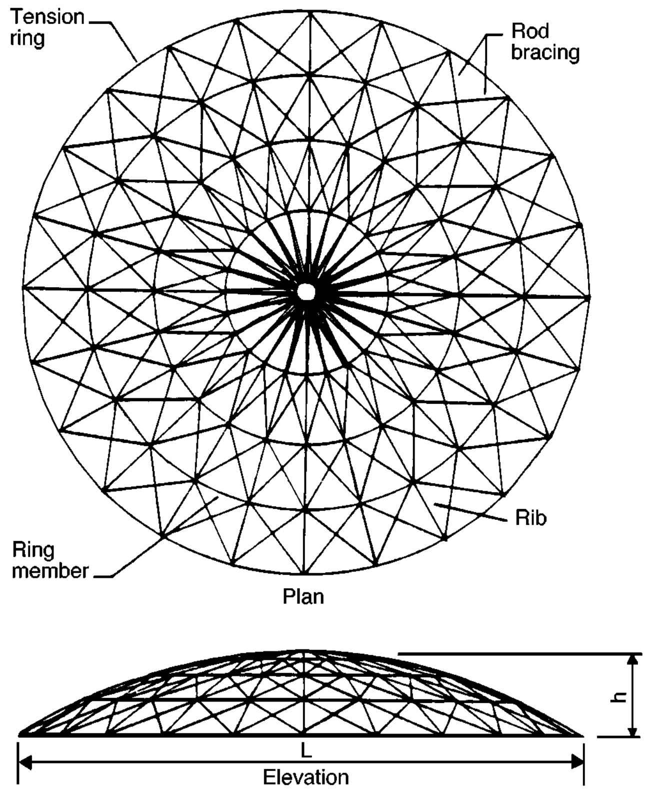

Figure 16–7. Member layout for a radial-rib dome.

Glulam Beam

A panelized roof system using glulam roof framing is widely used for single-story commercial buildings in the southwestern United States. This system is based on supporting columns located at the corners of pre-established grids. The main glulam beams support purlins, which may be sawn timbers, glulam, parallel chord trusses, or prefabricated wood I-joists. These purlins, which are normally on 2.4-m (8-ft) centers, support preframed structural panels. The basic unit of the preframed system is a 1.2- by 2.4-m (4- by 8-ft) structural panel nailed to standard 38- by 89-mm or 38- by 140-mm (nominal 2- by 4-in. or 2- by 6-in.) stiffeners (subpurlins). The stiffeners run parallel to the 2.4-m (8-ft) 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. An entire panel is lifted into place to support the loose ends of the stiffeners. This system is fully described in the *Laminated Timber Design Guide* (AITC 1994a).

Arch Structure

Arch structures are particularly suited to applications in which large, unobstructed areas are needed, such as churches, recreational buildings, and aircraft hangars. Many arch forms are possible with the variety limited only by the imagination of the architect. Churches have used arches from the beginning of glulam manufacture in the United States. Additional information on the use and design of arches is given in *The Timber Construction Manual* (AITC 1994b).

Dome

Radial-rib domes consist of curved members extending from the base ring (tension ring) to a compression ring at the top of the dome along with other ring members at various elevations between the tension and compression rings (Fig. 16–7). 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. Connections between the ribs and the ring members are critical because of the high compressive loads in the ring members. During construction, care must be taken to stabilize the structure because the dome 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

Figure 16–8. This 161.5-m- (530-ft-) diameter Tacoma dome (Tacoma, Washington), built in 1982–1983, is one of the longest clear roof spans in the world. (Photo courtesy of Western Wood Structures, Inc., Tualatin, Oregon.)

programs are used in their design. Steel hubs used at the joints and supports are critical. An example of a Triax dome is shown in Figure 16–8.

Timber Bridges

Prior to the 20th century, timber was the major material used for both highway and railroad bridges. The development of steel and reinforced concrete provided other options, and these have become major bridge building materials. However, the U.S. inventory does contain a significant number of timber bridges, many of which continue to carry loads beyond their design life. A recent initiative in the United States has focused research and technology transfer efforts on improving the design and performance of timber bridges. As a result, hundreds of timber highway bridges were built across the United States during the 1990s; many using innovative designs and materials.

Bridges consist of a substructure and a superstructure. The substructure consists of abutments, piers, or piling, and it supports the superstructure that consists of stringers and/or a deck. The deck is often covered with a wearing surface of asphalt. Timber may be combined with other materials to form the superstructure, for example, timber deck over steel stringers. Covered bridges, although once popular, are usually not economically feasible. The various types of timber bridge superstructures are described in the following sections. Detailed information on modern timber bridges is given in T*imber Bridges: Design, Construction, Inspection, and Maintenance* (Ritter 1990).

Log Stringer

A simple bridge type that has been used for centuries consists of one or more logs used to span the opening. Several logs may be laid side-by-side and fastened together. The log stringer bridge has been used to access logging areas and is advantageous when adequate-sized logs are available and the bridge is only needed for a short time. Unless built with a durable species, the life span of log stringer bridges is usually limited to less than 10 years.

Sawn Lumber

Several types of bridges can be built with sawn lumber. Even though the span is usually limited to about 9 m (30 ft) because of the limited size of lumber available, this span length entails the majority of bridges in the United States.

Several timbers can be used to span the opening, and a transverse lumber deck can be placed over them to form a stringer and deck bridge. Lumber can be placed side-by-side and used to span the entire opening, forming a longitudinal deck bridge. The lumber can be fastened together with large spikes or held together with tensioned rods to form a “stress-laminated” deck.

Figure 16–9. Glulam beam bridge over the Dangerous River, near Yukatat, Alaska, consists of three 43.5-m (143-ft) spans. Each span is supported by four 2.3-m- (91.5-in.-) deep glulam beams.

Glulam

Structural glued-laminated (glulam) timber greatly extends the span capabilities of the same types of bridges described in the previous paragraph. Glulam stringers placed 0.6 to 1.8 m (2 to 6 ft) on center can support a glulam deck system and result in spans of 12 to 30 m (40 to 100 ft) or more (Fig. 16–9). Using glulam panels to span the opening results in a longitudinal deck system, but this is usually limited to about 9-m (30-ft) spans. These panels are either interconnected or supported at one or more locations with transverse distributor beams. Glulam beams can be used to form a solid deck and are held together with tensioned rods to form a stress-laminated deck. Curved glulam members can be used to produce various aesthetic effects and special types of bridges (Fig. 16–10).

Structural Composite Lumber

Two types of structural composite lumber (SCL)—laminated veneer and oriented strand—are beginning to be used to build timber bridges. Most of the same type of bridges built with either solid sawn or glulam timber can be built with SCL (Ch. 11).

Considerations for Wood Buildings

Many factors must be considered when designing and constructing wood buildings, including structural, insulation, moisture, and sound control. The following sections provide a brief description of the design considerations for these factors. Fire safety, another important consideration, is addressed in Chapter 17.

Structural

The structural design of any building consists of combining the prescribed performance requirements with the anticipated loading. One major performance requirement is that there be an adequate margin of safety between the structures ultimate capacity and the maximum anticipated loading. The probability that the building will ever collapse is minimized using material property information recommended by the material manufacturers along with code-recommended design loads.

Another structural performance requirement relates to serviceability. These requirements are directed at ensuring that the structure is functional, and the most notable one is that

Figure 16–10. Three-hinge glulam deck arch bridge at the Keystone Wye interchange off U.S. Highway 16, near Mount Rushmore, South Dakota. The arch spans 47 m (155 ft) and supports an 8-m- (26-ft-) wide roadway.

deformations are limited. It is important to limit deformations so that floors are not too "bouncy" or that doors do not bind under certain loadings. Building codes often include recommended limits on deformation, but the designer may be provided some latitude in selecting the limits. The basic reference for structural design of wood in all building systems is the *National Design Specification for Wood Construction* (AF&PA 1991).

Thermal Insulation and Air Infiltration Control

For most U.S. climates, the exterior envelope of a building needs to be insulated either to keep heat in the building or prevent heat from entering. Wood frame construction is well-suited to application of both cavity insulation and surface-applied insulation. The most common materials used for cavity insulation are glass fiber, mineral fiber, cellulose insulation, and spray-applied foams. For surface applications, a wide variety of sheathing insulations exist, such as rigid foam panels. Insulating sheathing placed on exterior walls may also have sufficient structural properties to provide required lateral bracing. Prefinished insulating paneling can be used as an inside finish on exterior walls or one or both sides of the interior partitions. In addition, prefinished insulation can underlay other finishes.

Attic construction with conventional rafters and ceiling joists or roof trusses can be insulated between framing members with batt, blanket, or loose-fill insulation. In some warm climates, radiant barriers and reflective insulations can provide an additional reduction in cooling loads. The "Radiant Barrier Attic Fact Sheet" from the U.S. Department of Energy (1991) provides information on climatic areas that are best suited for radiant barrier applications. This document also provides comparative information on the relative performance of these products and conventional fibrous insulations.

