

# Wood-Based Composite Materials

## Panel Products, Glued-Laminated Timber, Structural Composite Lumber, and Wood–Nonwood Composite Materials

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The term composite is being used in this chapter to describe any wood material adhesively bonded together. Wood-based composites encompass a range of products, from fiberboard to laminated beams. Wood-based composites are used for a number of nonstructural and structural applications in product lines ranging from panels for interior covering purposes to panels for exterior uses and in furniture and support structures in buildings (Fig. 11–1). Maloney (1986) proposed a classification system to logically categorize the array of wood-based composites. The classification in Table 11-1 reflects the latest product developments.

The basic element for wood-based composites is the fiber, with larger particles composed of many fibers. Elements used in the production of wood-based composites can be made in a variety of sizes and shapes. Typical elements include fibers, particles, flakes, veneers, laminates, or lumber. Figure 11–2 shows the variation and relative size of wood elements. Element size and geometry largely dictate the product manufactured and product performance. Performance standards are in place for many conventional wood-based composite products (Table 11–2).

A variety of wood sources are appropriate for use in wood-based composites. Wood with localized defects (such as knots) can often be used effectively in wood-based composites. Reducing wood with defects to wood elements mitigates the influence of these characteristics in the manufactured products. Recovered wood from construction waste or industrial manufacturing processes, and wood derived from small-diameter timber, forest residues, or exotic and invasive species, may also be effectively used in wood-based composites. Because natural wood properties vary among species, between trees of the same species, and between pieces from the same tree, solid wood cannot match composite products in the uniformity and range of properties that can be controlled.

**Table 11–1. Classification of wood-based composites<sup>a</sup>****Veneer-based material**

Plywood  
Laminated veneer lumber (LVL)  
Parallel-strand lumber (PSL)

**Laminates**

Glue-laminated timbers  
Overlaid materials  
Laminated wood–nonwood composites<sup>b</sup>  
Multiwood composites (COM-PLY<sup>c</sup>)

**Composite material**

Fiberboard (low-, medium-, or high-density)  
Cellulosic fiberboard  
Hardboard  
Particleboard  
Waferboard  
Flakeboard  
Oriented strandboard (OSB)  
Laminated strand lumber (LSL)  
Oriented strand lumber (OSL)

**Wood–nonwood composites**

Wood fiber–polymer composites  
Inorganic-bonded composites

<sup>a</sup>Adapted from Maloney (1986).

<sup>b</sup>Panels or shaped materials combined with nonwood materials such as metal, plastic, and fiberglass.

<sup>c</sup>Registered trademark of APA–The Engineered Wood Association.

## Scope

This chapter gives an overview of the general types and composition of wood-based composite products and the materials and processes used to manufacture them. It describes conventional wood-based composite panels and structural composite materials intended for general construction, interior use, or both. This chapter also describes wood–nonwood composites. Mechanical properties of these types of composites are presented and discussed in Chapter 12. Because wood-based composites come in a variety of forms, we briefly describe several of the most common commercial products.

This chapter is organized into three sections. The first section covers conventional wood-based composite panels. Materials, adhesives, and additives common to conventional wood-based composites are summarized. Specific products addressed include panel products such as plywood, oriented strandboard, particleboard, and fiberboard. Specialty composites are also discussed. The second section covers structural composite lumber, including glued-laminated timber, laminated veneer lumber, parallel strand lumber, laminated strand lumber, and oriented strand lumber. Wood–nonwood composites are discussed in the third section, including inorganic-bonded composites and wood–thermo-plastic composites. Books have been written about each of



**Figure 11–1. Wood-based composites used in the new Centennial Research Facility at the Forest Products Laboratory. Glulam timbers support composite I-joists and plywood sheathing. (Photo by Steve Schmieding, Forest Products Laboratory.)**

these categories, and the constraints of this chapter necessitate that the discussion be general and brief. References are provided for more detailed information.

## Conventional Wood-Based Composite Panels

Conventional wood-based composites are manufactured products made primarily from wood with only a few percent resin and other additives. A useful way to classify conventional wood-based composites based on specific gravity, density, raw material, and processing methods is shown in Figure 11–3, which presents an overview of the most common types of commercial panel products discussed in this chapter and a quick reference to how these composite materials compare with solid wood from the standpoint of density and general processing considerations. The raw material classifications of fibers, particles, and veneers are shown on the left y-axis. Specific gravity and density are shown on the top and bottom horizontal axes (x-axes), respectively. The right y-axis, wet and dry processes, describes in general terms the processing method used to produce a particular product. Selection of wood elements, adhesives, and processing techniques all contribute to product performance. Figure 11–4 shows examples of some commercial wood-based composites.

### Elements

The primary component of wood-based composites is the wood element, often 94% or more by mass. Common elements for conventional wood-based composites include veneers, strands, particles, and fibers. The physical characteristics of common elements can be seen in Figure 11–5. Properties of composite materials can be changed by changing the size and geometry of the elements and by combining, reorganizing, or stratifying elements.

**Table 11–2. Commercial product or performance standards for wood-based composites**

Product category	Applicable standard	Name of standard	Source
Plywood	PS 1–07	Voluntary product standard PS 1–07 construction and industrial plywood	NIST 2007
	PS 2–04	Voluntary product standard PS 2–04 performance standard for wood-based structural-use panels	NIST 2004
	HP–1–2004	Voluntary product standard HP–1–2004 hardwood and decorative plywood	HPVA 2004
Oriented strandboard (OSB)	PS 2–04	Voluntary product standard PS 2–04 performance standard for wood-based structural-use panels	NIST 2004
Particleboard	ANSI A 208.1–2009	Particleboard standard	CPA 2009a
Fiberboard	ANSI A 208.2–2009	MDF standard	CPA 2009b
	ANSI A 135.4–2004	Basic hardboard	CPA 2004a
	ANSI A 135.5–2004	Pre-finished hardboard paneling	CPA 2004b
	ANSI A 135.6–2006	Hardboard siding	CPA 2006
	ASTM C 208–08a	Cellulosic fiberboard	ASTM 2008c
Glued-laminated timber (glulam)	ANSI/AITC 190.1	American National Standard for Wood Products—structural glued-laminated timber	AITC 2007a
Structural composite lumber (including laminated veneer lumber (LVL), laminated strand lumber (LSL), and parallel strand lumber (PSL))	ASTM D 5456–07	Standard specification for evaluation of structural composite lumber products	ASTM 2008b

## Adhesives

Bonding in most conventional wood-based composites is provided by thermosetting (heat-curing) adhesive resins. Chapter 9 provides a more thorough discussion of thermoset adhesive resins. Commonly used resin–binder systems include phenol-formaldehyde, urea-formaldehyde, melamine-formaldehyde, and isocyanate.

### Phenol-Formaldehyde

Phenol-formaldehyde (PF) resins are typically used in the manufacture of construction plywood and oriented strandboard where exposure to weather during construction is a concern. Other moisture exposure situations, such as temporary weather exposure, occasional plumbing leaks, or wet foot traffic, may also necessitate the use of PF resins. PF resins are commonly referred to as phenolic resins. Phenolic resins are relatively slow-curing compared with other thermosetting resins. In hot-pressed wood-based composites, use of phenolic resin necessitates longer press times and higher press temperatures. Hot-stacking of pressed material shortly after emergence from the press is a fairly common

industrial practice, used to attain adequate resin cure without greatly extending press time. Significant heat exposure associated with pressing of phenolic-bonded composites commonly results in a noticeable reduction in their hygroscopicity. Cured phenolic resins remain chemically stable at elevated temperatures. Their bonds also are sometimes referred to as being “boil-proof” because of their ability to maintain composite dimensional and mechanical properties under wet conditions. The inherently darker color of PF resin compared with other resins may make them aesthetically unsuitable for product applications such as interior paneling and furniture.

### Urea-Formaldehyde

Urea-formaldehyde (UF) resins are typically used in the manufacture of products used in interior applications, primarily particleboard and medium-density fiberboard (MDF), because moisture exposure leads to a breakdown of the bond-forming reactions. Excessive heat exposure will also result in chemical breakdown of cured UF resins, therefore UF-bonded panels are typically cooled after emergence

