1.1 INTRODUCTION

The purpose of this book is to present the design process for wood structures in a quick and simple way, yet thoroughly enough to cover the analysis and design of the major structural elements. In general, building plans and details are defined by an architect and are usually given to a structural engineer for design of structural elements and to present the design in the form of structural drawings. In this book we take a project-based approach covering the design process that a structural engineer would go through for a typical wood-framed structure.

The intended audience for this book is students taking a course in timber or structural wood design and structural engineers and similarly qualified designers of wood or timber structures looking for a simple and practical guide for design. The reader should have a working knowledge of statics, strength of materials, structural analysis (including truss analysis), and load calculations in accordance with building codes (dead, live, snow, wind, and seismic loads). Design loads are reviewed in Chapter 2. The reader must also have available:


The Project-based Approach

Wood is nature’s most abundant renewable building material and a widely used structural material in the United States, where more than 80% of all buildings are of wood construction. The number of building configurations and design examples that could be presented is unlimited. Some applications of wood in construction include residential buildings, strip malls, offices, hotels, schools and colleges, healthcare and recreation facilities, senior living and retirement homes, and religious buildings. The most common wood structures are residential and multifamily dwellings as well as hotels. Residential structures are usually one to three stories in height, while multifamily and hotel structures can be up to four stories in height. Commercial, industrial, and other structures that have higher occupancy loads and factors of safety are not typically constructed with wood, although wood may be used as a secondary structure, such as a storage mezzanine. The structures that support amusement park rides are mostly built out of wood because of the relatively low maintenance cost of exposed wood structures and its unique ability to resist the repeated cycles of dynamic loading (fatigue) imposed on the structure by the amuse-
ment park rides. The approach taken here is a simplified version of the design process required for each major structural element in a timber structure. In Figures 1.1 and 1.2 we identify the typical structural elements in a wood building. The elements are described in greater detail in the next section.

1.2 TYPICAL STRUCTURAL COMPONENTS OF WOOD BUILDINGS

The majority of wood buildings in the United States are typically platform construction, in which the vertical wall studs are built one story at a time and the floor below provides the platform to build the next level of wall that will in turn support the floor above. The walls usually span vertically between the sole or sill plates at a floor level and the top plates at the floor or roof level above. This is in contrast to the infrequently used balloon-type construction, where the vertical

![Perspective overview of a building section.](image-url)
studs are continuous for the entire height of the building and the floor framing is supported on brackets off the face of the wall studs. The typical structural elements in a wood-framed building system are described below.

**Rafters (Figure 1.3)** These are usually sloped sawn-dimension lumber roof beams spaced at fairly close intervals (e.g., 12, 16, or 24 in.) and carry lighter loads than those carried by the roof trusses, beams, or girders. They are usually supported by roof trusses, ridge beams, hip beams, or walls. The span of rafters is limited in practice to a maximum of 14 to 18 ft. Rafters of varying spans that are supported by hip beams are called jack rafters (see Figure 1.6). Sloped roof rafters with a nonstructural ridge, such as a 1X ridge board, require ceiling tie joists or collar ties to resist the horizontal outward thrust at the exterior walls that is due to gravity loads on the sloped rafters. A rafter-framed roof with ceiling tie joists acts like a three-member truss.

**Joists (Figure 1.4)** These are sawn-lumber floor beams spaced at fairly close intervals of 12, 16, or 24 in. that support the roof or floor deck. They support lighter loads than do floor beams or girders. Joists are typically supported by floor beams, walls, or girders. The spans are usually limited in practice to about 14 to 18 ft. Spans greater than 20 ft usually require the use of preengineered products, such as I-joists or open-web joists, which can vary from 12 to 24 in. in depth. Floor joists can be supported on top of the beams, either in-line or lapped with other joists framing into the beam, or the joist can be supported off the side of the beams using joist hangers. In the former case, the top of the joist does not line up with the top of the beam as it does in the latter case. Lapped joists are used more commonly than in-line joists because of the ease of framing and the fact that lapped joists are not affected by the width (i.e., the smaller dimension) of the supporting beam.
**Double or Triple Joists**  These are two or more sawn lumber joists that are nailed together to act as one composite beam. They are used to support heavy concentrated loads or the load from a partition wall or a load-bearing wall running parallel to the span of the floor joists, in addition to the tributary floor loads. They are also used to frame around stair openings (see header and trimmer joists).

**Header and Trimmer Joists**  These are multiple-dimension lumber joists that are nailed together (e.g., double joists) and used to frame around stair openings. The trimmer joists are parallel to the long side of the floor opening and support the floor joists and the wall at the edge of the stair. The header joists support the stair stringer and floor loads and are parallel to the short side of the floor opening.

**Beams and Girders (Figure 1.5)**  These are horizontal elements that support heavier gravity loads than rafters and joists and are used to span longer distances. Wood beams can also be built from several joists nailed together. These members are usually made from beam and stringer...
(B&S) sawn lumber, glued laminated timber (glulam) or parallel strand lumber (PSL), or laminated veneer lumber (LVL).

**Ridge Beams** These are roof beams at the ridge of a roof that support the sloped roof rafters. They are usually supported at their ends on columns or posts (see Figure 1.3).

**Hip and Valley Rafters** These are sloped diagonal roof beams that support sloped jack rafters in roofs with hips or valleys, and support a triangular roof load due to the varying spans of the jack rafters (see Figure 1.6). The hip rafters are simply supported at the exterior wall and on the sloped main rafter at the end of the ridge. The jack or varying span rafters are supported on the hip rafters and the exterior wall. The top of a hip rafter is usually shaped in the form of an inverted V, while the top of a valley rafter is usually V-shaped. Hip and valley rafters are designed like ridge beams.

**Columns or Posts** These are vertical members that resist axial compression loads and may occasionally resist additional bending loads due to lateral wind loads or the eccentricity of the gravity loads on the column. Columns or posts are usually made from post and timber (P&T) sawn lumber or glulam. Sometimes, columns or posts are built up using dimension-sawn lumber. Wood posts may also be used as the chords of shear walls, where they are subjected to axial loads.
tension or compression forces from the overturning effect of the lateral and seismic loads on the building.