Existing frame construction can be insulated pneumatically using suitable loose-fill insulating material. When loose-fill materials are used in wall retrofit applications, extra care must be taken during the installation to eliminate the existence of voids within the wall cavity. All cavities should be checked prior to installation for obstructions, such as fire stop headers and wiring, that would prevent the cavity from being completely filled. Care must also be taken to install the material at the manufacturer's recommended density to ensure that the desired thermal performance is obtained.

Accessible space can be insulated by manual placement of batt, blanket, or loose-fill material.

In addition to being properly insulated, the exterior envelope of all buildings should be constructed to minimize air flow into or through the building envelope. Air flow can degrade the thermal performance of insulation and cause excessive moisture accumulation in the building envelope.

More information on insulation and air flow retarders can be found in the ASHRAE *Handbook of Fundamentals*, chapters 22 to 24 (ASHRAE 1997).

Moisture Control

Moisture control is necessary to avoid moisture-related problems with building energy performance, building maintenance and durability, and human comfort and health. Moisture degradation is the largest factor limiting the useful life of a building and can be visible or invisible. Invisible degradation includes the degradation of thermal resistance of building materials and the decrease in strength and stiffness of some materials. Visible degradation may be in the form of (a) mold and mildew, (b) decay of wood-based materials, (c) spalling caused by freeze–thaw cycles, (d) hydration of plastic materials, (e) corrosion of metals, (f) damage caused by expansion of materials from moisture (for example, buckling of wood floors), and (g) decline in visual appearance (for example, buckling of wood siding or efflorescence of masonry materials). In addition, high moisture levels can lead to mold spores in indoor air and odors, seriously affecting the occupant's health and comfort. Detailed discussions on the effects of moisture can be found in the ASHRAE *Handbook of Fundamentals,* chapters 22 and 23, (ASHRAE 1997) and Lstiburek and Carmody (1991).

Mold, Mildew, Dust Mites, and Human Health

Mold and mildew in buildings are offensive, and the spores can cause respiratory problems and allergic reactions in humans. Mold and mildew will grow on most surfaces if the relative humidity at the surface is above a critical value and the surface temperatures are conducive to growth. The longer the surface remains above this critical relative humidity level, the more likely mold will appear; the higher the humidity or temperature, the shorter the time needed for germination. The surface relative humidity is a complex function of material moisture content, material properties, local temperature, and humidity conditions. In addition, mold growth depends on the type of surface. Mildew and mold can usually be avoided by limiting surface relative humidity conditions >80% to short periods. Only for nonporous surfaces that are regularly cleaned should this criterion be relaxed. Most molds grow at temperatures approximately above 4°C (40°F). Moisture accumulation at temperatures below 4°C (40°F) may not cause mold and mildew if the material is allowed to dry out below the critical moisture content before the temperature increases above 4°C (40°F).

Dust mites can trigger allergies and are an important cause of asthma. They thrive at high relative humidity levels (>70%) at room temperature, but will not survive at sustained relative humidity levels less than 50%. However, these relative humidity levels relate to local conditions in the typical places that mites tend to inhabit (for example, mattresses, carpets, soft furniture).

Paint Failure and Other Appearance Problems

Moisture trapped behind paint films may cause failure of the paint (Ch. 15). Water or condensation may also cause streaking or staining. Excessive swings in moisture content of wood-based panels or boards may cause buckling or warp. Excessive moisture in masonry and concrete can produce efflorescence, a white powdery area or lines. When combined with low temperatures, excessive moisture can cause freeze–thaw damage and spalling (chipping).

Structural Failures

Structural failures caused by decay of wood are rare but have occurred. Decay generally requires a wood moisture content equal to or greater than fiber saturation (usually about 30%) and between 10°C (50°F) and 43°C (100°F). Wood moisture content levels above fiber saturation are only possible in green lumber or by absorption of liquid water from condensation, leaks, ground water, or other saturated materials in contact with the wood. To maintain a safety margin, a 20% moisture content is sometimes used during field inspections as the maximum allowable level. Once established, decay fungi produce water that enables them to maintain moisture conditions conducive to their growth. See Chapter 13 for more information on wood decay.

Rusting or corrosion of nails, nail plates, or other metal building products is also a potential cause of structural failure. Corrosion may occur at high relative humidity levels near the metal surface or as a result of liquid water from elsewhere. Wood moisture content levels >20% encourage corrosion of steel fasteners in wood, especially if the wood is treated with preservatives. In buildings, metal fasteners are often the coldest surfaces, which encourages condensation and corrosion of fasteners.

Effect on Heat Flow

Moisture in the building envelope can significantly degrade the thermal performance of most insulation materials but especially the thermal resistance of fibrous insulations and open cell foams. The degradation is most pronounced when daily temperature reversals across the insulation drive moisture back and forth through the insulation.

Moisture Control Strategies

Strategies to control moisture accumulation fall into two general categories: (1) minimize moisture entry into the building envelope and (2) remove moisture from the building envelope. When basic moisture transport mechanisms and specific moisture control practices are understood, roof, wall, and foundation constructions for various climates can be reviewed in a systematic fashion to determine if every potentially significant moisture transport mechanism is explicitly controlled. It is not possible to prevent moisture migration completely; therefore, construction should include drainage, ventilation, and removal by capillary suction, or other provisions to carry away unwanted water.

The major moisture transport mechanisms, in order of importance, are (a) liquid water movement, including capillary movement; (b) water vapor transport by air movement; and (c) water vapor diffusion. In the past, much attention has focused on limiting movement by diffusion with vapor retarders (sometimes called vapor barriers), even though vapor diffusion is the least important of all transport mechanisms. Control of moisture entry should be accomplished in accordance with the importance of the transport mechanism: (a) control of liquid entry by proper site grading and installing gutters and downspouts and appropriate flashing around windows, doors, and chimneys; (b) control of air leakage by installing air flow retarders or careful sealing by taping and caulking; and (c) control of vapor diffusion by placing vapor retarders on the "warm" side of the insulation.

Options for moisture control under heating conditions often differ from those under cooling conditions, even though the physical principles of moisture movement are the same. Which moisture control options apply depends on whether the local climate is predominantly a heating or cooling climate. In heating climates, ventilation with outdoor air and limiting indoor sources of moisture (wet fire wood, unvented dryers, humidifiers) can be effective strategies. In cooling climates, proper dehumidification can provide moisture control. More information on the definition of heating and cooling climates and specific moisture control strategies can be found in the ASHRAE *Handbook of Fundamentals,* chapter 23 (ASHRAE 1997).

Sound Control

An important design consideration for residential and office buildings is the control of sound that either enters the structure from outside or is transmitted from one room to another. Wood frame construction can achieve the levels of sound control equal to or greater than more massive construction, such as concrete. However, to do so requires designing for both airborne and impact noise insulation.

Airborne noise insulation is the resistance to transmission of airborne noises, such as traffic or speech, either through or around an assembly such as a wall. Noises create vibrations on the structural surfaces that they contact, and the design challenge is to prevent this vibration from reaching and leaving the opposite side of the structural surface. Sound transmission class (STC) is the rating used to characterize airborne noise insulation. A wall system with a high STC rating is effective in preventing the transmission of sound. Table 16–1 lists the STC ratings for several types of wall systems; detailed information for both wall and floor are given in FPL–GTR–43 (Rudder 1985).

Impact noise insulation is the resistance to noise generated by footsteps or dropping objects, generally addressed at floor–ceiling assemblies in multi-family dwellings. Impact insulation class (IIC) is the rating used to characterize the impact noise insulation of an assembly. Both the character of the flooring material and the structural details of the floor influence the IIC rating. Additional information on IIC ratings for wood construction is given in FPL–GTR–59 (Sherwood and Moody 1989).

Table 16–1. Sound transmission class (STC) ratings for typical wood-frame walls

STC rating	Privacy afforded	Wall structure
25	Normal speech easily understood	6-mm (1/4-in.) wood panels nailed on each side of standard 38- by 89-mm (nominal 2- by 4-in.) studs.
30	Normal speech audible but not intelligible	9.5-mm (3/8-in.) gypsum wallboard nailed to one side of standard 38- by 89-mm (nominal 2- by 4-in.) studs.
35	Loud speech audible and fairly understandable	20-mm (5/8-in.) gypsum wallboard nailed to both sides of standard 38- by 89-mm (nominal 2- by 4-in.) studs.
40	Loud speech audible but not intelligible	Two layers of 20-mm (5/8-in.) gypsum wallboard nailed to both sides of standard 38- by 89-mm (nominal 2- by 4-in.) studs.
45	Loud speech barely audible	Two sets of standard 38- by 64-mm (nominal 2- by 3-in.) studs staggered 0.2 m (8 in.) on centers fastened by standard 38- by 89-mm (nominal 2- by 4-in.) base and head plates with two layers of 20-mm (5/8-in.) gypsum wallboard nailed on the outer edge of each set of studs.
50	Shouting barely audible	Standard 38- by 89-mm (nominal 2- by 4-in.) wood studs with resilient channels nailed horizontally to both sides with 20-mm (5/8-in.) gypsum wallboard screwed to channels on each side.
55	Shouting not audible	Double row of standard 38- by 89-mm (nominal 2- by 4-in.) studs 0.4 m (16 in.) on centers fastened to separate plates spaced 25 mm (1 in.) apart. Two layers of 20-mm (5/8-in.) gypsum wallboard screwed 0.3 m (12 in.) on center to the studs. An 89-mm- (3.5-in.-) thick sound-attenuation blanket is installed in one stud cavity.