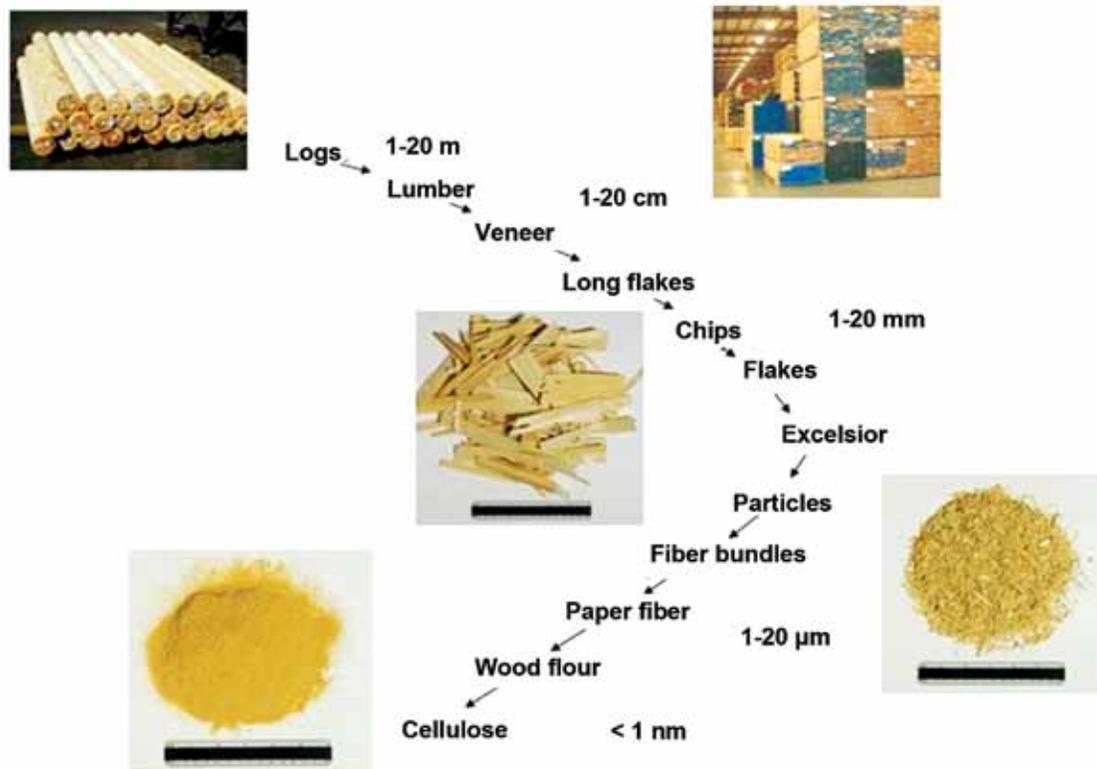


Figure 11–2. Basic wood elements, from largest to smallest (Kretschmann and others 2007).

from the press. Advantages of UF resins include lower curing temperatures than PF resins and ease of use under a variety of curing conditions. UF resins are the lowest cost thermosetting adhesive resins. They offer light color, which often is a requirement in the manufacture of decorative products. However, the release of formaldehyde from products bonded with UF is a growing health concern.

#### Melamine-Formaldehyde

Melamine-formaldehyde (MF) resins are used primarily for decorative laminates, paper treating, and paper coating. They are typically more expensive than PF resins. MF resins may, despite their high cost, be used in bonding conventional wood-based composites. MF resins are often used in combination with UF. MF–UF resins are used when an inconspicuous (light color) adhesive is needed and when greater water resistance than can be attained with UF resin is required.

#### Isocyanates

The isocyanate wood adhesive is a polymeric methylene diisocyanate (pMDI). It is used as an alternative to PF resin, primarily in composite products fabricated from strands. pMDI resins are typically more costly than PF resins but have more rapid cure rates and will tolerate higher moisture contents in the wood source. pMDI resin is sometimes used in core layers of strand-based composites, with slower-curing PF resin used in surface layers. Facilities that use

pMDI are required to take special precautionary protective measures because the uncured resin can result in chemical sensitization of persons exposed to it. Cured pMDI resin poses no recognized health concerns.

#### Bio-Based Adhesives

Bio-based adhesives, primarily protein glues, were widely used prior to the early 1970s in construction plywood. In the mid-1970s, they were supplanted by PF adhesives, on the basis of the superior bond durability provided by phenolics. The move toward “green” products has led to a renewed interest in bio-based adhesives. Several soy-protein-based resin systems, with bond durabilities similar to those provided by PF resins, have recently been developed and commercialized. Durable adhesive systems may also be derived from tannins or from lignin. Tannins are natural phenol compounds that are present in the bark of a number of tree species. The tannins can be extracted from bark, modified, and reacted with formaldehyde to produce an intermediate polymer that is a satisfactory thermosetting adhesive. Lignin-based resins have also been developed from spent pulping liquor, which is generated when wood is pulped for paper or chemical feedstocks. In the manufacture of wet-process fiberboard, lignin, which is an inherent component of lignocellulosic material, is frequently used as binder (Suchsland and Woodson 1986), although “natural” lignin bonding is sometimes augmented with small amounts of PF resin.

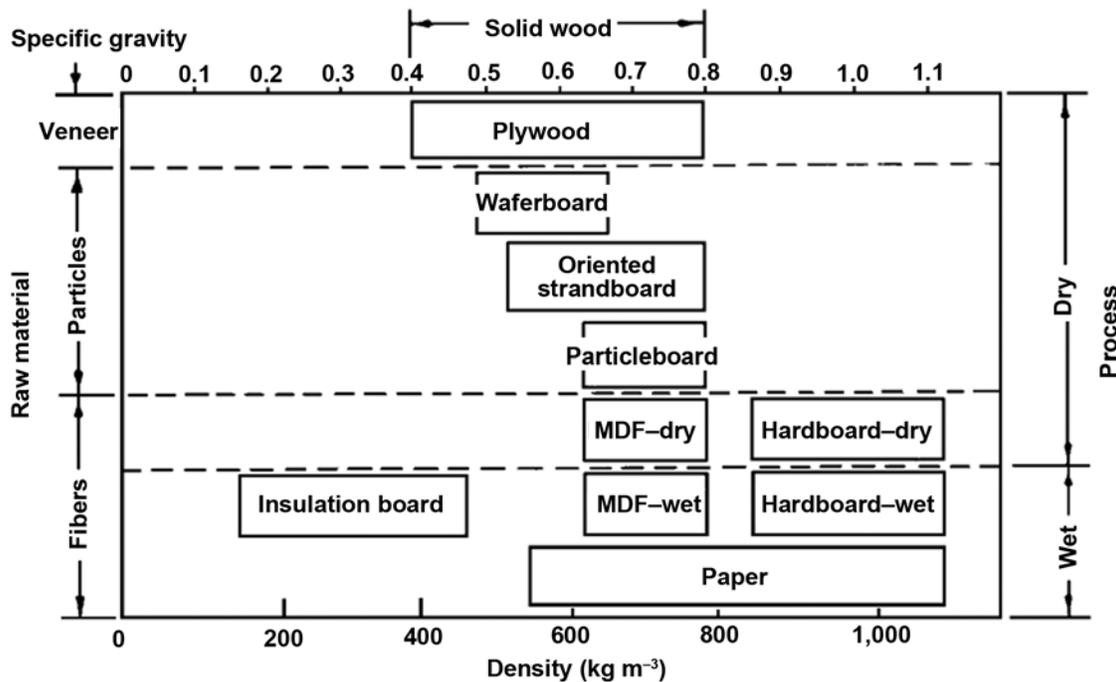


Figure 11–3. Classification of wood composite panels by particle size, density, and process (Suchsland and Woodson 1986). Note that insulation board is now known as cellulosic fiberboard.

### Resin Choice

Often a particular resin will dominate for a particular product, but each has its advantages. Factors taken into account include materials to be bonded together, moisture content at time of bonding, mechanical property and durability requirements of the composite products, anticipated end-use of the product, and resin system costs.

PF, UF, and pMDI resins systems are expected to remain the dominant adhesives used for bonded wood-based composites. However, cost and reliable availability of petrochemicals may affect the relative predominance of PF, UF, and pMDI adhesives versus bio-based adhesives. More stringent regulation concerning emissions from formaldehyde-containing products (driven by concern over indoor air quality) may affect the continued commercial predominance of UF resin in interior products. For example, the California Air Resources Board (CARB) has established formaldehyde emission standards that cover hardwood plywood, particleboard, and MDF. As a result, bio-based adhesive and resin systems may gain market share compared with petroleum-based synthetic resins.

### Additives

A number of additives are used in the production of conventional composite products. The most common additive is wax, which is used to provide products with some resistance to liquid water absorption. In flake-, particle-, and fiberboard products, wax emulsions provide limited-term

water resistance and dimensional stability when the board is wetted. Even small amounts (0.5% to 1%) act to retard the rate of liquid water pickup for limited time periods. These improved short-term water penetration properties are important for ensuring the success of subsequent secondary gluing operations and for providing protection upon accidental wetting of the product during and after construction. The addition of wax has practically no effect on water vapor sorption or dimensional changes associated with changes in humidity. Other additives used for specialty products include preservatives, moldicides, and fire retardants. Composites containing additives are more thoroughly discussed in the section on Specialty Composite Materials.

### Plywood

Plywood is a panel product built up wholly or primarily of sheets of veneer called plies. It is constructed with an odd number of layers with the grain direction of adjacent layers oriented perpendicular to one another. A layer can consist of a single ply or of two or more plies laminated with their grain direction parallel. A panel can contain an odd or even number of plies but always an odd number of layers. The outside plies are called faces, or face and back plies. Inner plies are plies other than the face or back plies. The outer layers and all odd-numbered layers have their grain direction oriented parallel to the long dimension of the panel. The grain in even-numbered layers is perpendicular to the length of the panel. Inner plies whose grain direction runs parallel to that of the faces are termed “centers” whereas inner plies

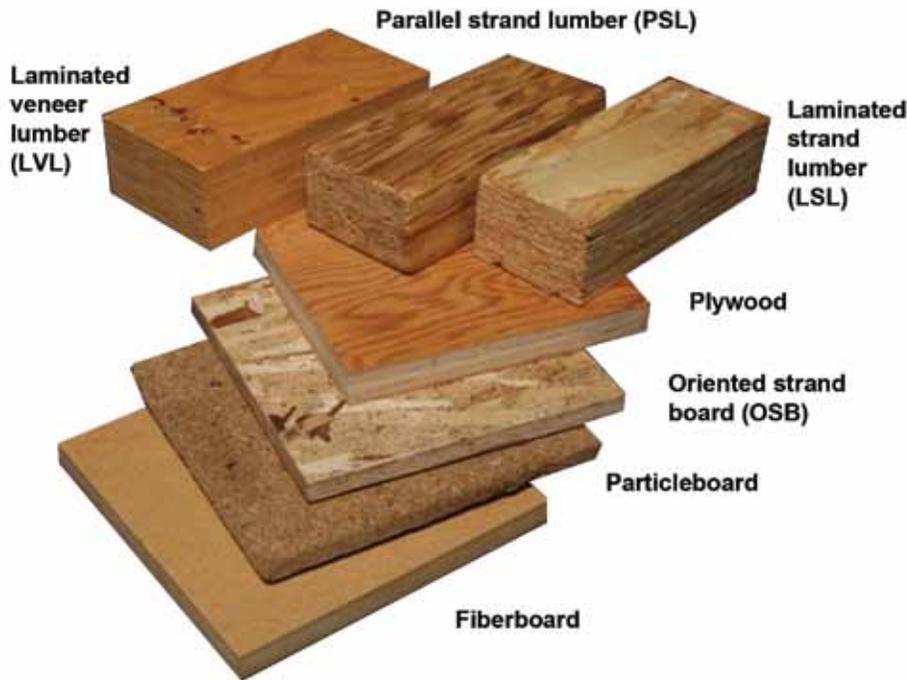


Figure 11–4. Examples of various composite products. From top left, clockwise: LVL, PSL, LSL, plywood, OSB, particleboard, and fiberboard.