**Roof Trusses (Figure 1.7)** These are made up typically of dimension-sawn lumber top and bottom chords and web members that are subject to axial tension or compression plus bending loads. Trusses are usually spaced at not more than 48 in. on centers and are used to span long distances up to 120 ft. The trusses usually span from outside wall to outside wall. Several truss configurations are possible, including the Pratt truss, the Warren truss, the scissor truss, the Fink truss, and the bowstring truss. In building design practice, prefabricated trusses are usually specified, for economic reasons, and these are manufactured and designed by truss manufacturers rather than by the building designer. Prefabricated trusses can also be used for floor framing. These are typically used for spans where sawn lumber is not adequate. The recommended span-to-depth ratios for wood trusses are 8 to 10 for flat or parallel chord trusses, 6 or less for pitched or triangular roof trusses, and 6 to 8 for bowstring trusses [16].

**Wall Studs (Figure 1.8)** These are axially loaded in compression and made of dimension lumber spaced at fairly close intervals (typically, 12, 16, or 24 in.). They are usually subjected to concentric axial compression loads, but exterior stud walls may also be subjected to a combined concentric axial compression load plus bending load due to wind load acting perpendicular to the wall. Wall studs may be subjected to eccentric axial load: for example, in a mezzanine floor with single-story stud and floor joists supported off the narrow face of the stud by joist hangers. Interior wall studs should, in addition to the axial load, be designed for the minimum 5 psf of interior wind pressure specified in the IBC.

Wall studs are usually tied together with plywood sheathing that is nailed to the narrow face of studs. Thus, wall studs are laterally braced by the wall sheathing for buckling about their weak axis (i.e., buckling in the plane of the wall). Stud walls also act together with plywood sheathing as part of the vertical diaphragm or shear wall to resist lateral loads acting parallel to the plane of the wall. **Jack studs** (also called **jamb** or **trimmer studs**) are the studs that support the ends of window or door headers; **king studs** are full-height studs adjacent to the jack studs and **cripple studs** are the stubs or less-than-full-height stud members above or below a window or door opening and are usually supported by header beams. The wall frame consisting of the studs, wall sheathing, top and bottom plates are usually built together as a unit on a flat horizontal surface and then lifted into position in the building.

**Header Beams (Figure 1.7)** These are the beams that frame over door and window openings, supporting the dead load of the wall framing above the door or window opening as well as the dead and live loads from the roof or floor framing above. They are usually supported with beam hangers off the end chords of the shear walls or on top of jack studs adjacent to the shear wall end chords. In addition to supporting gravity loads, these header beams may also act as the chords and drag struts of the horizontal diaphragms in resisting lateral wind or seismic loads. Header beams can be made from sawn lumber, parallel strand lumber, linear veneer lumber, or glued laminated timber, or from built-up dimension
lumber members nailed together. For example, a 2 × 10 double header beam implies a beam with two 2 × 10’s nailed together.

**Overhanging or Cantilever Beams (Figure 1.9)** These beams consist of a back span between two supports and an overhanging or cantilever span beyond the exterior wall support below. They are sometimes used for roof framing to provide a sunshade for the windows and to protect the exterior walls from rain, or in floor framing to provide a balcony. For these types of beams it is more efficient to have the length of the back span be at least three times the length of the overhang or cantilever span. The deflection of the tip of the cantilever or overhang and the uplift force at the back-span end support could be critical for these beams. They have to be designed for unbalanced or skip or pattern live loading to obtain the worst possible load scenario. It should be noted that roof overhangs are particularly susceptible to
large wind uplift forces, especially in hurricane-prone regions.

**Blocking or Bridging** These are usually 2× solid wood members or x-braced wood members spanning between roof or floor beams, joists, or wall studs, providing lateral stability to the beams or joists. They also enable adjacent flexural members to work together as a unit in resisting gravity loads, and help to distribute concentrated loads applied to the floor. They are typically spaced at no more than 8 ft on centers. The bridging (i.e., cross-bracing) in roof trusses is used to prevent lateral-torsional buckling of the truss top and bottom chords.

**Top Plates** These are continuous 2× horizontal flat members located on top of the wall studs at each level. They serve as the chords and drag struts or collectors to resist in-plane bending and direct axial forces due to the lateral loads on the roof and floor diaphragms, and where the spacing of roof trusses rafters or floor joists do not match the stud spacing, they act as flexural members spanning between studs and bending about their weak axis to transfer the truss, rafter or joist reactions to the wall studs. They also help to tie the structure together in the horizontal plane at the roof and floor levels.

**Bottom Plates** These continuous 2× horizontal members or sole plates are located immediately below the wall studs and serve as bearing plates to help distribute the gravity loads from the wall studs. They also help to transfer lateral the loads between the various levels of a shear wall. The bottom plates located on top of the concrete or masonry foundation wall are called sill plates and these are usually pressure treated because of the presence of moisture since they are in direct contact with concrete or masonry. They also serve as bearing plates and help to transfer the lateral base shear from the shear wall into the foundation wall below by means of the sill anchor bolts.

### 1.3 TYPICAL STRUCTURAL SYSTEMS IN WOOD BUILDINGS

The above-grade structure in a typical wood-framed building consists of the following structural systems: roof framing, floor framing, and wall framing.

**Roof Framing**

Several schemes exist for the roof framing layout:

1. Roof trusses spanning in the transverse direction of the building from outside wall to outside wall (Figure 1.10a).

---

**FIGURE 1.10** Roof truss layout: (a) roof truss; (b) vaulted ceiling; (c) rafter and collar tie.
2. Sloped rafters supported by ridge beams and hip or valley beams or exterior walls, used to form cathedral or vaulted ceilings (Figure 1.10b).

3. Sloped rafters with a 1\texttimes{} ridge board at the roof ridge line, supported on the exterior walls by the outward thrust resisted by collar or ceiling ties (Figure 1.10c). The intersecting rafters at the roof ridge level support each other by providing a self-equilibrating horizontal reaction at that level. This horizontal reaction results in an outward thrust at the opposite end of the rafter at the exterior walls, which has to be resisted by the collar or ceiling ties.