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Chapter 17

Fire Safety

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Contents

Fire safety is an important concern in all types of construction. The high level of national concern for fire safety is reflected in limitations and design requirements in building codes. These code requirements are discussed in the context of fire safety design and evaluation in the initial section of this chapter. Since basic data on fire behavior of wood products are needed to evaluate fire safety for wood construction, the second major section of this chapter covers fire performance characteristics of wood products. The chapter concludes with a discussion of flame-retardant treatments that can be used to reduce the combustibility of wood.

Fire Safety Design and Evaluation

Fire safety involves prevention, containment, detection, and evacuation. Fire prevention basically means preventing the ignition of combustible materials by controlling either the source of heat or the combustible materials. This involves proper design, installation or construction, and maintenance of the building and its contents. Proper fire safety measures depend upon the occupancy or processes taking place in the building. Design deficiencies are often responsible for spread of heat and smoke in a fire. Spread of a fire can be prevented with design methods that limit fire growth and spread within a compartment and with methods that contain fire to the compartment of origin. Egress, or the ability to escape from a fire, often is a critical factor in life safety. Early detection is essential for ensuring adequate time for egress.

Statutory requirements pertaining to fire safety are specified in the building codes or fire codes. These requirements fall into two broad categories: material requirements and building requirements. Material requirements include such things as combustibility, flame spread, and fire endurance. Building requirements include area and height limitations, firestops and draftstops, doors and other exits, automatic sprinklers, and fire detectors.

Adherence to codes will result in improved fire safety. Code officials should be consulted early in the design of a building because the codes offer alternatives. For example, floor areas can be increased if automatic sprinkler systems are added. Code officials have the option to approve alternative materials and methods of construction and to modify provisions of the codes when equivalent fire protection and structural integrity is documented.

Most building codes in the United States are based on model building codes produced by the three building code organizations (Building Officials and Code Administrators International, Inc.; International Conference of Building Officials; and the Southern Building Code Congress International, Inc.). These three organizations are developing a single international building code that will replace the existing three model building codes. In addition to the building codes and the fire codes, the National Fire Protection Association's Life Safety Code provides guidelines for life safety from fire in buildings and structures. As with the model building codes, provisions of the life safety code are statutory requirements when adopted by local or State authorities.

In the following sections, various aspects of the building code provisions pertaining to fire safety of building materials are discussed under the broad categories of (a) types of construction, (b) fire growth within compartment, and (c) containment to compartment of origin. These are largely requirements for materials. Information on prevention and building requirements not related to materials (for example, detection) can be found in publications such as those listed at the end of this chapter. Central aspects of the fire safety provisions of the building codes are the classification of buildings by types of construction and the use or occupancy.

Types of Construction

Based on classifications of building type and occupancy, the codes set limits on the areas and heights of buildings. Major building codes generally recognize five classifications of construction based on types of materials and required fire resistance ratings. The two classifications known as fire-resistant construction (Type I) and noncombustible construction (Type II) basically restrict the construction to noncombustible materials. Wood is permitted to be used more liberally in the other three classifications, which are ordinary (Type III), heavy timber (Type IV), and light-frame (Type V). Heavy timber construction has wood columns, beams, floors, and roofs of certain minimum dimensions. Ordinary construction has smaller wood members used for walls, floors, and roofs including wood studs, wood joists, wood trusses, and wood I-joists. In both heavy timber and ordinary construction, the exterior walls must be of noncombustible materials. In light-frame construction, the walls, floors, and roofs may be of any dimension lumber and the exterior walls may be of combustible materials. Type II, III, and IV constructions are further subdivided based on fire-resistance requirements. Light-frame construction, or Type V, is subdivided into two parts, protected (1-hour) and unprotected.

In protected light-frame construction, most of the structural elements have a 1-hour fire resistance rating. There are no general requirements for fire resistance for buildings of unprotected light-frame construction.

Based on their performance in the American Society for Testing and Materials (ASTM) E136 test, both untreated and fire-retardant-treated wood are combustible materials. However, the building codes permit substitution of fire-retardant-treated wood for noncombustible materials in some specific applications otherwise limited to noncombustible materials.

In addition to the type of construction, the height and area limitations also depend on the use or occupancy of a structure. Fire safety is improved by automatic sprinklers, property line setbacks, or more fire-resistant construction. Building codes recognize the improved fire safety resulting from application of these factors by increasing the allowable areas and heights beyond that designated for a particular type of construction and occupancy. Thus, proper site planning and building design may result in a desired building area classification being achieved with wood construction.

Fire Growth Within Compartment

A second major set of provisions in the building codes are those that regulate the exposed interior surface of walls and ceilings (that is, the interior finish). Codes typically exclude trim and incidental finish, as well as decorations and furnishings that are not affixed to the structure, from the more rigid requirements for walls and ceilings. For regulatory purposes, interior finish materials are classified according to their flame spread index. Thus, flame spread is one of the most tested fire performance properties of a material. Numerous flame spread tests are used, but the one cited by building codes is ASTM E84, the "25-ft tunnel" test. In this test method, the 508-mm-wide, 7.32-m-long specimen completes the top of the tunnel furnace. Flames from a burner at one end of the tunnel provide the fire exposure, which includes forced draft conditions. The furnace operator records the flame front position as a function of time and the time of maximum flame front travel during a 10-min period. The standard prescribes a formula to convert these data to a flame spread index (FSI), which is a measure of the overall rate of flame spreading in the direction of air flow. In the codes, the classes for flame spread index are I (FSI of 0 to 25), II (FSI of 26 to 75), and III (FSI of 76 to 200). Some codes use A, B, and C instead of I, II, and III. Generally, codes specify FSI for interior finish based on building occupancy, location within the building, and availability of automatic sprinkler protection. The more restrictive classes, Classes I and II, are generally prescribed for stairways and corridors that provide access to exits. In general, the more flammable classification (Class III) is permitted for the interior finish of other areas of the building that are not considered exit ways or where the area in question is protected by automatic sprinklers. In other areas, there are no flammability restrictions on the interior finish and unclassified materials (that is, more than 200 FSI) can be used.

Table 17–1. ASTM E84 flame spread indexes for 19-mm-thick solid lumber of various wood species as reported in the literature

Species[a]	Flame spread index[b]	Smoke developed index[b]	Source[c]
Softwoods			
Yellow-cedar (Pacific Coast yellow cedar)	78	90	CWC
Baldcypress (cypress)	145–150	—	UL
Douglas-fir	70–100	—	UL
Fir, Pacific silver	69	58	CWC
Hemlock, western (West Coast)	60–75	—	UL
Pine, eastern white (eastern white, northern white)	85, 120–215[d]	122, —	CWC, UL
Pine, lodgepole	93	210	CWC
Pine, ponderosa	105–230[d]	—	UL
Pine, red	142	229	CWC
Pine, Southern (southern)	130–195	—	UL
Pine, western white	75[e]	—	UL
Redcedar, western	70	213	HPVA
Redwood	70	—	UL
Spruce, eastern (northern, white)	65	—	UL, CWC
Spruce, Sitka (western, Sitka)	100, 74	—, 74	UL, CWC
Hardwoods			
Birch, yellow	105–110	—	UL
Cottonwood	115	—	UL
Maple (maple flooring)	104	—	CWC
Oak (red, white)	100	100	UL
Sweetgum (gum, red)	140–155	—	UL
Walnut	130–140	—	UL
Yellow-poplar (poplar)	170–185	—	UL

[a]In cases where the name given in the source did not conform to the official nomenclature of the Forest Service, the probable official nomenclature name is given and the name given by the source is given in parentheses.
[b]Data are as reported in the literature (dash where data do not exist). Changes in the ASTM E84 test method have occurred over the years. However, data indicate that the changes have not significantly changed earlier data reported in this table. The change in the calculation procedure has usually resulted in slightly lower flame spread results for untreated wood. Smoke developed index is not known to exceed 450, the limiting value often cited in the building codes.
[c]CWC, Canadian Wood Council (CWC 1996); HPVA, Hardwood Plywood Manufacturers Association (Tests) (now Hardwood Plywood & Veneer Assoc.); UL, Underwriters Laboratories, Inc. (Wood-fire hazard classification. Card Data Service, Serial No. UL 527, 1971).
[d]Footnote of UL: In 18 tests of ponderosa pine, three had values over 200 and the average of all tests is 154.
[e]Footnote of UL: Due to wide variations in the different species of the pine family and local connotations of their popular names, exact identification of the types of pine tested was not possible. The effects of differing climatic and soil conditions on the burning characteristics of given species have not been determined.