Figure 11–5. Common wood elements used in wood-based composites from top left, clockwise: shavings, sawdust, fiber, large particles, wafers, and strands.

whose grain direction runs perpendicular to that of the faces are termed “crossbands.” To distinguish the number of plies (individual sheets of veneer in a panel) from the number of layers (number of times the grain orientation changes), panels are sometimes described as three-ply, three-layer or four-ply, three-layer, etc. The center layer may be veneer, lumber, particleboard, or fiberboard; however, all-veneer construction is most common in construction and industrial plywood.

Plywood panels are used in various applications, including construction sheathing, furniture, and cabinet panels.

Plywood is also used as a component in other engineered wood products and systems in applications such as prefabricated I-joists, box beams, stressed-skin panels, and panelized roofs.

#### Characteristics

The properties of plywood depend on the quality of the veneer plies, the order of layers, the adhesive used, and the degree to which bonding conditions are controlled during production. The durability of the adhesive-to-wood bond depends largely on the adhesive used but also on control of bonding conditions and on veneer quality. The grade of the panel depends upon the quality of the veneers used, particularly of the face and back.

Plywood panels have significant bending strength both along the panel and across the panel, and the differences in strength and stiffness along the panel length versus across the panel are much smaller than those differences in solid wood. Plywood also has excellent dimensional stability along its length and across its width. Minimal edge-swelling makes plywood a good choice for adhesive-bonded tongue-and-groove joints, even where some wetting is expected. Unlike most panels fabricated from particles, it undergoes minimal irreversible thickness swelling if wetted. The alternating grain direction of its layers makes plywood resistant to splitting, allowing fasteners to be placed very near the edges of a panel. In uses where internal knotholes and voids may pose a problem, such as in small pieces, plywood can be ordered with a solid core and face veneers.

### Classes of Plywood

Two classes of plywood are commonly available, covered by separate standards: (a) construction and industrial plywood and (b) hardwood and decorative plywood.

Most construction and industrial plywood used in the United States is produced domestically, and U.S. manufacturers export some material. The bulk of construction and industrial plywood is used where performance is more important than appearance. However, some grades of construction and industrial plywood are made with faces selected primarily for appearance and are used either with clear natural finishes or lightly pigmented finishes. Construction and industrial plywood has traditionally been made from softwoods such as Douglas-fir and southern yellow pine. However, true firs, western hemlock, and western pines are also used (Bowyer and others 2007). A large number of hardwoods qualify for use under the standard. PF resin is the primary adhesive type used in construction and industrial plywood. Construction and industrial plywood is categorized by exposure capability and grade using Voluntary Product Standard PS 1-07 (NIST 2007).

Hardwood and decorative plywood is made of many different species, both in the United States and overseas. Well over half of all panels used in the United States are imported. Hardwood plywood is normally used in applications including decorative wall panels and furniture and cabinet panels where appearance is more important than strength. Most of the production is intended for interior or protected uses, although a very small proportion is made with adhesives suitable for exterior service, such as in marine applications. A substantial portion of all hardwood plywood is available completely finished. Hardwood and decorative plywood is categorized by species and characteristics of face veneer, bond durability, and composition of center layers (veneer, lumber, particleboard, MDF, or hardboard) (HP-1-2004, HPVA 2004).

### Exposure Capability

Construction and industrial plywood is classified as either Exposure 1 or Exterior in Voluntary Product Standard PS 1-07 (NIST 2007). Exposure 1 plywood is intended for applications not permanently exposed to weather, whereas Exterior plywood is suitable for repeated wetting and drying, or long-term exposure to weather. Bond quality of plywood of either bond classification (Exposure 1 or Exterior) is evaluated by the same test procedure, but a higher level of performance in the test procedure is required for Exterior plywood. The test procedure involves water saturation, boiling, and high-temperature exposure (in excess of boiling temperature). The majority of construction and industrial plywood sold in North America is of Exposure 1 classification. Exposure 1 panels may undergo rain-wetting during building construction but will be protected from wetting after the building is enclosed.

Two exposure classes of hardwood and decorative plywood are recognized by ANSI/HPVA HP-1-2004, Exterior and Interior. The standard actually lists two different Exterior classes, Technical and Type I, but the bond performance requirements for these classes, as determined by test procedures outlined in the standard, are the same.

### Plywood Grades

Plywood grades may indicate the intended use, a type of surface treatment, or the grades of the face and back veneers, and in some cases, a combination of these. Agencies that provide quality certification services for plywood mills have coined their own trademarked grade names for specified end uses through proprietary product standards. Grade stamps are used to identify plywood products (Figs. 11-6 and 11-7). An example of plywood CARB third-party identification is also shown in Figure 11-7.

Veneer quality is a factor in construction and industrial plywood based on visually observable characteristics. Knots, decay, splits, insect holes, surface roughness, number of surface repairs, and other defects are considered. Veneer species and characteristics are also a major factor in categorization of hardwood and decorative plywood.

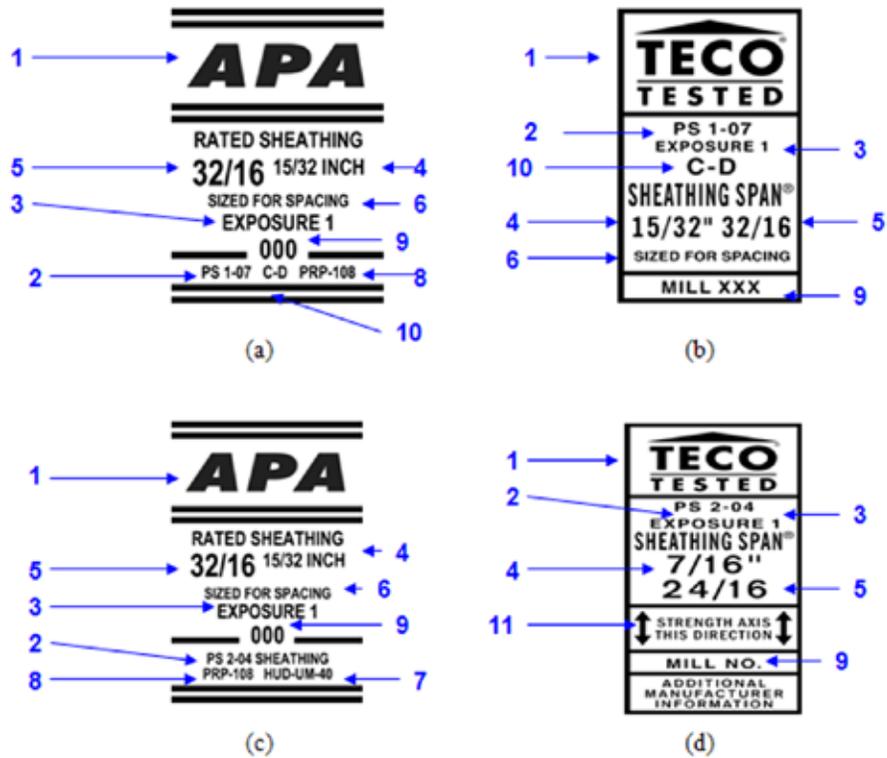
### Specialty Plywood Panels

Plywood is easily pressure-treated with waterborne preservatives and fire retardants. Because plywood is not prone to irreversible thickness swelling, its bond integrity is unaffected by pressure treatment with waterborne chemicals. Treatment is typically performed by commercial entities specializing in treatment rather than by the plywood manufacturer. Treatments for plywood have been standardized (AWPA 2007a,b). This allows specification by reference to a commercial standard. Special grades of plywood are produced for specific uses such as boat construction, concrete form work, or special exterior applications such as highway signage.

### Oriented Strandboard

Oriented strandboard (OSB) is an engineered structural-use panel manufactured from thin wood strands bonded together with water-resistant resin, typically PF or pMDI. It is used extensively for roof, wall, and floor sheathing in residential and commercial construction. The wood strands typically have an aspect ratio (strand length divided by width) of at least 3. OSB panels are usually made up of three layers of strands, the outer faces having longer strands aligned in the long-direction of the panel and a core layer that is counter-aligned or laid randomly using the smaller strands or fines. The orientation of different layers of aligned strands gives OSB its unique characteristics, including greater bending strength and stiffness in the oriented or aligned direction. Control of strand size, orientation, and layered construction allows OSB to be engineered to suit different uses.