4. Wood framing, which involves using purlins, joists, beams, girders, and interior columns to support the roof loads such as in panelized flat roof systems as shown in Figure 1.11. Purlins are small sawn lumber members such as 2 \times{} 4s and 2 \times{} 6s that span between joists, rafter, or roof trusses in panelized roof systems with spans typically in the 8 to 10 ft range, and a spacing of 24 inches.

**Floor Framing**

The options for floor framing basically involve using wood framing members, such as floor joists, beams, girders, interior columns, and interior and exterior stud walls, to support the floor loads. The floor joists are either supported on top of the beams or supported off the side faces of the beams with joist hangers. The floor framing supports the floor sheathing, usually plywood or oriented strand board (OSB), which in turn provides lateral support to the floor framing members and acts as the floor surface, distributing the floor dead and live loads. In addition, the floor sheathing acts as the horizontal diaphragm that transfers the lateral wind and seismic loads to the vertical diaphragms or shear walls. Examples of floor framing layouts are shown in Figure 1.12.

**Wall Framing**

Wall framing in wood-framed buildings consists of repetitive vertical 2 \times{} 4 or 2 \times{} 6 wall studs spaced at 16 or 24 in. on centers, with plywood or OSB attached to the outside face of the
wall. It also consists of a top plate at the top of the wall, a sole or sill plate at the bottom of the wall, and header beams supporting loads over door and window openings. These walls support gravity loads from the roof and floor framing and resist lateral wind loads perpendicular to the face of the wall as well as acting as a shear wall to resist lateral wind or seismic loads in the plane of the wall. It may be necessary to attach sheathing to both the interior and exterior faces of the wall studs to achieve greater shear capacity in the shearwall. Occasionally, diagonal let-in bracing is used to resist lateral loads in lieu of structural sheathing, but this is not common (see Figure 1.13). A typical wall section is shown in Figure 1.14 (see also Figure 1.8).

**Shear Walls in Wood Buildings**

The lateral wind and seismic forces acting on wood buildings result in sliding, overturning, and racking of a building, as illustrated in Figure 1.15. Sliding of a building is resisted by the friction between the building and the foundation walls, but in practice this friction is neglected.
1.4 WOOD STRUCTURAL PROPERTIES

Wood is a biological material and is one of the oldest structural materials in existence. It is nonhomogeneous and orthotropic, and thus its strength is affected by the direction of load relative to the direction of the grain of the wood, and it is naturally occurring and can be renewed by planting or growing new trees. Since wood is naturally occurring and nonhomogeneous, its structural properties can vary widely, and because wood is a biological material, its strength is highly dependent on environmental conditions. Wood buildings have been known to be very durable, lasting hundreds of years, as evidenced by the many historic wood buildings in the United States. In this chapter we discuss the properties of wood that are of importance to architects and engineers in assessing the strength of wood members and elements.

Wood fibers are composed of small, elongated, round or rectangular tubelike cells (see Figure 1.16) with the cell walls made of cellulose, which gives the wood its load-carrying ability. The cells or fibers are oriented in the longitudinal direction of the tree log and are bound together by a material called lignin, which acts like glue. The chemical composition of wood consists of approximately 60% cellulose, 30% lignin, and 12% sugar end extractives. The water in the cell walls is known as bound water, and the water in the cell cavities is known as free water. When wood is subjected to drying or seasoning, it loses all its free water before it begins to lose bound water from the cell walls. It is the bound water, not the free water, that affects the shrinking or swelling of a wood member. The cells or fibers are usually oriented in the vertical direction of the tree. The strength of wood depends on the direction of the wood grain. The direction parallel to the tree trunk or longitudinal direction is referred to as the parallel-to-grain direction; the radial and tangential directions are both referred to as the perpendicular-to-grain direction.

Tree Cross Section

There are two main classes of trees: hardwood and softwood. This terminology is not indicative of how strong a tree is because some softwoods are actually stronger than hardwoods. Hardwoods are broad-leaved, whereas softwoods have needlelike leaves and are mostly evergreen. Hardwood

and sill plate anchors are usually provided to resist the sliding force. The overturning moment, which can be resolved into a downward and upward couple of forces, is resisted by the dead weight of the structure and by hold-down anchors at the end chords of the shear walls. Racking of a building is resisted by let-in diagonal braces or by plywood or OSB sheathing nailed to the wall studs acting as a shear wall.

The uplift forces due to upward vertical wind loads (or suction) on the roofs of wood buildings are resisted by the dead weight of the roof and by using toenailing or hurricane or hold-down anchors. These anchors are used to tie the roof rafter or trusses to the wall studs. The uplift forces must be traced all the way down to the foundation. If a net uplift force exists in the wall studs at the ground-floor level, the sill plate anchors must be embedded deep enough into the foundation wall or grade beam to resist this uplift force, and the foundation must also be checked to ensure that it has enough dead weight, from its self weight and the weight of soil engaged, to resist the uplift force.
trees take longer to mature and grow than softwoods, are mostly tropical, and are generally more dense than softwoods. Consequently, they are more expensive and used less frequently than softwood lumber or timber in wood building construction in the United States. Softwoods constitute more than 75% of all lumber used in construction in the United States [6], and more than two-thirds of softwood lumber are western woods such as douglas fir-larch and spruce. The rest are eastern woods such as southern pine. Examples of hardwood trees include balsa, oak, birch, and basswood.

A typical tree cross section is shown Figure 1.17. The growth of timber trees is indicated by an annual growth ring added each year to the outer surface of the tree trunk just beneath the bark. The age of a tree can be determined from the number of annual rings in a cross section of the tree log at its base. The tree cross section shows the two main sections of the tree, the sapwood and the heartwood. Sapwood is light in color and may be as strong as heartwood, but it is less resistant to decay. Heartwood is darker and older and more resistant to decay. However, sapwood is lighter and more amenable than heartwood to pressure treatment. Heartwood is darker and functions as a mechanical support for a tree, while sapwood contains living cells for nourishment of the tree.

Advantages and Disadvantages of Wood as a Structural Material

Some advantages of wood as a structural material are as follows:

- Wood is renewable.
- Wood is machinable.
- Wood has a good strength-to-weight ratio.
- Wood will not rust.
- Wood is aesthetically pleasing.