The FSI for most domestic wood species is between 90 and 160 (Table 17–1). Thus, unfinished lumber, 10 mm or thicker, is generally acceptable for interior finish applications requiring a Class III rating. Flame-retardant treatments are usually necessary when a Class I or II flame spread index is required for a wood product. A few domestic softwood species can meet the Class II flame spread index and only require flame-retardant treatments to meet a Class I rating. A few imported species have reported FSIs of less than 25.

Additional FSI for many solid-sawn and panel products are provided in the American Forest and Paper Association's (AF&PA) design for code acceptance (DCA) No. 1, "Flame Spread Performance of Wood Products" (AWC 1999).

There are many other test methods for flame spread or flammability. Most are used only for research and development or quality control, but some are used in product specifications and regulations of materials in a variety of applications.

Since the fire exposure is on the underside of a horizontal specimen in the ASTM E84 test, it is not suitable for materials that melt and drip or are not self-supporting. Code provisions pertaining to floors and floor coverings may be based on another test criterion, the critical radiant flux test (ASTM E648, Critical Radiant Flux of Floor-Covering Systems Using a Radiant Heat Energy Source). The critical radiant flux apparatus is also used to test the flammability of cellulosic insulation (ASTM E970, Critical Radiant Flux of Exposed Attic Floor Insulation Using a Radiant Heat Energy Source). In the critical radiant flux test, the placement of the radiant panel is such that the radiant heat being imposed on the surface has a gradient in intensity down the length of the horizontal specimen. Flames spread from the ignition source at the end of high heat flux (or intensity) to the other end until they reach a location where the heat flux is not sufficient for further propagation. This is reported as the critical radiant flux. Thus, low critical radiant flux reflects materials with high flammability. Typical requirements are for a minimum critical radiant flux level of 2.2 or 4.5 kW/m^2 depending on location and occupancy. Data in the literature indicate that oak flooring has a critical radiant flux of 3.5 kW/m^2 (Benjamin and Adams 1976).

There is also a smoldering combustion test for cellulosic insulation. Cellulosic insulation is regulated by a product safety standard of the U.S. Consumer Product Safety Commission (Interim Safety Standard for Cellulosic Insulation: Cellulosic Insulation Labeling and Requirements, 44FR 39938, 16CFR Part 1209, 1979; also Gen. Serv. Admin. Spec. HH–I–515d). Proper chemical treatments of cellulosic insulation are required to reduce its tendency for smoldering combustion and to reduce flame spread. Proper installation around recessed light fixtures and other electrical devices is necessary.

Other tests for flammability include those that measure heat release. Other flammability tests and fire growth modeling are discussed in the Fire Performance Characteristics of Wood section.

Rated roof covering materials are designated either Class A, B, or C according to their performance in the tests described in ASTM E108, Fire Tests of Roof Coverings. This test standard includes intermittent flame exposure, spread of flame, burning brand, flying brand, and rain tests. There is a different version of the pass/fail test for each of the three classes. Class A test is the most severe and Class C the least. In the case of the burning brand tests, the brand for the Class B test is larger than that for the Class C test. Leach-resistant fire-retardant-treated shingles are available that carry a Class B or C fire rating.

Information on ratings for different products can be obtained from industry literature, evaluation reports issued by the model code organizations, and listings published by testing laboratories or quality assurance agencies. Products listed by Underwriters Laboratories, Inc., and other such organizations are stamped with the rating information.

Flashover

With sufficient heat generation, the initial growth of a fire in a compartment leads to the condition known as flashover. The visual criteria for flashover are full involvement of the compartment and flames out the door or window. The intensity over time of a fire starting in one room or compartment of a building depends on the amount and distribution of combustible contents in the room and the amount of ventilation.

The standard full-scale test for pre-flashover fire growth is the room/corner test (International Organization for Standardization (ISO) 9705, Fire Tests—Full-Scale Room Test for Surface Products). In this test, a gas burner is placed in the corner of the room, which has a single door for ventilation. Three of the walls are lined with the test material, and the ceiling may also be lined with the test material. Other room/corner tests use a wood crib or similar item as the ignition source. Such a room/corner test is used to regulate foam plastic insulation, a material that is not properly evaluated in the ASTM E84 test.

Observations are made of the growth of the fire and the duration of the test until flashover occurs. Instruments record the heat generation, temperature development within the room, and the heat flux to the floor. Results of full-scale room/corner tests are used to validate fire growth models and bench-scale test results. Fire endurance tests evaluate the relative performance of the assemblies during a post-flashover fire.

Containment to Compartment of Origin

The growth, intensity, and duration of the fire is the “load” that determines whether a fire is confined to the room of origin. Whether a given fire will be contained to the compartment depends on the fire resistance of the walls, doors, ceilings, and floors of the compartment. Requirements for fire resistance or fire endurance ratings of structural members and assemblies are another major component of the building code provisions. Fire resistance is the ability of materials or their assemblies to prevent or retard the passage of excessive heat, hot gases, or flames while continuing to support their structural loads. Fire-resistance ratings are usually obtained by conducting standard fire tests. In the standard fire-resistance test (ASTM E119), there are three failure criteria: element collapse, passage of flames, or excessive temperature rise on the non-fire-exposed surface (average increase of several locations exceeding 139°C or 181°C at a single location).

The self-insulating qualities of wood, particularly in the large wood sections of heavy timber construction, are an important factor in providing a degree of fire resistance. In Type IV or heavy timber construction, the need for fire-resistance requirements is achieved in the codes by specifying minimum sizes for the various members or portions of a building and other prescriptive requirements. In this type of construction, the wood members are not required to have specific fire-resistance ratings. The acceptance of heavy timber construction is based on historical experience with its performance in actual fires. Proper heavy timber construction includes using approved fastenings, avoiding concealed spaces under floors or roofs, and providing required fire resistance in the interior and exterior walls.

In recent years, the availability and code acceptance of a procedure to calculate the fire-resistance ratings for large timber beams and columns have allowed their use in fire-rated buildings not classified as heavy timber construction (Type IV). In the other types of construction, the structural members and assemblies are required to have specified fire-resistance ratings. Details on the procedure for large timbers can be found in American Institute of Timber Construction (AITC) Technical Note 7 and the AF&PA DCA #2 "Design of Fire-Resistive Exposed Wood Members" (AWC 1985).

The fire resistance of glued-laminated structural members, such as arches, beams, and columns, is approximately equivalent to the fire resistance of solid members of similar size. Available information indicates that laminated members glued with phenol, resorcinol, or melamine adhesives are at least equal in their fire resistance to a one-piece member of the same size. Laminated members glued with casein have only slightly less fire resistance.

Light-frame wood construction can provide a high degree of fire containment through use of gypsum board as the interior finish. This effective protective membrane provides the initial fire resistance rating. Many recognized assemblies involving wood-frame walls, floors, and roofs provide a 1- or 2-hour fire resistance rating. Fire-rated gypsum board (Type X or C) is used in rated assemblies. Type X and the higher grade Type C gypsum boards have textile glass filaments and other ingredients that help to keep the gypsum core intact during a fire. Fire-resistance ratings of various assemblies are listed in the model codes and other publications such as the *Fire Resistance Design Manual* (Gypsum Association). Traditional constructions of regular gypsum wallboard (that is, not fire rated) or lath and plaster over wood joists and studs have fire-resistance ratings of 15 to 30 min.

While fire-resistance ratings are for the entire wall, floor, or roof assembly, the fire resistance of a wall or floor can be viewed as the sum of the resistance of the interior finish and the resistance of the framing members. In a code-accepted procedure, the fire rating of a light-frame assembly is calculated by adding the tabulated times for the fire-exposed membrane to the tabulated times for the framing. For example, the fire-resistance rating of a wood stud wall with 16-mm-thick Type X gypsum board and rock wool insulation is computed by adding the 20 min listed for the stud wall, the 40 min listed for the gypsum board, and the 15 min listed for the rock wool insulation to obtain a rating for the assembly of 75 min. Additional information on this component additive method (CAM) can be found in the AF&PA DCA No. 4 "Component Additive Method (CAM) for Calculating and Demonstrating Assembly Fire Endurance" (AWC 1991). More sophisticated mechanistic models are being developed.

The relatively good structural behavior of a traditional wood member in a fire test results from the fact that its strength is generally uniform through the mass of the piece. Thus, the unburned fraction of the member retains high strength, and its load-carrying capacity is diminished only in proportion to its loss of cross section. Innovative designs for structural wood members may reduce the mass of the member and locate the principal load-carrying components at the outer edges where they are most vulnerable to fire, as in structural sandwich panels. With high strength facings attached to a low-strength core, unprotected load-bearing sandwich panels have failed to support their load in less than 6 min when tested in the standard test. If a sandwich panel is to be used as a load-bearing assembly, it should be protected with gypsum wallboard or some other thermal barrier. In any protected assembly, the performance of the protective membrane is the critical factor in the performance of the assembly.