OSB technology and the raw material used originally evolved from waferboard technology, for which aspen was



- 1) Third-party inspection agency
- 2) Conformance to indicated product standard
- 3) Exposure durability classification
- 4) Thickness
- 5) Span rating
- 6) Denotes panels that have been sized to allow for spacing of panel edges during installation to reduce the possibility of buckling
- 7) Recognition as a quality assurance agency
- 8) Performance rated panel standard indicating structural-use panel test procedures
- 9) Manufacturing mill identification number
- 10) Grade of face and core veneers
- 11) Strength axis (OSB only)

**Figure 11-6. Typical grade stamps for plywood and OSB. (Courtesy of TECO, Sun Prairie, Wisconsin, and APA-The Engineered Wood Association, Tacoma, Washington. Used by permission.)**

the predominant wood species used. As the industry learned to control strand size, placement, and orientation, the performance and utility of OSB products improved to the point that their performance was similar to that of structural plywood. As a result, product acceptance and the industry expanded as OSB began to replace softwood plywood in construction applications.

### Raw Materials

In North America, aspen is the predominant wood used for OSB. Species other than aspen, such as Southern Pine, spruce, birch, yellow-poplar, sweetgum, sassafras, and beech, are also suitable raw materials for OSB production. High-density species such as beech and birch are often mixed with low-density species such as aspen to maintain panel properties (Bowyer and others 2007).

### Manufacturing Process

To manufacture OSB, debarked logs are sliced into long, thin wood elements called strands. The strands are dried, blended with resin and wax, and formed into thick, loosely consolidated mats that are pressed under heat and pressure into large panels. Figure 11-8 shows an OSB manufacturing process. A more detailed description of each individual manufacturing step follows.

During stranding, logs are debarked and then sent to a soaking pond or directly to the stranding process. Long log disk or ring stranders are commonly used to produce wood strands typically measuring 114 to 152 mm (4.5 to 6 in.) long, 12.7 mm (0.5 in.) wide, and 0.6 to 0.7 mm (0.023 to 0.027 in.) thick. Green strands are stored in wet bins and dried in a traditional triple-pass dryer, a single-pass dryer, a

<p>FORMALDEHYDE EMISSION 0.05 PPM MEETS CARB ATCM PHASE 2 REQUIREMENTS</p> <p>2 →</p> <p>LAY UP 16 3.6 MM THICK HP-SG-96</p> <p>3 ↗</p>	<p>SIMULATED ← 4 DECORATIVE FINISH ON PLYWOOD</p> <p>1 ↙</p>  <p>5 → MILL 000 SPECIALTY GRADE ← 6</p>	<p>FLAME SPREAD CLASS C 200 OR LESS ASTM E84 ← 7</p> <p>BOND LINE TYPE II ← 8 ANSI/HPVA HP-1-2004 ← 9</p>
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**DESIGNATION KEY**

1. **HPVA Laboratory Registered Trademark** - Hardwood Plywood & Veneer Association; CARB TPC-8.
2. **Formaldehyde Emissions Classification** - in accordance with *ASTM E1333 Standard Test Method for Determining Formaldehyde Concentrations in Air and Emissions Rates from Wood Products Using a Large Chamber*. Demonstrates compliance below California Air Resource Board (CARB), U.S. Department of Housing and Urban Development (HUD), and other approved regulations and standards on air emissions
3. **Structural Layup Description** – meets structural panel attributes as outlined in HPVA design guide *HP-SG-96, Structural Design Guide for Hardwood Plywood Wall Panels*
4. **Face Species or Finish Type** (not required for specialty or simulated finishes)
5. **HPVA Mill Number**
6. **Face/Back Veneer Grade** (grade of back follows face for industrial panels and is optional for specialty grade panels)
7. **Flame Spread Index Classification** - in accordance with *ASTM E84 Standard Test Method for Surface Burning Characteristics of Building Materials*
8. **Plywood Bond Line Type** – Type I (interior), Type II (exterior)
9. **ANSI/HPVA HP-1-2004** - Standard Governing Manufacture

**SAMPLE HPVA TPC-8 CARB Certification Label:**

HARDWOOD PLYWOOD & VENEER ASSOCIATION	
 <p>ARB TPC-8 MILL 000</p> <p>COMPANY NAME LOCATION</p> <p>PRODUCT LOT NUMBER:</p>	<p>INDUSTRIAL HARDWOOD PLYWOOD <u>ARB TPC-8 Certified</u></p> <hr/> <p>MEETS CARB ATCM</p> <p>FORMALDEHYDE EMISSIONS PHASE 2 0.05 PPM</p>

Figure 11–7. Typical grade stamps for hardwood plywood. (Courtesy of Hardwood Plywood & Veneer Association, Reston, Virginia. Used by permission.)

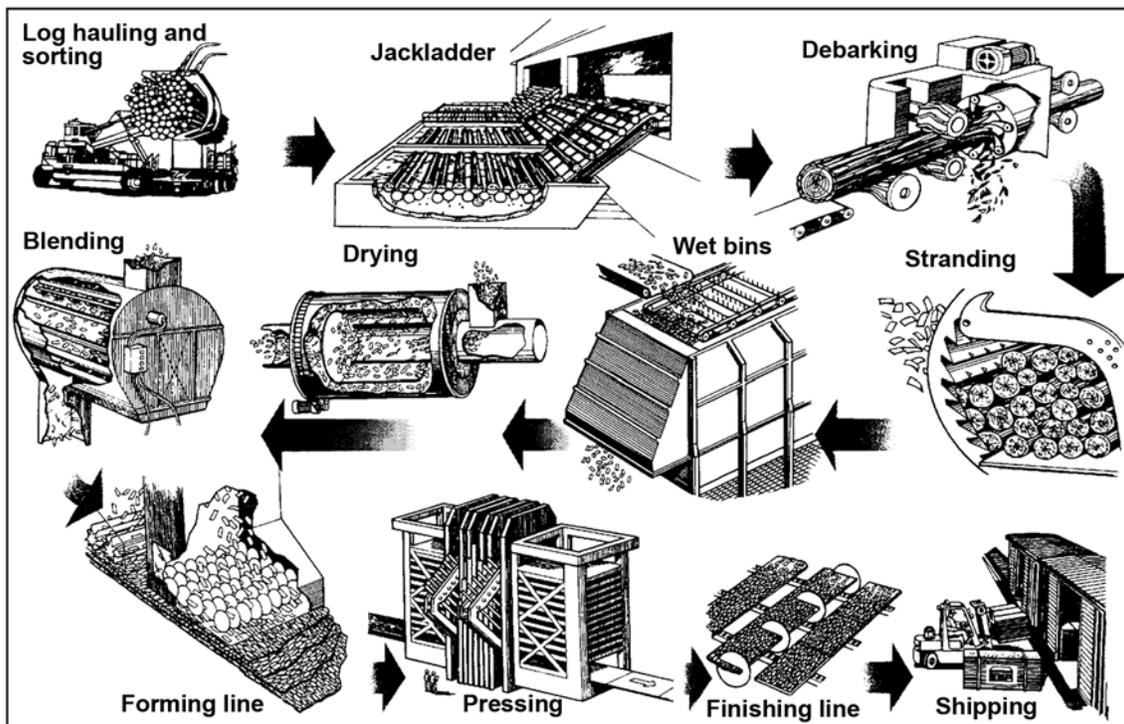


Figure 11-8. Schematic of OSB manufacturing process. (Courtesy of TECO, Sun Prairie, Wisconsin. Used by permission.)

combination triple-pass/single-pass dryer, or a three-section conveyor dryer. A recent development is a continuous chain dryer, in which the strands are laid on a chain mat that is mated with an upper chain mat and the strands are held in place as they move through the dryer. New drying techniques allow the use of longer strands, reducing surface inactivation of strands, and lowering dryer outfeed temperatures. Dried strands are screened and sent to dry bins.

Dried strands are blended with adhesive and wax in a highly controlled operation, with separate rotating blenders used for face and core strands. Typically, different resin formulations are used for face and core layers. Face resins may be liquid or powdered phenolics, whereas core resins may be phenolics or isocyanates. Several different resin application systems are used; spinning disk resin applicators are the most common.

The strands with adhesive applied are sent to mat formers. Mat formers take on a number of configurations, ranging from electrostatic equipment to mechanical devices containing spinning disks to align strands along the panel's length and star-type cross-orienters to position strands across the panel's width. All formers use the long and narrow characteristic of the strand to place it between spinning disks or troughs before it is ejected onto a moving screen or conveyor belt below the forming heads. Oriented layers of strands within the mat are dropped sequentially onto a moving conveyor. The conveyor carries the loose, layered mat into the press.

Once the mat is formed, it is hot-pressed. Hot-pressing consolidates the mat by heating it at 177 to 204 °C (350 to 400 °F), which cures the resin in 3–5 minutes. As many as sixteen 3.7- by 7.3-m (12- by 24-ft) panels may be formed simultaneously in a multiple-opening press. A more recent development is the continuous press which presses the mat between rollers as it is conveyed.

#### OSB Grade Marks and Product Certification

OSB that has been grade marked is manufactured to comply with voluntary industry product performance standards. Inspection or certification programs also generally require that the quality control system of a production plant meet specified criteria. OSB panels conforming to product performance standards are marked with grade stamps (Fig. 11-6).

#### Particleboard

Particleboard is produced by mechanically reducing the wood raw material into small particles, applying adhesive to the particles, and consolidating a loose mat of the particles with heat and pressure into a panel product. The particleboard industry initially used cut flakes as a raw material. However, economic concerns prompted development of the ability to use sawdust, planer shavings, and to a lesser extent, mill residues and other waste materials. To manufacture particleboard with good strength, smooth surfaces, and equal swelling, manufacturers ideally use a homogeneous raw material.