The disadvantages of wood include the following:

- Wood can burn.
- Wood can decay or rot and can be attacked by insects such as termites and marine borers. Moisture and air promote decay and rot in wood.
- Wood holds moisture.
- Wood is susceptible to volumetric instability (i.e., wood shrinks).
- Wood’s properties are highly variable and vary widely between species and even between trees of the same species. There is also variation in strength within the cross section of a tree log.

1.5 FACTORS AFFECTING THE STRENGTH OF WOOD

Several factors that affect the strength of a wood member are discussed in this section: (1) species group, (2) moisture content, (3) duration of loading, (4) size and shape of the wood member, (5) defects, (6) direction of the primary stress with respect to the orientation of the wood grain, and (7) ambient temperature.

Species and Species Group

Structural lumber is produced from several species of trees. Some of the species are grouped together to form a species group, whose members are “grown, harvested and manufactured together.” The NDS code’s tabulated stresses for a species group were derived statistically from the results of a large number of tests to ensure that all the stresses tabulated for all species within a species group are conservative and safe. A species group is a combination of two or more species. For example, Douglas fir-larch is a species group that is obtained from a combination of Douglas fir and western larch species. Hem-fir is a species group that can be obtained from a combination of western hemlock and white fir.

Structural wood members are derived from different stocks of trees, and the choice of wood species for use in design is typically a matter of economics and regional availability. For a given
location, only a few species groups might be readily available. The species groups that have the highest available strengths are Douglas fir-larch and southern pine, also called southern yellow pine. Examples of widely used species groups (i.e., combinations of different wood species) of structural lumber in wood buildings include Douglas fir-larch (DF-L), hem-fir, spruce-pine-fir (SPF), and southern yellow pine (SYP). Each species group has a different set of tabulated design stresses in the NDS-S, and wood species within a particular species group possess similar properties and have the same grading rules.

### Moisture Content

The strength of a wood member is greatly influenced by its moisture content, which is defined as the percentage amount of moisture in a piece of wood. The *fiber saturation point* (FSP) is the moisture content at which the free water (i.e., the water in cell cavities) has been fully dissipated. Below the FSP, which is typically between 25 and 35% moisture content for most wood species, wood starts to shrink by losing water from the cell walls (i.e., the bound water). The *equilibrium moisture content* (EMC), the moisture content at which the moisture in a wood member has come to a balance with that in the surrounding atmosphere, occurs typically at between 10 and 15% moisture content for most wood species in a protected environment. The moisture content in wood can be measured using a hand held moisture meter. As the moisture content increases up to the FSP (the point where all the free water has been dissipated), the wood strength decreases, and as the moisture content decreases below the FSP, the wood strength increases, although this increase may be offset by some strength reduction from the shrinkage of the wood fibers. The moisture content (MC) of a wood member can be calculated as

\[
MC(\%) = \frac{\text{weight of moist wood} - \text{weight of oven-dried wood}}{\text{weight of oven-dried wood}} \times 100%
\]

There are two classifications of wood members based on moisture content: green and dry. *Green lumber* is freshly cut wood and the moisture content can vary from as low as 30% to as high as 200% [6]. *Dry* or *seasoned lumber* is wood with a moisture content no higher than 19% for sawn lumber and less than 16% for glulam (see Table 1.1) Wood can be seasoned by air drying or by kiln drying. Most wood members are used in dry or seasoned conditions where the wood member is protected from excessive moisture. An example of a building where wood will be in a moist or green condition is an exposed bus garage or shed. The effect of the moisture content is taken into account in design by use of the moisture adjustment factor, \(C_{25}\), which is discussed in Chapter 3.

### Seasoning of Lumber

The *seasoning* of lumber, the process of removing moisture from wood to bring the moisture content to an acceptable level, can be achieved through air drying or kiln drying. *Air drying* involves stacking lumber in a covered shed and allowing moisture loss or drying to take place naturally over time due to the presence of air. Fans can be used to accelerate the seasoning process. *Kiln drying* involves placing lumber pieces in an enclosure or kiln at significantly higher temperatures. The kiln temperature has to be strictly controlled to prevent damage to the wood members from seasoning defects such as warp, bow, sweep, twists, or crooks. Seasoned wood is recommended for building construction because of its dimensional stability. The shrinkage that occurs when unseasoned wood is used can lead to problems in the structure as the shape changes.

### Table 1.1 Moisture Content Classifications for Sawn Lumber and Glulam

<table>
<thead>
<tr>
<th>Lumber Classification</th>
<th>Sawn Lumber (MC, %)</th>
<th>Glulam (MC, %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>(\leq 19)</td>
<td>(&lt; 16)</td>
</tr>
<tr>
<td>Green</td>
<td>(&gt; 19)</td>
<td>(\geq 16)</td>
</tr>
</tbody>
</table>
TABLE 1.2 Size Classifications for Sawn Lumber

<table>
<thead>
<tr>
<th>Lumber Classification</th>
<th>Size</th>
</tr>
</thead>
</table>
| Dimension lumber      | Nominal thickness: from 2 to 4 in.  
|                       | Nominal width: ≥2 in. but ≤16 in.  
|                       | Examples: 2 × 4, 2 × 6, 2 × 8, 4 × 14, 4 × 16 |
| Beam and stringer (B&S)| Rectangular cross section  
|                       | Nominal thickness: ≥5 in.  
|                       | Nominal width: ≥2 in. + nominal thickness  
|                       | Examples: 5 × 8, 5 × 10, 6 × 10 |
| Post and timber (P&T)  | Approximately square cross section  
|                       | Nominal thickness: ≥5 in.  
|                       | Nominal width: ≥2 in. + nominal thickness  
|                       | Examples: 5 × 5, 5 × 6, 6 × 6, 6 × 8 |
| Decking               | Nominal thickness: 2 to 4 in.  
|                       | Wide face applied directly in contact with framing  
|                       | Usually, tongue-and-grooved  
|                       | Used as roof or floor sheathing  
|                       | Example: 2 × 12 lumber used in a flatwise direction |

upon drying out. The amount of shrinkage in a wood member varies considerably depending on the direction of the wood grain.