Unprotected light-frame wood buildings do not have the natural fire resistance achieved with heavier wood members. In these, as in all buildings, attention to good construction details is important to minimize fire hazards. Quality of workmanship is important in achieving adequate fire resistance. Inadequate nailing and less than required thickness of the interior finish can reduce the fire resistance of an assembly. The method of fastening the interior finish to the framing members and the treatment of the joints are significant factors in the fire resistance of an assembly. The type and quantity of any insulation installed within the assembly may also affect the fire resistance of an assembly. Electrical receptacle outlets, pipe chases, and other through openings that are not adequately firestopped can affect the fire resistance. In addition to the design of walls, ceilings, floors, and roofs for fire resistance, stairways, doors, and firestops are of particular importance.

Fires in buildings can spread by the movement of hot fire gases through open channels in concealed spaces. Codes specify where firestops and draftstops are required in concealed spaces, and they must be designed to interfere with the passage of flames up or across a building. In addition to going along halls, stairways, and other large spaces, heated gases also follow the concealed spaces between floor joists and between studs in partitions and walls of frame construction. Obstruction of these hidden channels provides an effective means of restricting fire from spreading to other parts of the structure. Firestops are materials used to block off relatively small openings passing through building components such as floors and walls. Draftstops are barriers in larger concealed spaces such as those found within wood joist floor assemblies with suspended dropped ceilings or within an attic space with pitched chord trusses.

Doors can be critical in preventing the spread of fires. Doors left open or doors with little fire resistance can easily defeat the purpose of a fire-rated wall or partition. Listings of fire-rated doors, frames, and accessories are provided by various fire testing agencies. When a fire-rated door is selected, details about which type of door, mounting, hardware, and closing mechanism need to be considered.

Fire Safety Engineering

The field of fire safety engineering is undergoing rapid changes because of the development of more engineering and scientific approaches to fire safety. This development is evidenced by the publication of *The Society of Fire Protection Engineers Handbook of Fire Protection Engineering* and formation of fire safety engineering subcommittees in ISO and ASTM. Steady advances are being made in the fields of fire dynamics, fire hazard calculations, fire design calculations, and fire risk analysis. Such efforts support the worldwide trend to develop alternative building codes based on performance criteria rather than prescriptive requirements. Additional information on fire protection can be found in the various publications of the National Fire Protection Association (NFPA).

Fire Performance Characteristics of Wood

Wood will burn when exposed to heat and air. Thermal degradation of wood occurs in stages. The degradation process and the exact products of thermal degradation depend upon the rate of heating as well as the temperatures. The sequence of events for wood combustion is as follows:

- The wood, responding to heating, decomposes or pyrolyzes into volatiles and char. Char is the dominant product at internal temperatures less than 300°C, whereas volatiles become much more pronounced above 300°C.
- The volatiles, some of which are flammable, can be ignited if the volatile–air mixture is of the right composition in a temperature range of about 400°C to 500°C within the mixture. This gas-phase combustion appears as flames.
- With air ventilation, the char oxidation becomes significant around 200°C with two peaks in intensity reported at 360°C and 520°C. This char oxidation is seen as glowing or smoldering combustion until only ash residue remains. This solid-phase combustion will not proceed if flaming combustion prevents a supply of fresh air to the char surfaces.

Several characteristics are used to quantify this burning behavior of wood, including ignition from heat sources, growing rate of heat release leading to room flashover, flame spread in heated environments, smoke and toxic gases, flashover, and charring rates in a contained room.

Ignition

Ignition of wood takes place when wood is subject to sufficient heat and in atmospheres that have sufficient oxygen. Ignition can be of two types: piloted or unpiloted. Piloted ignition occurs in the presence of an ignition source (such as a spark or a flame). Unpiloted ignition is ignition that occurs where no pilot source is available. The wood surface is ignited by the flow of energy or heat flux from a fire or other heated objects. This flow of energy or heat flux can have both convective and radiative components.

Piloted ignition above a single flat surface has recently been studied in some depth because of the advent of fire growth research. The surface temperature of wood materials has been measured somewhere between 300°C to 400°C prior to piloted ignition. Surface temperature at ignition is an illusive quantity that is experimentally difficult to obtain. Equipment such as the Ohio State University (OSU) apparatus (ASTM E906), the cone calorimeter (ASTM 1354), and the lateral ignition and flame spread test (LIFT) apparatus (ASTM 1321) are used to obtain data on time to piloted ignition as a function of heater irradiance. Table 17–2 indicates the decrease in time to ignition with the increase in imposed heat flux for different species of wood measured with the OSU apparatus. Similar, perhaps identical, materials have been tested recently in cone calorimeter and LIFT apparatuses with somewhat similar results. From such tests, values of ignition temperature, critical ignition flux (heat flux below which ignition would not occur), and thermophysical properties have been derived using a transient heat conduction theory. These properties are also material dependent; they depend heavily on density of the material and moisture content. A range of wood products tested have ignition surface temperatures of 300°C to 400°C and a critical ignition flux of between 10 and 13 kW/m^2 in the cone calorimeter. The ignition surface temperature is lower for low density woods. Estimates of piloted ignition in various scenarios can be obtained using the derived thermal properties and an applicable heat conduction model.

Some, typically old, apparatuses for testing piloted ignition measured the temperature of the air flow rather than the imposed heat flux with the time to ignition measurement. These results were often reported as the ignition temperature and as varying with time to ignition, which is misleading. When the imposed heat flux is due to a radiant source, such reported air flow ignition temperature can be as much as 100°C lower than the ignition surface temperature. For a proper heat conduction analysis in deriving thermal properties, measurements of the radiant source flux and air flow rate are also required. Since imposed heat flux to the surface and the surface ignition temperature are the factors that directly determine ignition, some data of piloted ignition are inadequate or misleading.

Unpiloted ignition depends on special circumstances that result in different ranges of ignition temperatures. At this time, it is not possible to give specific ignition data that apply to a broad range of cases. For radiant heating of cellulosic solids, unpiloted transient ignition has been reported at 600°C. With convective heating of wood, unpiloted ignition has been reported as low as 270°C and as high as 470°C.

Unpiloted spontaneous ignition can occur when a heat source within the wood product is located such that the heat is not readily dissipated. This kind of ignition involves smoldering and generally occurs over a longer period of time. Smoldering is thermal degradation that proceeds without flames or

Table 17–2. Flammability data for selected wood species

Species	Density[a] (kg/m^3)	Ignition time[b] (s)		Higher heating value[c] (MJ/kg)	Effective heat of combustion[d] (MJ/kg)		Average heat release rate[b] (kW/m^2)	
		18-kW/m^2 heat flux	55-kW/m^2 heat flux		18-kW/m^2 heat flux	55-kW/m^2 heat flux	18-kW/m^2 heat flux	55-kW/m^2 heat flux
Softwoods								
Pine, Southern	508	740	5	20.5	9.1	13.9	40.4	119.6
Redwood	312	741	3	21.1	10.7	14.2	39.0	85.9
Hardwoods								
Basswood	312	183	5	20.0	10.9	12.2	52.8	113.0
Oak, red	660	930	13	19.8	9.0	11.7	48.7	113.3

[a]Based on weight and volume of ovendried wood.
[b]Ignition times, effective heat of combustion, and average rate of heat release (HRR) obtained using an ASTM E906 heat release apparatus modified to measured heat release using oxygen consumption method. Test durations were 50 to 98 min for 18-kW/m^2 heat flux and 30 to 53 min for 55-kW/m^2 heat flux. Test was terminated prior to the usual increase in HRR to a second peak as the specimen is consumed.
[c]From oxygen bomb calorimeter test.
[d]Apparent effective heat of combustion based on average HRR and mass loss rate, which includes the moisture driven from the wood. See footnote b.

visible glowing. Examples of such fires are (a) panels or paper removed from the press or dryer and stacked in large piles without adequate cooling and (b) very large piles of chips or sawdust with internal exothermic reactions such as biological activities. Potential mechanisms of internal heat generation include respiration, metabolism of microorganisms, heat of pyrolysis, abiotic oxidation, and adsorptive heat. These mechanisms, often in combination, may proceed to smoldering or flaming ignition through a thermal runaway effect within the pile if sufficient heat is generated and is not dissipated. The minimum environmental temperature to achieve ignition is called the self-accelerating decomposition temperature and includes the effects of specimen mass and air ventilation.

Unpiloted ignitions that involve wood exposed to low level external heat sources over very long periods is an area of dispute. This kind of ignition, which involves considerable charring, does appear to occur, based on fire investigations. However, these circumstances do not lend themselves easily to experimentation and observation. There is some evidence that the char produced under low heating temperatures can have a different chemical composition, which results in a somewhat lower ignition temperature than normally recorded. Thus, a major issue is the question of safe working temperature for wood exposed for long periods. Temperatures between 80°C to 100°C have been recommended as safe surface temperatures for wood. Since thermal degradation is a prerequisite for ignition of the char layer, conservative criteria for determining safe working temperatures can be the temperature and duration needed for thermal degradation. Schaffer (1980) used a residual weight criterion of 40% of the initial weight to suggest that wood can safely be heated to 150°C for a year or more before satisfying this conservative predictor of heating time to reach an incipient smoldering state.

Building codes do not generally regulate building materials on the basis of ignition or ignitability. As a result, general fire safety design criteria have not been developed. Rather, this subject is considered in conjunction with limits on combustibility and flame spread.