## Chapter 11 Wood-Based Composite Materials

Particleboard is typically made in layers. But unlike OSB, the faces of particleboard usually consist of fine wood particles and the core is made of coarser material. The result is a smoother surface for laminating, overlaying, painting, or veneering. Particleboard is readily made from virtually any wood material and from a variety of agricultural residues. Low-density insulating or sound-absorbing particleboard can be made from kenaf core or jute stick. Low-, medium-, and high-density panels can be produced with cereal straw, which has been used in North America. Rice husks are commercially manufactured into medium- and high-density products in the Middle East.

All other things being equal, reducing lignocellulosic materials to particles requires less energy than reducing the same material into fibers. However, particleboard is generally not as strong as fiberboard because the fibrous nature of lignocellulosics (that is, their high aspect ratio) is not exploited as well. Particleboard is widely used in furniture, where it is typically overlaid with other materials for decorative purposes. It is the predominant material used in ready-to-assemble furniture. Particleboard can also be used in flooring systems, in manufactured houses, and as underlayment. Thin panels can also be used as a paneling substrate. Since most applications are interior, particleboard is usually bonded with a UF resin, although PF and MF resins are sometimes used for applications requiring more moisture resistance.

### Manufacturing Process

Manufacturing particleboard is a dry process. The steps involved in particleboard manufacturing include particle preparation, particle classification and drying, adhesive application, mat formation, pressing, and finishing.

Standard particleboard plants use combinations of hogs, chippers, hammermills, ring flakers, ring mills, and attrition mills to obtain particles. Particles are classified and separated to minimize negative effect on the finished product. Very small particles (fines) increase particle surface area and thus increase resin requirements. Oversized particles can adversely affect the quality of the final product because of internal flaws in the particles. While some particles are classified through the use of air streams, screen classification methods are the most common. In screen classification, the particles are fed over a vibrating flat screen or a series of screens. The screens may be wire cloth, plates with holes or slots, or plates set on edge. Particles are typically conveyed by mechanical means. Sometimes damp conditions are maintained to reduce break-up of particles during conveying.

Desirable particles have a high degree of slenderness (long, thin particles), no oversize particles, no splinters, and no dust. Depending on the manufacturing process and board

configurations, specifications for the ideal particle size are different. For a common three-layer board, core particles are longer and surface particles shorter, thinner, and smaller. For a five-layer board, the particles for the intermediate layer between surface and core are long and thin, which builds a good carrier for the fine surface and gives the boards high bending strength and stiffness. Particleboard used for quality furniture uses much smaller core particles. The tighter core gives a better quality edge which allows particleboard to compete more favorably with MDF.

The raw materials (or furnish) do not usually arrive at the plant at a low enough moisture content for immediate use. Furnish that arrives at the plant can range from 10% to 200% dry basis moisture content. For use with liquid resins, for example, the furnish must be reduced to about 2% to 7% moisture content. The moisture content of particles is critical during hot-pressing operations and depends on whether resin is to be added dry or as a solution or emulsion. The moisture content of materials leaving the dryers is usually in the range of 4% to 8%. The main methods used to dry particles are rotary, disk, and suspension drying. A triple-pass rotary dryer consists of a large horizontal, heated, rotating drum. Operating temperatures depend on the moisture content of the incoming furnish. The drum is set at a slight angle, and material is fed into the high end and discharged at the low end. A series of flights forces the furnish to flow from one end to the other three times before being discharged. The rotary movement of the drum moves the material from input to output.

Frequently used resins for particleboard include UF and, to a much lesser extent, PF, MF, and isocyanates. The type and amount of resin used for particleboard depends on the type of product desired. Based on the weight of dry resin solids and oven-dry weight of the particles, the overall resin content can range between 4% and 10%, but usually ranges between 6% and 9% for UF resins. The resin content of the outer layers is usually higher (about 8% to 15%) than that of the core (about 4% to 8%). UF resin is usually introduced in water solutions containing about 50% to 65% solids. Besides resin, wax is added to improve short-term moisture resistance. The amount of wax ranges from 0.3% to 1% based on the oven-dry weight of the particles.

After the particles have been prepared, they are laid into an even and consistent mat to be pressed into a panel. This is accomplished in batch mode or by continuous formation. The batch system traditionally employs a caul or tray on which a deckle frame is placed. The mat is formed by the back-and-forth movement of a tray or hopper feeder. The production of three-layer boards requires three or more forming stations.

In more common continuous mat-forming systems the particles are distributed in one or several layers on traveling

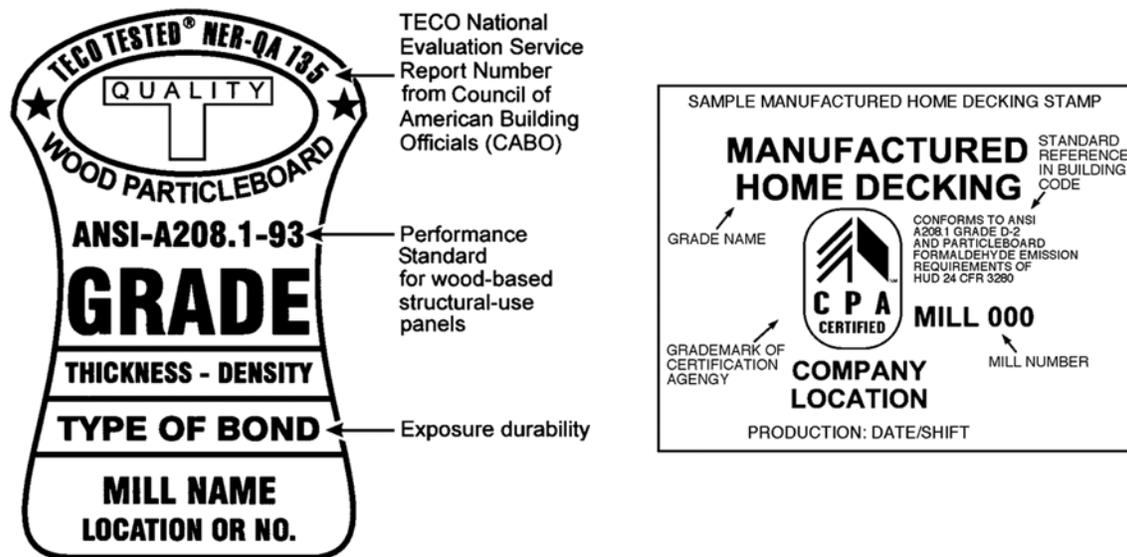


Figure 11-9. Examples of grade stamps for particleboard. (Courtesy of TECO, Sun Prairie, Wisconsin, and Composite Panel Association, Leesburg, Virginia. Used by permission.)

cauls or on a moving belt. Mat thickness is controlled volumetrically. Batch-formed or continuous-formed mats are often pre-pressed to reduce mat height and help consolidate the mat for pressing.

After pre-pressing, the mats are hot-pressed into panels. Presses can be divided into platen and continuous types. Further development in the industry has made possible the construction of presses for producing increasingly larger panel sizes in both single- and multi-opening presses. Both of these types of presses can be as wide as 3.7 m (12 ft). Multi-opening presses can be as long as 10 m (33 ft), and continuous presses, up to 30 m (100 ft) long.

After pressing, panels are trimmed to obtain the desired length and width and to square the edges. Trim losses usually amount to 0.5% to 8%, depending on the size of the panel, the process employed, and the control exercised. Trimmers usually consist of saws with tungsten carbide tips. After trimming, the panels are sanded or planed prior to packaging and shipping. Particleboards may also be veneered or overlaid with other materials to provide a decorative surface, or they may be finished with lacquer or paint. Treatments with fire-resistant chemicals are also available.

#### Particleboard Grade Marks and Product Certification

A grade mark on particleboard ensures that the product has been periodically tested for compliance with voluntary industry product performance standards. Inspection or certification programs also generally require that the quality control system of a production plant meets strict criteria. Particleboard panels conforming to these product performance standards are marked with grade stamps (Fig. 11-9).

#### Fiberboard

The term fiberboard includes hardboard, medium-density fiberboard (MDF), and cellulosic fiberboard. Several things differentiate fiberboard from particleboard, most notably the physical configuration of the wood element. Because wood is fibrous by nature, fiberboard exploits the inherent strength of wood to a greater extent than does particleboard.

To make fibers for composites, bonds between the wood fibers must be broken. Attrition milling, or refining, is the easiest way to accomplish this. During refining, material is fed between two disks with radial grooves. As the material is forced through the preset gap between the disks, it is sheared, cut, and abraded into fibers and fiber bundles. Refiners are available with single- or double-rotating disks, as well as steam-pressurized and unpressurized configurations.

Refining can be augmented by steaming or chemical treatments. Steaming the lignocellulosic weakens the lignin bonds between the cellulosic fibers. As a result, fibers are more readily separated and are usually less damaged than fibers processed by dry processing methods. Chemical treatments, usually alkali, are also used to weaken the lignin bonds. Although treatments help increase fiber quality and reduce energy requirements, they may also reduce yield and modify the fiber chemistry. For MDF, steam-pressurized refining is typical.

Fiberboard is normally classified by density and can be made by either dry or wet processes (Fig. 11-3). Dry processes are applicable to boards with high density (hardboard) and medium density (MDF). Wet processes are applicable to both high-density hardboard and low-density

cellulosic fiberboard. The following subsections briefly describe the manufacturing of high- and medium-density dry-process fiberboard, wet-process hardboard, and wet-process low-density cellulosic fiberboard. Suchsland and Woodson (1986) and Maloney (1993) provide more detailed information.