**Duration of Loading**

The longer a load acts on a wood member, the lower the strength of the wood member, and conversely, the shorter the duration, the stronger the wood member. This is because wood is susceptible to creep or the tendency for continuously increasing deflections under constant load because of the continuous loss of water from the wood cells due to drying shrinkage. The effect of load duration is taken into account in design by use of the load duration adjustment factor, $C_{D}$, discussed in Chapter 3.

**Size Classifications of Sawn Lumber**

As the size of a wood member increases, the difference between the actual behavior of the member and the ideal elastic behavior assumed in deriving the design equations becomes more pronounced. For example, as the depth of a flexural member increases, the deviation from the assumed elastic properties increases and the strength of the member decreases. The various size classifications for structural sawn lumber are shown in Table 1.2, and it should be noted that for sawn lumber, the thickness refers to the smaller dimension of the cross section and the width refers to the larger dimension of the cross section. Different design stresses are given in the NDS-S for the various size classifications listed in Table 1.2.

Dimension lumber is typically used for floor joists or roof rafters, and 2 × 8, 2 × 10, and 2 × 12 are the most frequently used floor joist sizes. For light-frame residential construction, dimension lumber is generally used. Beam and stringer lumber is used as floor beams or girders and as door or window headers, and post and timber lumber is used for columns or posts.

**Nominal Dimension versus Actual Size of Sawn Lumber**

Wood members can come in dressed or undressed sizes, but most wood structural members come in dressed form. When rough wood is dressed on two sides, it is denoted as S2S; rough wood that is dressed on all four sides is denoted as S4S. Undressed 2 × 6 S4S lumber has an actual or nominal size of 2 × 6 in., whereas the dressed size is 1 1/2 × 5 1/2 in. (Figure 1.18). The lumber size is usually called out on structural and architectural drawings using the nominal dimensions of the lumber. The reader is reminded that for a sawn lumber cross section, the thickness is the smaller dimension and the width is the larger dimension of the cross section. In this book we assume that all wood is dressed on four sides (i.e., S4S). Section properties for wood members are given in Tables 1A and 1B of NDS-S [2].
Wood Defects

The various categories of defects in wood are natural, conversion, and seasoning defects. The nature, size, and location of defects affect the strength of a wood member because of the stress concentrations that they induce in the member. They also affect the finished appearance of the member. Some examples of natural defects are knots, shakes, splits, and fungal decay. Conversion defects occur due to unsound milling practices, one example being wanes. Seasoning defects result from the effect of uneven or unequal drying shrinkage, examples being various types of warps, such as cups, bows, sweep, crooks, or twists [6–8, 12, 14]. The most common types of defects in wood members are illustrated in Figure 1.19 and include the following:

- **Knots.** These are formed where limbs grow out from a tree stem.
- **Split or check.** This occurs due to separation of the wood fibers at an angle to annual rings and is caused by drying of the wood.
- **Shake.** This occurs due to separation of the wood fibers parallel to the annual rings.
- **Decay.** This is the rotting of wood due to the presence of wood-destroying fungi.
- **Wane.** In this defect the corners or edges of a wood cross section lack wood material or have some of the bark of the tree as part of the cross section. This leads to a reduction in the cross-sectional area of the member which affects the structural capacity of the member.

Defects lead to a reduction in the net cross section, and their presence introduces stress concentrations in the wood member. The amount of strength reduction depends on the size and location of the defect. For example, for an axially loaded tension member, a knot anywhere in the cross section would reduce the tension capacity of the member. On the other hand, a knot at the neutral axis of the beam would not affect the bending strength but may affect the shear strength if it is located near the supports. For visually graded lumber, the grade stamp, which indicates the design stress grade assigned by the grading inspector, takes into account the number and location of defects in that member.

It is recommended that lumber not be cut indiscriminately on site, as this could affect the strength of a member adversely [8]. Let us illustrate with an example. A 20-ft-long piece of 2 × 14 sawn lumber with a knot at the neutral axis at midspan has been delivered to a site to be used as a simply supported beam. The contractor would like to cut this member to use as a joist on a 12-ft span. To avoid reducing the shear strength of the member, it would need to be cut equally at both ends to maintain the relative location of the knot with respect to both ends of the member. Failure to do this would result in lower strength than that assigned by the grading inspector.

Other types of defects include warping and compression or reaction wood. **Warping** results from uneven drying shrinkage of wood, leading the wood member to deviate from the horizontal
or vertical plane. Examples of warping include members with a bow, cup, sweep, or crook. This defect does not affect the strength of the wood member but affects the constructability of the member. For example, if a bowed member is used as a joist or beam, there will be an initial sag or deflection in the member, depending on how it is oriented. This could affect the construction of the floor or roof in which it is used.

*Compression or reaction wood* is caused by a tree that grows abnormally in bent shape due either to natural effects or bending due to the effect of wind and snow loads. In a leaning tree trunk, one side of the tree cross section is subject to combined compression stresses from bending due to the crookedness of the tree trunk and axial load on the cross section from the self-weight of the tree. The wood fibers in the compression zone of the tree trunk will be more brittle and hard and will possess very little tensile strength, due to the existing internal compressive stresses. Compression wood should not be used for structural members.

**Orientation of the Wood Grain**

Wood is an orthotropic material with strengths that vary depending on the direction of the stress applied relative to the grain of the wood. As a result of the tubular nature of wood, three independent directions are present in a wood member: longitudinal, radial, and tangential. The variation in strength in a wood member with the direction of loading can be illustrated by a group of drinking straws glued tightly together. The group of straws will be strongest when the load is applied parallel to the length of the straws (i.e., longitudinal direction); loads applied in any other direction (i.e., radial or tangential) will crush the walls of the straws or pull apart the glue. The longitudinal direction is referred to as the *parallel-to-grain direction*, and the tangential and radial directions are both referred to as the *perpendicular-to-grain direction*. Thus, wood is strongest when the load or stress is applied in a direction parallel to the direction of the wood grain, is weakest when the stress is perpendicular to the direction of the wood grain, and has the least amount of shrinkage in the longitudinal or parallel-to-grain direction. The various axes in a wood member with respect to the grain direction are shown in Figure 1.20.