Heat Release

Heat release rates are important because they indicate the potential fire hazard of a material and also the combustibility of a material. Materials that release their potential chemical energy (and also the smoke and toxic gases) relatively quickly are more hazardous than those that release it more slowly. There are materials that will not pass the current definition of noncombustible in the model codes but will release only limited amounts of heat during the initial and critical periods of fire exposure. There is also some criticism of using limited flammability to partially define noncombustibility. One early attempt was to define combustibility in terms of heat release in a potential heat method (NFPA 259), with the low levels used to define low combustibility or noncombustibility. This test method is being used to regulate materials under some codes. The ground-up wood sample in this method is completely consumed during the exposure to 750°C for 2 h, which makes the potential heat for wood identical to the gross heat of combustion from the oxygen bomb calorimeter (the higher heating value in Table 17–2). The typical gross heat of combustion averaged around 20 MJ/kg for ovendried wood, depending on the lignin and extractive content of the wood.

A better or a supplementary measure of degrees of combustibility is a determination of the rate of heat release (RHR) or heat release rate (HRR). This measurement efficiently assesses the relative heat contribution of materials—thick, thin, untreated, or treated—under fire exposure. The cone calorimeter (ASTM E1354) is the most commonly used bench-scale HRR apparatus and is based on the oxygen consumption method. An average value of 13.1 kJ/g of oxygen consumed was the constant found for organic solids and is accurate with very few exceptions to within 5%. Thus, it is sufficient to measure the mass flow rate of oxygen consumed in a combustion system to determine the net HRR. The procedure known as ASTM E906 (the OSU apparatus) is a well-known and widely used calorimeter based on measurements of heat content of incoming and exiting air flow through the apparatus. Because of the errors caused by the heat losses and the fact that the mass flow rate is controlled in the OSU apparatus, several researchers have modified it to the oxygen consumption method. These bench-scale apparatuses use a radiant source to provide the external heat exposure to the test specimen. The imposed heat flux is kept constant at a specified heat flux level. The intermediate-scale apparatus (ASTM E1623) for testing 1- by 1-m assemblies or composites and the room full-scale test (ISO 9705) also use the oxygen consumption technique to measure the HRR of fires at larger scales.

The cone calorimeter is ideal for product development with its small specimen size of 100 by 100 mm. The specimen is continuously weighed by use of a load cell. In conjunction with HRR measurements, the effective heat of combustion as a function of time is calculated by the ASTM E1354 method. Basically, the effective heat of combustion is the HRR divided by the mass loss rate as determined from the cone calorimeter test as a function of time. A typical HRR profile as shown in Figure 17–1 for plywood begins with a sharp peak upon ignition, and as the surface chars, the HRR drops to some minimum value. After the thermal wave travels completely through the wood thickness, the back side of a wood sample reaches pyrolysis temperature, thus giving rise to a second, broader, and even higher HRR peak. For fire-retardant-treated wood products, the first HRR peak may be reduced or eliminated. Table 17–3 provides the peak and averaged HRR at 1-, 3-, and 5-min periods for various wood species.

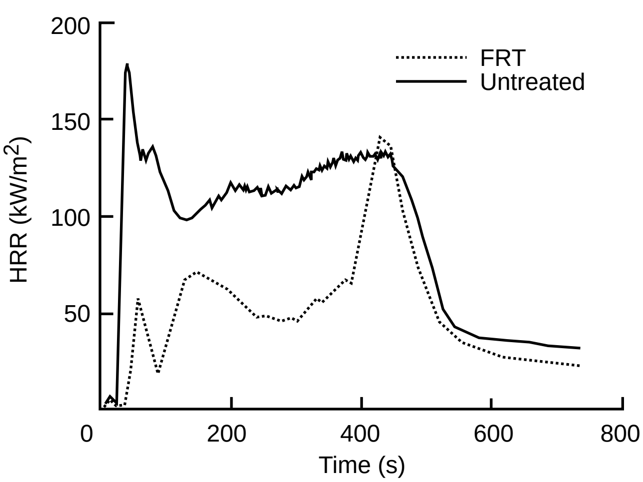

Figure 17–1. Heat release curves for untreated and FRT plywood exposed to 50-kW/m^2 radiance.

Heat release rate depends upon the intensity of the imposed heat flux. Table 17–2 provides the average effective heat of combustion and average HRR for four wood species and two levels of heat flux (18 and 55 kW/m^2). These results were obtained in an OSU apparatus modified by the Forest Products Laboratory (FPL). Similar values were also obtained in the cone calorimeter (Table 17–3). Generally, the averaged effective heat of combustion is about 65% of the oxygen bomb heat of combustion (higher heating value) with a small linear increase with irradiance. The HRR itself has a large linear increase with the heat flux. Data indicate that HRRs decrease with increasing moisture content of the sample and are markedly reduced by fire-retardant treatment (Fig. 17–1).

Flame Spread

The spread of flames over solids is a very important phenomenon in the growth of compartment fires. Indeed, in fires where large fuel surfaces are involved, the increase in HRR with time is primarily due to the increase in burning area. Many data have been acquired with the flame spread tests used in building codes. Table 17–1 lists the FSI and smoke index of ASTM E84 for solid wood. Some consistencies in the FSI behavior of the hardwood species can be related to their density. Considerable variations are found for wood-based composites; for example, the FSI of four structural flakeboards ranged from 71 to 189.

As a prescriptive regulation, the ASTM E84 tunnel test is a success in the reduction of fire hazards but is impractical in providing scientific data for fire modeling or in useful bench-scale tests for product development. Other full-scale tests (such as the ISO 9705 room/corner test) also use both an ignition burner and the ensuing flame spread to assist flow but can produce quite different results because of the size of the ignition burner or the test geometry. This is the case with foam plastic panels that melt and drip during a fire test. In the tunnel test, with the test material on top, a material that melts can have low flammability since the specimen does not stay in place. With an adequate burner in the room/corner test, the same material will exhibit very high flammability.

A flame spreads over a solid material when part of the fuel, ahead of the pyrolysis front, is heated to the critical condition of ignition. The rate of flame spread is controlled by how rapidly the fuel reaches the ignition temperature in response to heating by the flame front and external sources. The material's thermal conductivity, heat capacitance, thickness, and blackbody surface reflectivity influence the material's thermal response, and an increase in the values of these properties corresponds to a decrease in flame spread rate. On the other hand, an increase in values of the flame features, such as the imposed surface fluxes and spatial lengths, corresponds to a increase in the flame spread rate.

Table 17–3. Heat release data for selected wood species[a]

Species	Density[b] (kg/m^3)	Heat release rate (kW/m^2) Peak	60-s avg	180-s avg	300-s avg	Average effective heat of combustion[c] (MJ/kg)	Ignition time (s)
Softwoods							
Pine, red	525	209	163	143	132	12.9	24
Pine, white	359	209	150	117	103	13.6	17
Redcedar, eastern	—	175	92	95	85	11.7	25
Redwood	408	227	118	105	95	13.2	17
Hardwoods							
Birch	618	218	117	150	141	12.2	29
Maple, hard	626	218	128	146	137	11.7	31
Oak, red	593	214	115	140	129	11.4	28

[a]Data for 50-kW/m^2 heat flux in cone calorimeter. Tested in specimen holder without retaining frame. Specimens conditioned to 23°C, 50% relative humidity.
[b]Ovendry mass and volume.
[c]Tests terminated when average mass loss rate dropped below 1.5 g/s m^2 during 1-min period.

Flame spread occurs in different configurations, which are organized by orientation of the fuel and direction of the main flow of gases relative to that of flame spread. Downward and lateral creeping flame spread involves a fuel orientation with buoyantly heated air flowing opposite of the flame spread direction. Related bench-scale test methods are ASTM E162 for downward flame spread, ASTM E648 for horizontal flame spread to the critical flux level, and ASTM E1321 (LIFT apparatus) for lateral flame spread on vertical specimen to the critical flux level. The heat transfer from the flame to the virgin fuel is primarily conductive within a spatial extent of a few millimeters and is affected by ambient conditions such as oxygen, pressure, buoyancy, and external irradiance. For most wood materials, this heat transfer from the flame is less than or equal to surface radiant heat loss in normal ambient conditions, so that excess heat is not available to further raise the virgin fuel temperature; flame spread is prevented as a result. Therefore, to achieve creeping flame spread, an external heat source is required in the vicinity of the pyrolysis front.

Upward or ceiling flame spread involves a fuel orientation with the main air flowing in the same direction as the flame spread (assisting flow). At present, there are no small-scale tests for upward flame spread potential. Thus, testing of flame spread in assisting flow exists mostly in both the tunnel tests and the room/corner burn tests. The heat transfer from the flame is both conductive and radiative, has a large spatial feature, and is relatively unaffected by ambient conditions. Rapid acceleration in flame spread can develop because of a large, increasing magnitude of flame heat transfer as a result of increasing total HRR in assisting flows. These complexities and the importance of the flame spread processes explain the many and often incompatible flame spread tests and models in existence worldwide.