### Dry-Process Fiberboard

Dry-process fiberboard is made in a similar fashion to particleboard. Resin (UF or MF–UF) and other additives are applied to the fibers by spraying in short-retention blenders or introduced as wet fibers are fed from the refiner into a blow-line dryer. Alternatively, some fiberboard plants add the resin in the refiner. The adhesive-coated fibers are then air-laid into a mat for subsequent pressing, much the same as mat formation for particleboard.

Pressing procedures for dry-process fiberboard differ somewhat from particleboard procedures. After the fiber mat is formed, it is typically pre-pressed in a band press. The densified mat is then trimmed by disk cutters and transferred to caul plates for the hardboard pressing operation; for MDF, the trimmed mat is transferred directly to the press. Many dry-formed boards are pressed in multi-opening presses. Continuous pressing using large, high-pressure band presses is also gaining in popularity. Panel density is constantly monitored by moisture sensors using infrared light as an indicator of panel quality.

MDF is frequently used in place of solid wood, plywood, and particleboard in many furniture applications. It is also used for interior door skins, mouldings, and interior trim components. ANSI A208.2 classifies MDF by physical and mechanical properties, and identifies dimensional tolerances and formaldehyde emission limits (CPA 2009b). An example of an MDF formaldehyde emissions certification tag is shown in Figure 11–10.

### Wet-Process Hardboard

Wet-process hardboards differ from dry-process fiberboards in several significant ways. First, water is used as the fiber distribution medium for mat formation. The technology is really an extension of paper manufacturing technology. Secondly, some wet-process boards are made without additional binders. If the lignocellulosic contains sufficient lignin and if lignin is retained during the refining operation, lignin can serve as the binder. Under heat and pressure, lignin will flow and act as a thermosetting adhesive, enhancing the naturally occurring hydrogen bonds.

Refining is an important step for developing strength in wet-process hardboards. The refining operation must also yield a fiber of high “freeness” (that is, it must be easy to remove water from the fibrous mat). The mat is typically formed on a Fourdrinier wire, like papermaking, or on cylinder formers. The wet process employs a continuously traveling mesh screen, onto which the soupy pulp flows rapidly and

smoothly. Water is drawn off through the screen and then through a series of press rolls.

Wet-process hardboards are pressed in multi-opening presses heated by steam. The press cycle consists of three phases and lasts 6 to 15 min. The first phase is conducted at high pressure, and it removes most of the water while bringing the board to the desired thickness. The primary purpose of the second phase is to remove water vapor. The third phase is relatively short and results in the final cure. A maximum pressure of about 5 MPa (725 lb in<sup>-2</sup>) is used in the first and third phases. Heat is essential during pressing to induce fiber-to-fiber bond. A high temperature of up to 210 °C (410 °F) is used to increase production by causing faster vaporization of the water. Insufficient moisture removal during pressing adversely affects strength and may result in “springback” or blistering.

Wet-formed composite technology has lost market share compared with dry-formed technology over the past few decades because of processing speed and perceived environmental issues related to process water. However, wet-formed technology does offer unique opportunities for forming geometric shapes that yield enhanced structural performance and decrease weight, elimination of fiber drying prior to forming, and reduced need for adhesive resins. It also greatly increases the ability to use recovered paper and some other woody fibers. Recent advances in process wastewater recycling and remediation also bode well for wet-formed technologies. Wet-formed composite technology may become more important because of reduced energy demands, increased composite structural performance and decreased weight, and the virtual elimination of (or drastic reduction in) process water concerns.

Several treatments are used to increase dimensional stability and mechanical performance of hardboard. Heat treatment, tempering, and humidification may be done singularly or in conjunction with one another. Heat treatment—exposure of pressed fiberboard to dry heat—improves dimensional stability and mechanical properties, reduces water adsorption, and improves interfiber bonding. Tempering is the heat treatment of pressed boards, preceded by the addition of oil. Tempering improves board surface hardness, resistance to abrasion, scratching, scarring, and water. The most common oils used include linseed oil, tung oil, and tall oil. Humidification is the addition of moisture to bring the board moisture content to levels roughly equivalent to those anticipated in its end-use environment. Air of high humidity is forced through the stacks where it provides water vapor to the boards. Another method involves spraying water on the back side of the board. Typical hardboard products are prefinished paneling, house siding, floor underlayment, and concrete form board. A typical grade stamp for hardboard siding is shown in Figure 11–11.

Sample Bundle Tag for non-EPP MDF Certified to ANSI A208.2-2009.

**COMPLIES WITH ANSI A208.1-2009 AND  
CALIFORNIA 93120 PHASE 1 FORMALDEHYDE  
EMISSION LIMITS**



**MILL 000**

CALIFORNIA ARB APPROVED THIRD PARTY CERTIFIER TPC-1

**MANUFACTURER'S NAME  
LOCATION  
PRODUCTION SHIFT/CREW  
PRODUCTION LOT/BATCH**

**Figure 11–10. Example of MDF formaldehyde emissions certification tag.  
(Courtesy of Composite Panel Association, Leesburg, Virginia. Used by  
permission.)**

### Cellulosic Fiberboard

Cellulosic fiberboards are low-density, wet-laid panel products. In the manufacture of cellulosic fiberboard, the need for refining and screening is a function of the raw material available, the equipment used, and the desired end-product. Cellulosic fiberboards typically do not use a binder, and they rely on hydrogen bonds to hold the board components together. Sizing agents are usually added to the furnish (about 1%) to provide the finished board with a modest degree of water resistance and dimensional stability.

As in the manufacture of wet-process hardboard, cellulosic fiberboard manufacture is a modification of papermaking. A thick fibrous sheet is made from a low-consistency pulp suspension in a process known as wet felting. Felting can be accomplished through use of a deckle box, Fourdrinier screen, or cylinder screen. A deckle box is a bottomless frame that is placed over a screen. A measured amount of pulp suspension is put in the box and a vacuum is applied to remove most of the water. The use of a Fourdrinier screen for felting is similar to that for papermaking, except that line speeds are reduced to 8 to 18 m min<sup>-1</sup> (25 to 60 ft min<sup>-1</sup>).

Cellulosic fiberboard formed in a deckle box is cold-pressed to remove the free water after the mat is formed. Compression rollers on the Fourdrinier machines squeeze

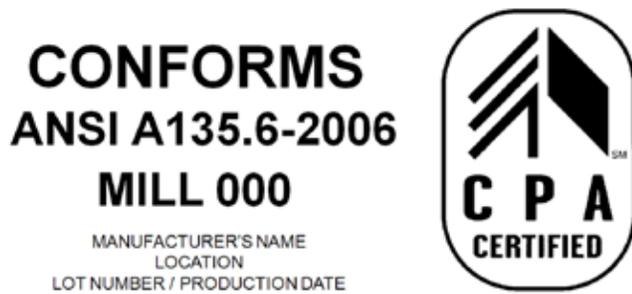
out the free water. The wet mats are then dried to the final moisture content. Dryers may be a continuous tunnel or a multideck arrangement. The board is generally dried in stages at temperatures ranging from 120 to 190 °C (248 to 374 °F). Typically, about 2 to 4 h is required to reduce moisture content to about 1% to 3%.

After drying, some boards are treated for specific applications. Boards may be given tongue-and-groove or shiplap edges or grooved to produce a plank effect. Other boards are laminated by means of asphalt to produce roof insulation.

Cellulosic fiberboard products include sound-deadening board, insulation boards, structural and nonstructural sheathings, backer board, and roof decking in various thicknesses. An example of a grade mark stamp for these cellulosic fiberboard products conforming to ASTM C 208 (ASTM 2008c) is shown in Figure 11–12.

### Finishing Techniques

Several techniques are used to finish fiberboard: trimming, sanding, surface treatment, punching, and embossing. Trimming consists of reducing products into standard sizes and shapes. Generally, double-saw trimmers are used to saw the panels. Trimmers consist of overhead-mounted saws or multiple saw drives. If thickness tolerance is critical, hardboard



**Figure 11–11. Typical grade stamp for hardboard siding. (Courtesy of Composite Panel Association, Leesburg, Virginia. Used by permission.)**



**Figure 11–12. Typical grade stamp for cellulose fiberboard. (Courtesy American Fiberboard Association, Palatine, Illinois. Used by permission.)**

is sanded prior to finishing. S1S (smooth on one side) panels require this process. Sanding reduces thickness variation and improves surface paintability. Single-head, wide-belt sanders are used with 24- to 36-grit abrasive. Surface treatments improve the appearance and performance of boards. Panels are cleaned by spraying with water and then dried at about 240 °C (464 °F) for 30 s. Panel surfaces are then modified with paper overlay, paint, or stain or are printed directly on the panel. Punching changes panels into perforated sheets used as peg board. Embossing consists of pressing the unconsolidated mat of fibers with a textured form. This process results in a slightly contoured panel surface that can enhance the resemblance of the panel to that of sawn or weathered wood, brick, and other materials.

### Specialty Composite Materials

Special-purpose composite materials are produced to obtain enhanced performance properties such as water resistance, mechanical strength, acidity control, and fire, decay, and insect resistance. Overlays and veneers can also be added to enhance both structural properties and appearance (Fig. 11–13).

#### Water-Repellant Composites

Sizing agents are used to increase the water repellency of wood-based composites. Sizing agents cover the surface of fibers, reduce surface energy, and increase fiber hydrophobicity. Sizing agents can be applied in two ways. In the first method, water is used as a medium to ensure thorough mixing of sizing and fiber. The sizing is precipitated from the water and is fixed to the fiber surface. In the second method, the sizing is applied directly to the fibers.