**Axial or Bending Stress Parallel to the Grain** This is the strongest direction for a wood member, and examples of stresses and loads acting in this direction are illustrated in Figure 1.21a.

**Axial or Bending Stress Perpendicular to the Grain** The strength of wood in compression parallel to the grain is usually stronger than wood in compression perpendicular to the grain (see Figure 1.21b). Wood has zero strength in tension perpendicular to the grain since only the lignin or glue is available to resist this tension force. Consequently, the NDS code does not permit the loading of wood in tension perpendicular to the grain.

**Stress at an Angle to the Grain** This case lies between the parallel-to-grain and perpendicular-to-grain directions and is illustrated in Figure 1.21c.

**Ambient Temperature**

Wood is affected adversely by temperature beyond 100°F. As the ambient temperature rises beyond 100°F, the strength of the wood member decreases. The structural members in most insulated wood buildings have ambient temperatures of less than 100°F.

### 1.6 LUMBER GRADING

Lumber is usually cut from a tree log in the longitudinal direction, and because it is naturally occurring, it has quite variable mechanical and structural properties, even for members cut from the same tree log. Lumber of similar mechanical and structural properties is grouped into a single category known as a *stress grade*. This simplifies the lumber selection process and increases economy. The higher the stress grade, the stronger and more expensive the wood member is. The classification of lumber with regard to strength, usage, and defects according to the grading rules of an approved grading agency is termed *lumber grading*. 
INTRODUCTION: WOOD PROPERTIES, SPECIES, AND GRADES

Types of Grading

The two types of grading systems for structural lumber are visual grading and mechanical grading. The intent is to classify the wood members into various stress grades such as Select Structural, No. 1 and Better, No. 1, No. 2, Utility, and so on. A grade stamp indicating the stress grade and the species or species group is placed on the wood member, in addition to the moisture content, the mill number where the wood was produced, and the responsible grading agency. The grade stamp helps the engineer, architect, and contractor be certain of the quality of the lumber delivered to the site and that it conforms to the contract specifications for the project. Grading rules may vary among grading agencies, but minimum grading requirements are set forth in the American Lumber Product Standard US DOC PS-20 developed by the National Institute for Standards and Technology (NIST). Examples of grading agencies in the United States [2] include the Western Wood Products Association (WWPA), the West Coast Lumber Inspection Bureau (WCLIB), the Northern Softwood Lumber Bureau (NSLB), the Northeastern Lumber Manufacturers Association (NELMA), the Southern Pine Inspection Bureau (SPIB), and the National Lumber Grading Authority (NLGA).

Visual Grading

Visual grading, the oldest and most common grading system, involves visual inspection of wood members by an experienced and certified grader in accordance with established grading...
rules of a grading agency and application of a grade stamp. In visual grading, the lumber quality is reduced by the presence of defects, and the effectiveness of the grading system is very dependent on the experience of the professional grader. Grading agencies usually have certification exams that lumber graders have to take and pass annually to maintain their certification and to ensure accurate and consistent grading of sawn lumber. The stress grade of a wood member decreases as the number of defects increases and as their locations become more critical.

**Machine Stress Rating**

Mechanical grading is a nondestructive grading system that is based on the relationship between the stiffness and deflection of wood members. Each piece of wood is subjected to a nondestructive test in addition to a visual check. The grade stamp on machine-stress-rated (MSR) lumber includes the value of the tabulated bending stress and the pure bending modulus of elasticity. Because of the lower variability of material properties for MSR lumber, it is used in the fabrication of engineered wood products such as parallel strand lumber and laminated veneer lumber. **Machine-evaluated lumber** (MEL) relies on a relatively new grading process that uses a nondestructive x-ray inspection technique to measure density in addition to a visual check. The variability of MEL lumber is even lower than that of MSR lumber.

**Stress Grades**

The various lumber stress grades are listed below in order of decreasing strength. As discussed previously, the higher the stress grade, the higher the cost of the wood member.

- Dense Select Structural
- Select Structural
- No. 1 & Better
- No. 1
- No. 2
- No. 3
- Stud
- Construction
- Standard
- Utility

**Grade Stamps**

The use of a grade stamp on lumber assures the contractor and the engineer of record that the lumber supplied conforms to that specified in the contract documents. Lumber without a grade stamp should not be allowed on site or used in a project. A typical grading stamp on lumber might include the items shown in Figure 1.22.

1.7 SHRINKAGE OF WOOD

Shrinkage in a wood member takes place as moisture is dissipated from the member beyond the fiber saturation point. Wood shrinks as the moisture content decreases from its value at the installation of the member to the equilibrium moisture content, which can be as low as 8–10% in some protected environments. Shrinkage parallel to the grain of a wood member is negligible and much less than shrinkage perpendicular to the grain. Differential shrinkage is usually more critical than uniform shrinkage. Shrinkage effects in lumber can be minimized by using seasoned lumber or lumber with an equilibrium moisture content of 15% or less. To reduce the effects of shrinkage, minimize the use of details that transfer loads perpendicular to the grain. For wood members with two or more rows of bolts perpendicular to the direction of the wood grain, shrinkage across the width of the member causes tension stresses perpendicular to the grain in
the wood member between the bolt holes, which could lead to the splitting of the member parallel to the grain [17]. Shrinkage can also adversely affect the functioning of hold-down anchors in shear walls by causing a gap between the anchor nut and the top of sill plate. As a result, the shear wall has to undergo excessive lateral displacement before the hold-down anchors can be engaged.

The effect of shrinkage on tie-down anchor systems can be minimized by pretensioning the anchors or by using proprietary shrinkage compensating anchor devices. [18] One method that has been used successfully to control the moisture content in wood during construction in order to achieve the required moisture threshold is by using portable heaters to dry the wood continuously during construction [19]. The effect of shrinkage can also be minimized by delaying the installation of architectural finishes to allow time for much of the wood shrinkage to occur. It is important to control shrinkage effects in wood structures by proper detailing and by limiting the change in moisture content of the member to avoid adverse effects on architectural finishes and to prevent the excessive lateral deflection of shear walls, and loosening of connections or splitting of wood members at connections.