Smoke and Toxic Gases

One of the most important problems associated with fires is the smoke they produce. The term smoke is frequently used in an all-inclusive sense to mean the mixture of pyrolysis products and air that is present near the fire site. In this context, smoke contains gases, solid particles, and droplets of liquid. Smoke presents potential hazards because it interacts with light to obscure vision and because it contains noxious and toxic substances.

Generally, two approaches are used to deal with the smoke problem: limit smoke production and control the smoke that has been produced. The control of smoke flow is most often a factor in the design and construction of large or tall buildings. In these buildings, combustion products may have serious effects in areas remote from the actual fire site.

Currently, several bench-scale test methods provide comparative smoke yield information on materials and assemblies. Each method has entirely different exposure conditions; none is generally correlated to full-scale fire conditions or experience. Until the middle 1970s, smoke yield restrictions in building codes were almost always based on data from ASTM E84. The smoke measurement is based on a percentage attenuation of white light passing through the tunnel exhaust stream and detected by a photocell. This is converted to the smoke development index (SDI), with red oak flooring set at 100. The flame spread requirements for interior finish generally are linked to an added requirement that the SDI be less than 450.

In the 1970s, the apparatus known as the NBS smoke chamber was developed and approved as an ASTM standard for research and development (ASTM E662). This test is a static smoke test because the specimen is tested in a closed chamber of fixed volume and the light attenuation is recorded over a known optical path length. The corresponding light transmission is reported as specific optical density as a function of time. Samples are normally tested in both flaming (pilot flame) and nonflaming conditions using a radiant flux of 25 kW/m^2.

The dynamic measurement of smoke in the heat release calorimeter (ASTM E906 and E1354) has recently gained increasing recognition and use. The E906 and E1354 tests are dynamic in that the smoke continuously flows out the exhaust pipe where the optical density is measured continuously. The appropriate smoke parameter is the smoke release rate (SRR), which is the optical density multiplied by the volume flow rate of air into the exhaust pipe and divided by the product of exposed surface area of the specimen and the light path length. Often the smoke extinction area, which is the product of SRR and the specimen area, is preferred because it can be correlated linearly with HRR in many cases. This also permits comparison with the smoke measured in the room/corner fire test because HRR is a readily available test result. Although SRR can be integrated with time to get the same units as the specific optical density, they are not equivalent because static tests involve the direct accumulation of smoke in a volume, whereas SRR involves accumulation of freshly entrained air volume flow for each unit of smoke. Methods investigated to correlate smoke between different tests included alternative parameters such as particulate mass emitted per area of exposed sample.

Toxicity of combustion products is an area of concern. About 75% to 80% of fire victims are not touched by flame but die as a result of exposure to smoke, exposure to toxic gases, or oxygen depletion. These life-threatening conditions can result from burning contents, such as furnishings, as well as from the structural materials involved. The toxicity resulting from the thermal decomposition of wood and cellulosic substances is complex because of the wide variety of types of wood smoke. The composition and the concentration of the individual constituents depend on such factors as the fire exposure, the oxygen and moisture present, the species of wood, any treatments or finishes that may have been applied, and other considerations. Toxicity data may be more widely available in the future with the recent adoption of a standard test method (ASTM E1678).

Carbon monoxide is a particularly insidious toxic gas. Small amounts of carbon monoxide are particularly toxic because the hemoglobin in the blood is much more likely to combine with carbon monoxide than with oxygen, even with plenty of breathable oxygen. This poisoning is called carboxyhemoglobin. Recent research has shown that the kind of fires that kill people by toxicity are principally those that reach flashover in a compartment or room some distance from the people. The vast majority of fires that attain flashover generate dangerous levels of carbon monoxide, independent of what is burning. The supertoxicants, such as hydrogen cyanide and neurotoxin, have been proven to be extremely rare, even in the laboratory. These factors impact the choice of test furnace and the adjustment methods used in a standardized toxicity test.

Charring and Fire Resistance

As noted earlier in this chapter, wood exposed to high temperatures will decompose to provide an insulating layer of char that retards further degradation of the wood. The load-carrying capacity of a structural wood member depends upon its cross-sectional dimensions. Thus, the amount of charring of the cross section is the major factor in the fire endurance of structural wood members.

When wood is first exposed to fire, the wood chars and eventually flames. Ignition occurs in about 2 min under the standard ASTM E119 fire-test exposures. Charring into the depth of the wood then proceeds at a rate of approximately 0.8 mm/min for the next 8 min (or 1.25 min/mm). Thereafter, the char layer has an insulating effect, and the rate decreases to 0.6 mm/min (1.6 min/mm). Considering the initial ignition delay, the fast initial charring, and then the slowing down to a constant rate, the average constant charring rate is about 0.6 mm/min (or 1.5 in/h) (Douglas-fir, 7% moisture content). In the standard fire-resistance test, this linear charring rate is generally assumed for solid wood directly exposed to fire.

There are differences among species associated with their density, anatomy, chemical composition, and permeability. Moisture content is a major factor affecting charring rate. Density relates to the mass needed to be degraded and the thermal properties, which are affected by anatomical features. Charring in the longitudinal grain direction is reportedly double that in the transverse direction, and chemical composition affects the relative thickness of the char layer. Permeability affects the movement of moisture being driven from the wood or that being driven into the wood beneath the char layer. Normally, a simple linear model for charring where t is time (min), C is char rate (min/mm), and x_c is char depth (mm) is assumed:

$$t = Cx_c \tag{17–1}$$

The temperature at the base of the char layer is generally taken to be 300°C or 550°F (288°C). With this temperature criterion, empirical equations for charring rate have been developed. Equations relating charring rate under ASTM E119 fire exposure to density and moisture content are available for Douglas-Fir, Southern Pine, and White Oak. These equations for rates transverse to the grain are

$$C = (0.002269 + 0.00457\mu)\rho + 0.331 \text{ for Douglas Fir} \tag{17–2a}$$

$$C = (0.000461 + 0.00095\mu)\rho + 1.016 \text{ for Southern Pine} \tag{17–2b}$$

$$C = (0.001583 + 0.00318\mu)\rho + 0.594 \text{ for White Oak} \tag{17–2c}$$

where μ is moisture content (fraction of ovendry mass) and ρ is density, dry mass volume at moisture content μ (kg/m^3).

Table 17–4. Charring rate data for selected wood species

		Wood exposed to ASTM E119 exposure[a]				Wood exposed to a constant heat flux[b]					
						Linear charring rate[e] (min/mm)		Thermal penetration depth d[g] (mm)		Average mass loss rate (g/m^2 s)	
Species	Density[c] (kg/m^3)	Char contraction factor[d]	Linear charring rate[e] (min/mm)	Nonlinear charring rate[f] (min/mm$^{1.23}$)	Thermal penetration depth[g] (mm)	18-kW/m^2 heat flux	55-kW/m^2 heat flux	18-kW/m^2 heat flux	55-kW/m^2 heat flux	18-kW/m^2 heat flux	55-kW/m^2 heat flux
Softwoods											
Southern Pine	509	0.60	1.24	0.56	33	2.27	1.17	38	26.5	3.8	8.6
Western redcedar	310	0.83	1.22	0.56	33	—	—	—	—	—	—
Redwood	343	0.86	1.28	0.58	35	1.68	0.98	36.5	24.9	2.9	6.0
Engelmann spruce	425	0.82	1.56	0.70	34	—	—	—	—	—	—
Hardwoods											
Basswood	399	0.52	1.06	0.48	32	1.32	0.76	38.2	22.1	4.5	9.3
Maple, hard	691	0.59	1.46	0.66	31	—	—	—	—	—	—
Oak, red	664	0.70	1.59	0.72	32	2.56	1.38	27.7	27.0	4.1	9.6
Yellow-poplar	504	0.67	1.36	0.61	32	—	—	—	—	—	—

[a]Moisture contents of 8% to 9%.
[b]Charring rate and average mass loss rate obtained using ASTM E906 heat release apparatus. Test durations were 50 to 98 min for 18-kW/m^2 heat flux and 30 to 53 min for 55-kW/m^2 heat flux. Charring rate based on temperature criterion of 300°C and linear model. Mass loss rate based on initial and final weight of sample, which includes moisture driven from the wood. Initial average moisture content of 8% to 9%.
[c]Based on weight and volume of ovendried wood.
[d]Thickness of char layer at end of fire exposure divided by original thickness of charred wood layer (char depth).
[e]Based on temperature criterion of 288°C and linear model.
[f]Based on temperature criterion of 288°C and nonlinear model of Equation (17–3).
[g]As defined in Equation (17–6). Not sensitive to moisture content.

A nonlinear char rate model has been found useful. This alternative model is

$$t = m x_c^{1.23} \quad (17\text{–}3)$$

where m is char rate coefficient (min/mm$^{1.23}$).

Based on data from eight species (Table 17–4), the following equation was developed for the char rate coefficient:

$$m = -0.147 + 0.000564\rho + 1.21\mu + 0.532 f_c \quad (17\text{–}4)$$

where ρ is density, ovendry mass and volume, and f_c is char contraction factor (dimensionless).