Common sizing agents include rosin, wax, and asphalt. Rosin is obtained from living pine trees, from pine stumps, and as a by-product of kraft pulping of pines. Rosin is added in amounts of less than 3% solids based on dry fiber weight. Waxes are high-molecular-weight hydrocarbons derived from crude oil. Wax is used in solid form in dry-process fiberboard production. For wet processes, wax is added in solid form or as an emulsion. Wax tends to lower strength properties to a greater extent than rosin does. Asphalt is also used to increase water resistance, especially in low-density wet-process cellulosic fiberboard. Asphalt is a black–brown solid or semi-solid material that liquefies when heated. Asphalt is added to the process water as an emulsion and precipitated onto fiber by the addition of alum.

#### Flame-Retardant Composites

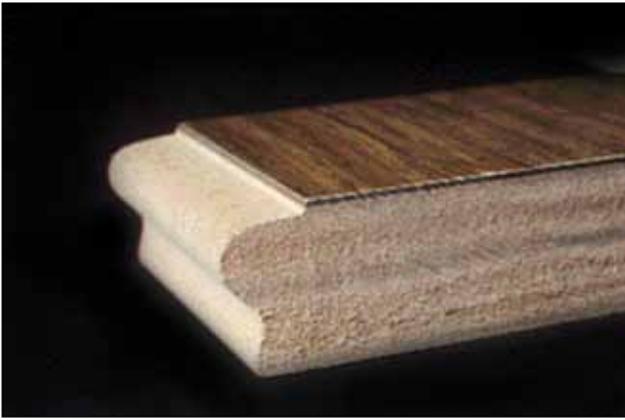
Two general application methods are available for improving the fire performance of composites with fire-retardant chemicals. One method consists of pressure impregnating the wood with waterborne or organic solvent-borne fire retardant chemicals (AWPA 2007a). The second method consists of applying fire-retardant chemical coatings to the wood surface. The pressure impregnation method is usually more effective and longer lasting; however, this technique is standardized only for plywood. It is not generally used with structural flake, particle, or fiber composites, because it can cause swelling that permanently damages the wood–adhesive bonds in the composite and results in the degradation of some physical and mechanical properties of the composite. For wood in existing constructions, surface application of fire-retardant paints or other finishes offers a possible method to reduce flame spread.

#### Preservative-Treated Composites

Composites can be protected from attack by decay fungi and harmful insects by applying selected chemicals as wood preservatives. The degree of protection obtained depends on the kind of preservative used and the ability to achieve proper penetration and retention of the chemicals. Wood preservatives can be applied using pressurized or non-pressurized processes (AWPA 2007b). As in the application of fire-retardant chemicals, the pressurized application of wood preservatives is generally performed after manufacture and is standardized for plywood. Post-manufacture pressurized treatments are not standardized for all types of flake, particle, or fiber composite due to the potential for swelling. Preservatives can be added during the composite manufacturing process, but the preservative must be resistant to vaporization during hot pressing. Proprietary flakeboard and fiberboard products with incorporated nonvolatile preservatives have been commercialized. Common preservative treatments include ammoniacal copper quat (ACQ), copper azol (CA), and boron compounds.

#### Performance and Standards

Standards for conventional wood-based composite products are typically established under a series of internationally



**Figure 11–13. Medium-density fiberboard with veneer overlay. Edges can be shaped and finished as required by end product.**

accredited consensus review processes involving users, producers, and general interests. Then, commercial wood composites are manufactured to conform to these commercial product or performance standards (Table 11–2). These product or performance standards are cited in the International Building Code (IBC) and other similar documents. The IBC is the model building code produced by the International Code Council (ICC), a non-profit organization established in 1994 dedicated to developing a single set of comprehensive and coordinated construction codes. Since the adoption of the first edition of the IBC in 2000, most building codes in the U.S. are based on the IBC. Previously, there were three model code organizations that produced model codes with largely regional acceptance. The ICC also produces the International Residential Code (IRC) and other related model code documents.

The ICC–Evaluation Service (ICC–ES) issues advisory reports on their evaluation of building products, components, methods, and materials for their compliance with the IBC. The ICC–ES was created in 2003 with the merger of the four existing evaluation services. ICC–ES also issues ICC–ES Acceptance Criteria documents for specific types of products that specify the performance criteria and the data that needs to be submitted for the evaluations. These evaluation reports and the acceptance criteria documents are available on the web site of the ICC–ES ([www.icc-es.org](http://www.icc-es.org)).

#### Types of Product Standards

Product standards may be classified as manufacturing standards or performance standards. The best example of a manufacturing method standard is Voluntary Product Standard PS 1–07 for construction and industrial plywood (NIST 2007). Specifications in the standard include which wood species and grades of veneer may be used, what repairs are permissible, and how repairs must be made. Limited performance-based evaluations may also be specified in manufacturing standards for issues relating to adhesive durability and strength.

Standard PS 2–04 (NIST 2004) is a performance-based standard because it applies to all structural-use wood-based panels, including plywood and OSB. This standard includes performance requirements and test methods suitable for a given application (qualification) and also require that properties of a qualified product remain in control during production over time (certification). With respect to plywood, the PS 2–04 standard is not a replacement for PS 1–07, which contains necessary veneer-grade and adhesive-bond requirements as well as lay-up provisions, but it is broad enough to also include many plywood grades not covered under PS 1–07. PS 2–04 specifies that certification be performed by an independent third party.

The American National Standards for particleboard and MDF (ANSI A208.1 and A208.2 respectively) are sponsored by the Composite Panel Association (CPA) in Leesburg, Virginia (CPA 2009a, b). These performance standards require the composite products to show certain minimally acceptable physical and mechanical properties. The test requirements give some indication of product quality, but the tests were not specifically developed to correlate with performance of whole panels in specific end uses.

#### Role of Standards in Construction

Conventional wood-based composite panels and lumber elements manufactured in conformance with product standards (Table 11–2) are approved under the International Building Code. These wood-based composites can be used for construction applications such as sheathing for roofs, sub-flooring, and walls. Similarly, many types of wood-based composite lumber can be used for joists, purlins, stringers, beams, and columns.

Design properties and basic installation guidelines of structural-use panels have become standardized by the ICC. The ICC requires independent third-party certification of these panels, and several such third-party certification agencies exist, such as APA–The Engineered Wood Association ([www.apawood.org](http://www.apawood.org)) and TECO ([www.tecotested.com](http://www.tecotested.com)). These agencies and others offer a variety of technical information on the proper selection, design, and installation of structural-use panels.

Plywood panels conforming to PS 1–07 are marked with grade stamps (Fig. 11–6a,b). Flake-based composites, such as OSB, are usually marketed as conforming to a product standard for sheathing or single-layer sub-flooring or underlayment and are also marked with grade stamps (Fig. 11–6c,d).

Structural-use panels are also span-rated. Span ratings refer to on-center spacing of support members (expressed in inches), with the long panel dimension (in plywood this is the same direction as the face grain) placed across the supports, assuming that there are at least two spans (a minimum of three supports). Span-rating of construction plywood and OSB simplifies materials specification in light-frame

construction by allowing specification without resorting to specific structural engineering design calculations. Panels in PS 2–04 are designated by application (wall, roof, sub-floor, or single floor) and by span rating. Specification by application and span is more convenient for builders than specification by species or species group, veneer grade, and panel thickness. A panel may be suitable for use as either roof sheathing or sub-flooring, with different span ratings for the two applications. Such panels will have a dual span-rating, the first (and larger) number indicating allowable span when used as roof sheathing, the second number indicating the allowable span when used as sub-flooring.

### Glulam Timber

Structural glued-laminated timber (glulam) is one of the oldest glued engineered wood products. Glulam is an engineered, stress-rated product that consists of two or more layers of lumber that are glued together with the grain of all layers, which are referred to as laminations, parallel to the length. Glulam is defined as a material that is made from suitably selected and prepared pieces of wood either in a straight or curved form, with the grain of all pieces essentially parallel to the longitudinal axis of the member. The maximum lamination thickness permitted is 50 mm (2 in.), and the laminations are typically made of standard 25- or 50-mm- (nominal 1- or 2-in.-) thick lumber. North American standards require that glulam be manufactured in an approved manufacturing plant. Because the lumber is joined end to end, edge to edge, and face to face, the size of glulam is limited only by the capabilities of the manufacturing plant and the transportation system.

Douglas Fir–Larch, Southern Pine, Hem–Fir, and Spruce–Pine–Fir (SPF) are commonly used for glulam in the United States. Nearly any species can be used for glulam timber, provided the mechanical and physical properties are suitable and gluing properties acceptable. Industry standards cover many softwoods and hardwoods, and procedures are in place for including other species.

#### Advantages

Compared with sawn timbers as well as other structural materials, glulam has several distinct advantages. These include size capability, architectural effects, seasoning, variation of cross sections, grades, and effect on the environment.

#### Size Capabilities

Glulam offers the possibility of manufacturing structural timbers that are much larger than the trees from which the component lumber was sawn. In the past, the United States had access to large trees that could produce relatively large sawn timbers. However, the present trend is to harvest smaller diameter trees on much shorter rotations, and nearly all new sawmills are built to accommodate relatively small logs. By combining the lumber in glulam, the production of

large structural elements is possible. Straight members up to 30 m (100 ft) long are not uncommon, and some span up to 43 m (140 ft). Sections deeper than 2 m (7 ft) have been used. Thus, glulam offers the potential to produce large timbers from small trees.