The amount of shrinkage across the width or thickness of a wood member or element (i.e., perpendicular to the grain or to the longitudinal direction) is highly variable, but can be estimated using the following equation (adapted from ASTM D1990 [15]):

\[
d_2 = d_1 \left[ \frac{1 - (a - bM_2)/100}{1 - (a - bM_1)/100} \right]
\]

where

- \(d_1\) = initial member thickness or width at the initial moisture content \(M_1\), in.
- \(d_2\) = final member thickness or width at the final moisture content \(M_2\), in.
- \(M_1\) = moisture content at dimension \(d_1\), %
- \(M_2\) = moisture content at dimension \(d_2\), %

The variables \(a\) and \(b\) are obtained from Table 1.3. The total shrinkage of a wood building detail or section is the sum of the shrinkage perpendicular to the grain of each wood member or element in that detail or section; longitudinal shrinkage or the shrinkage parallel to the grain is negligible.

### 1.8 DENSITY OF WOOD

The density of wood is a function of the moisture content of the wood and the weight of the wood substance or cellulose present in a unit volume of wood. Even though the cellulose–lignin combination in wood has a specific gravity of approximately 1.50 and is heavier than water, most wood used in construction floats because of the presence of cavities in the hollow cells of a wood member. The density of wood can vary widely between species, from as low as 20 lb/in\(^3\) to as high as 65 lb/in\(^3\) [2, 6], and the higher the density, the higher the strength of the wood member. An average wood density of 31.2 lb/in\(^3\) is used throughout this book.

### 1.9 UNITS OF MEASUREMENT

The U.S. system of units is used in this book, and accuracy to at most three significant figures is maintained in all the example problems. The standard unit of measurement for lumber in the United States is the board foot (bf), which is defined as the volume of 144 cubic inches of lumber.

### Table 1.3 Shrinkage Parameters

<table>
<thead>
<tr>
<th>Wood Species</th>
<th>Width</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redwood, western red cedar, northern white cedar</td>
<td>3.454</td>
<td>0.157</td>
</tr>
<tr>
<td>Other</td>
<td>6.031</td>
<td>0.215</td>
</tr>
</tbody>
</table>

Source: Ref. 15.
EXAMPLE 1.1
Shrinkage in Wood Members

Determine the total shrinkage across (a) the width and (b) the thickness of two green 2 × 6 Douglas fir-larch top plates loaded perpendicular to the grain as the moisture content decreases from an initial value of 30% to a final value of 15%.

Solution: For 2 × 6 sawn lumber, the actual width \(d_1 = 5.5\) in. and the actual thickness = 1.5 in. The initial moisture content and the final equilibrium moisture content are \(M_1 = 30\) and \(M_2 = 15\), respectively.

(a) **Shrinkage across the width of the two 2 × 6 top plates.** For shrinkage across the width of the top plate, the shrinkage parameters from Table 1.3 are obtained as follows:

\[
\begin{align*}
a &= 6.031 \\
b &= 0.215
\end{align*}
\]

From Equation 1-1, the final width \(d_2\) is given as

\[
d_2 = 5.5 \left[ 1 - \left( \frac{6.031 - (0.215)(15)}{6.031 - (0.215)(30)} \right) \right] = 5.32\, \text{in.}
\]

Thus, the total shrinkage across the width of the two top plates = \(d_1 - d_2 = 5.5\) in. − 5.32 in. = **0.18 in.**

(b) **Shrinkage across the thickness of the two 2 × 6 top plates.** For shrinkage across the thickness of the top plate, the shrinkage parameters from Table 1.3 are:

\[
\begin{align*}
a &= 5.062 \\
b &= 0.181
\end{align*}
\]

The final thickness \(d_2\) of each top plate from Equation 1-1 is given as

\[
d_2 = 1.5 \left[ 1 - \left( \frac{5.062 - (0.181)(15)}{5.062 - (0.181)(30)} \right) \right] = 1.46\, \text{in.}
\]

The total shrinkage across the thickness of the two top plates will be the sum of the shrinkage in each of the individual wood members:

\[
2\, \text{top plates} \times (d_1 - d_2) = (2)(1.5\, \text{in.} - 1.46\, \text{in.}) = 0.08\, \text{in.}
\]

using nominal dimensions. The *Engineering News-Record*, the construction industry leading magazine, publishes the prevailing cost of lumber in the United States and Canada in units of 1000 board feet (Mbf). For example, 2 × 6 lumber that is 18 ft long is equivalent to 18 board feet or 0.018 Mbf. That is,

\[
\frac{(2\, \text{in.})(6\, \text{in.})(18\, \text{ft} \times 12)}{144\, \text{in}^3} = 18\, \text{bf or 0.018 Mbf}
\]

1.10 BUILDING CODES

A building code is a minimum set of regulations adopted by a city or state that governs the design of building structures in that jurisdiction. The primary purpose of a building code is safety, and the intent is that in the worst-case scenario, even though a building is damaged beyond repair, it should stand long enough to enable its occupants to escape to safety. The most widely used building code in the United States is the *International Building Code* (IBC), first released in 2000.
EXAMPLE 1.2  
Shrinkage at Framed Floors

Determine the total shrinkage at each floor level for the typical wall section shown in Figure 1.23 assuming Hem Fir wood species, and the moisture content decreases from an initial value of 19% to a final value of 10%. How much gap should be provided in the plywood wall sheathing to allow for shrinkage?

**FIGURE 1.23** Wood shrinkage at a framed floor.

**Solution:** For a 2 × 6 sawn lumber, the actual thickness is 1.5 in. For a 2 × 12 sawn lumber, the actual width, \( d_1 = 11.25 \) in.