The char contraction factor is the thickness of the residual char layer divided by the original thickness of the wood layer that was charred (char depth). Average values for the eight species tested in the development of the equation are listed in Table 17–4.

These equations and data are valid when the member is thick enough to be a semi-infinite slab. For smaller dimensions, the charring rate increases once the temperature has risen above the initial temperature at the center of the member or at the unexposed surface of the panel. As a beam or column chars, the corners become rounded.

Charring rate is also affected by the severity of the fire exposure. Data on charring rates for fire exposures other than ASTM E119 have been limited. Data for exposure to constant temperatures of 538°C, 815°C, and 927°C are available in Schaffer (1967). Data for a constant heat flux are given in Table 17–4.

The temperature at the innermost zone of the char layer is assumed to be 300°C. Because of the low thermal conductivity of wood, the temperature 6 mm inward from the base of the char layer is about 180°C. This steep temperature gradient means the remaining uncharred cross-sectional area of a large wood member remains at a low temperature and can continue to carry a load. Moisture is driven into the wood as charring progresses. A moisture content peak is created inward from the char base. The peak moisture content occurs where the temperature of the wood is about 100°C, which is at about 13 mm from the char base.

Once a quasi-steady-state charring rate has been obtained, the temperature profile beneath the char layer can be expressed as an exponential term or a power term. An equation based on a power term is

$$T = T_i + (300 - T_i)(1 - x/d)^2 \quad (17\text{–}5)$$

where T is temperature (°C), T_i initial temperature (°C), x distance from the char front (mm), and d thermal penetration depth (mm).

In Table 17–4, values for the thermal penetration depth parameter are listed for both the standard fire exposure and the constant heat flux exposure. As with the charring rate, these temperature profiles assume a semi-infinite slab. The equation does not provide for the plateau in temperatures that often occurs at 100°C in moist wood. In addition to these empirical data, there are mechanistic models for estimating the charring rate and temperature profiles. The temperature profile within the remaining wood cross-section can be used with other data to estimate the remaining load-carrying capacity of the uncharred wood during a fire and the residual capacity after a fire.

Flame-Retardant Treatments

To meet building code and standards specifications, lumber and plywood are treated with flame retardants to improve their fire performance. The two general application methods are pressure treating and surface coating.

Fire-Retardant-Treated Wood

To meet the specifications in the building codes and various standards, fire-retardant-treated lumber and plywood is wood that has been pressure treated with chemicals to reduce its flame spread characteristics. Flame-retardant treatment of wood generally improves the fire performance by reducing the amount of flammable volatiles released during fire exposure or by reducing the effective heat of combustion, or both. Both results have the effect of reducing the HRR, particularly during the initial stages of fire, and thus consequently reducing the rate of flame spread over the surface. The wood may then self-extinguish when the primary heat source is removed.

The performance requirement for fire-retardant-treated wood is that its FSI is 25 or less when tested according to the ASTM E84 flame spread test and that it shows no evidence of significant progressive combustion when this 10-min test is continued for an additional 20 min. In addition, it is required that the flame front in the test shall not progress more than 3.2 m beyond the centerline of the burner at any given time during the test. Underwriters Laboratories, Inc., assigns the designation FR–S to products that satisfy these requirements. In applications where the requirement is not for fire-retardant-treated wood but only for Class I or II flame spread, the flame-retardant treatments only need to reduce the FSI to the required level in the ASTM E84 flame spread test (25 for Class I, 75 for Class II). Various laboratories perform fire-performance rating tests on these treated materials and maintain lists of products that meet certain standards.

Fire-retardant-treated wood and plywood are often used for interior finish and trim in rooms, auditoriums, and corridors where codes require materials with low surface flammability. While fire-retardant-treated wood is not considered a noncombustible material, many codes have accepted the use of fire-retardant-treated wood and plywood in fire-resistive and noncombustible construction for the framing of nonload-bearing walls, roof assemblies, and decking. Fire-retardant-treated wood is also used for such special purposes as wood scaffolding and for the frame, rails, and stiles of wood fire doors.

In addition to specifications for flame spread performance, fire-retardant-treated wood for use in certain applications is specified to meet other performance requirements. Wood treated with inorganic flame-retardant salts is usually more hygroscopic than is untreated wood, particularly at high relative humidities. Increases in equilibrium moisture content of this treated wood will depend upon the type of chemical, level of chemical retention, and size and species of wood involved. Applications that involve high humidity will likely require wood with low hygroscopicity. The American Wood Preservers' Association (AWPA) Standards C20 and C27 requirements for low hygroscopicity (Interior Type A treatment) stipulate that the material shall have an equilibrium moisture content of not more than 28% when tested in accordance with ASTM D3201 procedures at 92% relative humidity.

Exterior flame-retardant treatments should be specified whenever the wood is exposed to exterior weathering conditions. The AWPA Standards C20 and C27 also mandate that an exterior type treatment is one that has shown no increase in fire hazard classification after being subjected to the rain test specified in ASTM D2898 as Method A.

For structural applications, information on the fire-retardant-treated wood product needs to be obtained from the treater or chemical supplier. This includes the design modification factors for initial strength properties of the fire-retardant-treated wood, including values for the fasteners. Flame-retardant treatment generally results in reductions in the mechanical properties of wood. Fire-retardant-treated wood is often more brash than untreated wood.

In field applications with elevated temperatures, such as roof sheathings, there is the potential for further losses in strength with time. For such applications in elevated temperatures and high humidity, appropriate design modification factors need to be obtained from the treater or chemical supplier. The AWPA Standards C20 and C27 mandate that fire-retardant-treated wood that will be used in high-temperature applications (Interior Type A High Temperature), such as roof framing and roof sheathing, be strength tested in accordance with ASTM D5664 (lumber) or ASTM D5516 (plywood) or by an equivalent methodology. Some flame-retardant treatments are not acceptable because of thermal degradation of the wood that will occur with time at high temperatures. Screw-withdrawal tests to predict residual in-place strength of fire-retardant-treated plywood roof sheathing have been developed (Winandy and others 1998).

Corrosion of fasteners can be accelerated under conditions of high humidity and in the presence of flame-retardant salts.

For flame-retardant treatments containing inorganic salts, the type of metal and chemical in contact with each other greatly affects the rate of corrosion. Thus, information on proper fasteners also needs to be obtained from the treater or chemical supplier. Other issues that may require contacting the treater or chemical supplier include machinability, gluing characteristics, and paintability.

Flame-retardant treatment of wood does not prevent the wood from decomposing and charring under fire exposure (the rate of fire penetration through treated wood approximates the rate through untreated wood). Fire-retardant-treated wood used in doors and walls can slightly improve fire endurance of these doors and walls. Most of this improvement is associated with the reduction in surface flammability rather than any changes in charring rates.

Flame-Retardant Pressure Treatments

In the impregnation treatments, wood is pressure impregnated with chemical solutions using pressure processes similar to those used for chemical preservative treatments. However, considerably heavier absorptions of chemicals are necessary for flame-retardant protection. Standards C20 and C27 of the AWPA recommend the treating conditions for lumber and plywood. The penetration of the chemicals into the wood depends on the species, wood structure, and moisture content. Since some species are difficult to treat, the degree of impregnation needed to meet the performance requirements for fire-retardant-treated wood may not be possible. One option is to incise the wood prior to treatment to improve the depth of penetration.

Inorganic salts are the most commonly used flame retardants for interior wood products, and their characteristics have been known for more than 50 years. These salts include monoammonium and diammonium phosphate, ammonium sulfate, zinc chloride, sodium tetraborate, and boric acid. Guanylurea phosphate is also used. These chemicals are combined in formulations to develop optimum fire performance yet still retain acceptable hygroscopicity, strength, corrosivity, machinability, surface appearance, glueability, and paintability. Cost is also a factor in these formulations. Many commercial formulations are available. The AWPA Standard P17 provides information on formulations of some current proprietary waterborne treatments. The fire-retardant salts are water soluble and are leached out in exterior applications or with repeated washings. Water-insoluble organic flame retardants have been developed to meet the need for leach-resistant systems. Such treatments are also an alternative when a low hygroscopic treatment is needed. These water-insoluble systems include (a) resins polymerized after impregnation into wood and (b) graft polymer flame retardants attached directly to cellulose. An amino resin system based on urea, melamine, dicyandiamide, and related compounds is of the first type.

Flame-Retardant Coatings

For some applications, the alternative method of applying the flame-retardant chemical as a coating to the wood surface may be acceptable. Such commercial coating products are available to reduce the surface flammability characteristics of wood. The two types of coatings are intumescent and nonintumescent. The widely used intumescent coatings "intumesce" to form an expanded low-density film upon exposure to fire. This multicellular carbonaceous film insulates the wood surface below from the high temperatures. Intumescent formulations include a dehydrating agent, a char former, and a blowing agent. Potential dehydrating agents include polyammonium phosphate. Ingredients for the char former include starch, glucose, and dipentaerythritol. Potential blowing agents for the intumescent coatings include urea, melamine, and chlorinate parafins. Nonintumescent coating products include formulations of the water-soluble salts such as diammonium phosphate, ammonium sulfate, and borax.

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