The initial and final moisture contents are \( M_1 = 19 \) and \( M_2 = 10 \)

(a) **Shrinkage across the width of the 2 × 12 continuous blocking.** The shrinkage parameters from Table 1.3 for shrinkage across the width of the 2 × 12 are

\[
\begin{align*}
a &= 6.031, \quad b = 0.215 \\
\end{align*}
\]

From Equation 1-1, the final width \( d_2 \) is given as,

\[
\begin{align*}
d_2 &= 11.25 \left[ \frac{1 - [6.031 - (0.215)(10)]/100}{1 - [6.031 - (0.215)(19)]/100} \right] = 11.03 \text{ in.}
\end{align*}
\]

Thus, the total shrinkage across the width of the 2 × 12 is

\[
\begin{align*}
d_1 - d_2 &= 11.25 \text{ in.} - 11.03 \text{ in.} = 0.22 \text{ in.}
\end{align*}
\]

(b) **Shrinkage across the thickness of the two 2 × 6 top plates and one 2 × 6 sole plate.** The shrinkage parameters from Table 1.3 for shrinkage across the thickness of the 2 × 6 plates are

\[
\begin{align*}
a &= 5.062, \quad b = 0.181 \\
\end{align*}
\]

The final thickness \( d_2 \) of each plate from Equation 1-1 is given as,

\[
\begin{align*}
d_2 &= 1.5 \left[ \frac{1 - [5.062 - (0.181)(10)]/100}{1 - [5.062 - (0.181)(19)]/100} \right] = 1.475 \text{ in.}
\end{align*}
\]

The total shrinkage across the thickness of the two top plates and one sill plate will be the sum of the shrinkage in each of the individual wood member calculated as

\[
3 \text{ plates } \times (d_1 - d_2) = 3(1.5 \text{ in.} - 1.475 \text{ in.}) = 0.075 \text{ in.}
\]
The longitudinal shrinkage or shrinkage parallel to grain in the 2 × 6 studs is negligible. Therefore, the total shrinkage per floor, which is the sum of the shrinkage of all the wood members at the floor level, is

\[ 0.075 \text{ in.} + 0.22 \text{ in.} = 0.3 \text{ in.} \] Therefore, use \( \frac{1}{2} \) in. shrinkage gap.

An adequate shrinkage gap, typically about \( \frac{1}{2} \) in. deep, is provided in the plywood sheathing at each floor level to prevent buckling of the sheathing panels due to shrinkage. It should also be noted that for multi-story wood buildings, the effects of shrinkage are even more pronounced and critical. For example, a five-story building with a typical detail as shown in Figure 1.23 will have a total accumulated vertical shrinkage of approximately five times the value calculated above!

[3]. The IBC contains, among such other things as plumbing and fire safety, up-to-date provisions on the design procedures for wind and seismic loads as well as for other structural loads. The IBC 2006 now references the ASCE 7 load standards [4] for the calculation procedures for all types of structural loads. The load calculations in this book are based on the ASCE 7 standards. In addition, the IBC references the provisions of the various material codes, such as the ACI 318 for concrete, the NDS code for wood, and the AISC code for structural steel. Readers should note that the building code establishes minimum standards that are required to obtain a building permit. Owners of buildings are allowed to exceed these standards if they desire, but this may increase the cost of the building.

**NDS Code and NDS Supplement**

The primary design code for the design of wood structures in United States is the *National Design Specification (NDS) for Wood Construction* [1] published by the American Forest & Paper Association (AF&PA), in addition to the *NDS Supplement* (or NDS-S) [2], which consist of the tables listed in Table 1.4. These NDS-S tables provide design stresses for the various stress grades of a wood member obtained from full-scale tests on thousands of wood specimens. It should be noted that the tabulated design stresses are not necessarily the allowable stresses; to obtain allowable stresses, the NDS-S stresses have to be multiplied by the product of applicable stress adjustment factors. This is discussed further in Chapter 3.

<table>
<thead>
<tr>
<th>NDS-S Table</th>
<th>Applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>4A</td>
<td>Visually graded dimension lumber (all species except southern pine)</td>
</tr>
<tr>
<td>4B</td>
<td>Visually graded southern pine dimension lumber</td>
</tr>
<tr>
<td>4C</td>
<td>Machine or mechanically graded dimension lumber</td>
</tr>
<tr>
<td>4D</td>
<td>Visually graded timbers (5 in. × 5 in. and larger)</td>
</tr>
<tr>
<td>4E</td>
<td>Visually graded decking</td>
</tr>
<tr>
<td>4F</td>
<td>Non–North American visually graded dimension lumber</td>
</tr>
<tr>
<td>5A</td>
<td>Structural glued laminated softwood timber (members stressed primarily in bending)</td>
</tr>
<tr>
<td>5A–Expanded</td>
<td>Structural glued laminated softwood timber combinations (members stressed primarily in bending)</td>
</tr>
<tr>
<td>5B</td>
<td>Structural glued laminated softwood timber (members stressed primarily in axial tension or compression)</td>
</tr>
<tr>
<td>5C</td>
<td>Structural glued laminated hardwood timber (members stressed primarily in bending)</td>
</tr>
<tr>
<td>5D</td>
<td>Structural glued laminated hardwood timber (members stressed primarily in axial tension or compression)</td>
</tr>
</tbody>
</table>
REFERENCES

4. ASCE (2005), Minimum Design Loads for Buildings and Other Structures, American Society of Civil Engineers, Reston, VA.

PROBLEMS

1.1 List the typical structural components of a wood building.
1.2 What is moisture content, and how does it affect the strength of a wood member?
1.3 Define the terms equilibrium moisture content and fiber saturation point.
1.4 Describe the various size classifications for structural lumber, and give two examples of each size classification.
1.5 List and describe factors that affect the strength of a wood member.
1.6 How and why does the duration of loading affect the strength of a wood member?
1.7 What are common defects in a wood member?
1.8 Why does the NDS code not permit the loading of wood in tension perpendicular to the grain?
1.9 Describe the two types of grading systems used for structural lumber. Which is more commonly used?
1.10 Determine the total shrinkage across the width and thickness of a green triple 2 × 4 Douglas fir-larch top plate loaded perpendicular to grain as the moisture content decreases from an initial value of 30% to a final value of 12%.
1.11 Determine the total shrinkage over the height of a two-story building that has the exterior wall cross section shown in Figure 1.24 as the moisture content decreases from an initial value of 25% to a final value of 12%.

1.12 How many board feet are there in a 4 × 16 × 36 ft-long wood member? How many Mbf are in this member? Determine how many pieces of this member would amount to 4.84 Mbf (4840 bf).