#### Architectural Effects

By curving lumber during the manufacturing process, a variety of architectural effects can be obtained with glulam that are impossible or very difficult with other materials (Fig. 11–14). The degree of curvature is controlled by the thickness of the laminations. Thus, glulam with moderate curvature is generally manufactured with standard 19-mm- (nominal 1-in.-) thick lumber. Low curvatures are possible with standard 38-mm (nominal 2-in.) lumber, whereas 13 mm (1/2 in.) or thinner material may be required for very sharp curves. As noted later in this chapter, the radius of curvature is limited to between 100 and 125 times the lamination thickness.

#### Seasoning Advantages

The lumber used in the manufacture of glulam must be seasoned or dried prior to use, so the effects of checking and other drying defects are minimized. This allows design on the basis of seasoned wood, which permits greater design values than can be assigned to unseasoned timber.

#### Varying Cross Sections

Structural elements can be designed with varying cross sections along their length as determined by strength and stiffness requirements. Similarly, arches often have varying cross sections as determined by design requirements.

#### Varying Grades

One major advantage of glulam is that a large quantity of lower grade lumber can be used within the less highly stressed laminations of the beams. Grades are often varied within the beams so that the highest grades are used in the highly stressed laminations near the top and bottom edges, with the lower grades used in the inner section (toward the center) of the beams. Species can also be varied to match the structural requirements of the laminations.

### Types of Glulam Combinations

#### Bending Members

The configuring of various grades of lumber to form a glulam cross section is commonly referred to as a glulam combination. Glulam combinations subjected to flexural loads, called bending combinations, were developed to provide the most efficient and economical section for resisting bending stress caused by loads applied perpendicular to the wide faces of the laminations. This type of glulam is commonly referred to as a horizontally laminated member. Lower grades of laminating lumber are commonly used for the center portion of the combination, or core, where bending stress is low, while a higher grade of material is placed



**Figure 11–14. Erected in 1934 at the Forest Products Laboratory in Madison, Wisconsin, this building is one of the first constructed with glued-laminated timbers arched, designed, and built using engineering principles.**

on the outside faces where bending stress is relatively high. To optimize the bending stiffness of this type of glulam member, equal amounts of high-quality laminations on the outside faces should be included to produce a “balanced” combination. To optimize bending strength, the combination can be “unbalanced” with more high-quality laminations placed on the tension side of the member compared with the quality used on the compression side. For high-quality lumber placed on the tension side of the glulam combination, stringent requirements are placed on knot size, slope of grain, and lumber stiffness.

For compression-side laminations, knot size and slope-of-grain requirements are less stringent and only lumber stiffness is given high priority. In the case where the glulam member is used over continuous supports, the combination would need to be designed as a balanced member for strength and stiffness because of the exposure of both the top and bottom of the beam to tensile stresses. The knot and slope-of-grain requirements for this type of combination are generally applied equally to both the top and bottom laminations.

#### Axial Members

Glulam axial combinations were developed to provide the most efficient and economical section for resisting axial forces and flexural loads applied parallel to the wide faces of the laminations. Members having loads applied parallel to the wide faces of the laminations are commonly referred to as vertically laminated members. Unlike the practice for bending combinations, the same grade of lamination is used throughout the axial combination. Axial combinations may also be loaded perpendicular to the wide face of the

laminations, but the nonselective placement of material often results in a less efficient and less economical member than does the bending combination. As with bending combinations, knot and slope-of-grain requirements apply based on whether the axial member will be used as a tension or compression member.

#### Curved Members

Efficient use of lumber in cross sections of curved glulam combinations is similar to that in cross sections of straight, horizontally laminated combinations. Tension and compression stresses are analyzed as tangential stresses in the curved portion of the member. A unique behavior in these curved members is the formation of radial stresses perpendicular to the wide faces of the laminations. As the radius of curvature of the glulam member decreases, the radial stresses formed in the curved portion of the beam increase. Because of the relatively low strength of lumber in tension perpendicular-to-the-grain compared with tension parallel-to-the-grain, these radial stresses become a critical factor in designing curved glulam combinations. Curved members are commonly manufactured with standard 19- and 38-mm- (nominal 1- and 2-in.-) thick lumber. Naturally, the curvature that is obtainable with the standard 19-mm- (nominal 1-in.-) thick lumber will be sharper than that for the standard 38-mm- (nominal 2-in.-) thick lumber.

#### Tapered Straight Members

Glulam beams are often tapered to meet architectural requirements, provide pitched roofs, facilitate drainage, and lower wall height requirements at the end supports. The taper is achieved by sawing the member across one or more laminations at the desired slope. It is recommended that the taper cut be made only on the compression side of the glulam member, because violating the continuity of the tension-side laminations would decrease the overall strength of the member.

### Standards and Specifications

#### Manufacture

The ANSI/AITC A190.1 standard of the American National Standards Institute (AITC 2007a) contains requirements for the production, testing, and certification of structural glulam timber in the United States. A standard for glulam poles, ANSI O5.2 (ANSI 2006), addresses special requirements for utility uses.

#### Derivation of Design Values

ASTM D 3737 (ASTM 2008a) covers procedures to establish design values for structural glulam timber. Properties considered include bending, tension, compression parallel to grain, modulus of elasticity, horizontal shear, radial tension, and compression perpendicular to grain.

### Design Values and Procedures

Manufacturers of glulam timber have standardized the target design values in bending for beams. For softwoods, these design values are given in AITC 117, “Standard Specifications for Structural Glued-Laminated Timber of Softwood Species” (AITC 2004a). This specification contains design values and recommended modification of stresses for the design of glulam timber members in the United States. A comparable specification for hardwoods is AITC 119, “Standard Specifications for Structural Glued-Laminated Timber of Hardwood Species” (AITC 1996). For additional design information, see the *Timber Construction Manual* (AITC 2004b).

### Manufacture

The manufacture of glulam timber must follow recognized national standards to justify the specified engineering design values. When glulam is properly manufactured, both the quality of the wood and the adhesive bonds should demonstrate a balance in structural performance.

The ANSI/AITC standard A190.1 (AITC 2007a) has a two-phase approach to all phases of manufacturing. First is the qualification phase, in which all equipment and personnel critical to the production of a quality product are thoroughly examined by a third-party agency and the strength of samples of glued joints is determined. In the second phase, after successful qualification, daily quality assurance procedures and criteria are established, which are targeted to keep each of the critical phases of the process under control. An employee is assigned responsibility for supervising the daily testing and inspection. The third-party agency makes unannounced visits to the plants to monitor the manufacturing process and the finished product and to examine the daily records of the quality assurance testing.

The manufacturing process can be divided into four major parts: (a) drying and grading the lumber, (b) end jointing the lumber, (c) face bonding, and (d) finishing and fabrication. In instances where the glulam will be used in high-moisture-content conditions, the member must also be pressure-treated with preservative.

A final critical step in ensuring the quality of glulam is protection of the glulam timber during transit and storage.

### Lumber Drying and Grading

To minimize dimensional changes following manufacture and to take advantage of the increased structural properties assigned to lumber compared with large sawn timbers, the lumber must be properly dried prior to glulam manufacture. This generally means kiln drying. Matching the moisture content of the glulam timber at the time of manufacture to that which it will attain in application minimizes shrinkage and swelling, the main causes of checking. Most manufacturers use a continuous in-line moisture meter to check the

moisture content of each piece of lumber as it enters the manufacturing process. Pieces that have a high moisture level are removed and redried.

Grading standards published by the regional lumber grading associations describe the characteristics that are permitted in various grades of lumber. Manufacturing standards for glulam timber describe the combination of lumber grades necessary for specific design values (AITC 117) (AITC 2004). The rules for visually graded lumber are based entirely upon the characteristics that are readily apparent. The lumber grade description consists of limiting characteristics for knot sizes, slope of grain, wane, and several other characteristics.

Manufacturers generally purchase graded lumber and verify the grades through visual inspection of each piece and, if E-rated, testing of a sample. To qualify the material for some of the higher design stresses for glulam timber, manufacturers must also conduct additional grading for material to be used in the tension zone of certain beams. Another option is to purchase lumber manufactured under a quality assurance system that meets the required tensile strength. Another option practiced by at least one manufacturer has been to use laminated veneer lumber (LVL) to provide the required tensile strength.

### End Jointing

To manufacture glulam timber in lengths beyond those commonly available for lumber, laminations must be made by end jointing lumber to the proper length. The most common end joint, a fingerjoint, is about 28 mm (1.1 in.) long. Other configurations are also acceptable, provided they meet specific strength and durability requirements. The advantages of fingerjoints are that they require only a short length of lumber to manufacture (thus reducing waste) and continuous production equipment is readily available. Well-made joints are critical to ensure adequate performance of glulam timber. Careful control at each stage of the process—determining lumber quality, cutting the joint, applying the adhesive, mating, applying end pressure, and curing—is necessary to produce consistent high strength joints.

### Face Bonding

The assembly of laminations into full-depth members is another critical stage in manufacture. To obtain clear, parallel, and glueable surfaces, laminations must be planed to strict tolerances. The best procedure is to plane the two wide faces of the laminations just prior to the gluing process. This ensures that the final assembly will be rectangular and that the pressure will be applied evenly. Adhesives that have been pre-qualified are then spread, usually with a glue extruder. Phenol resorcinol is the most commonly used adhesive for face gluing, but other adhesives that have been adequately evaluated and proven to meet performance and durability requirements may also be used.

The laminations are then assembled into the required layout; after the adhesive is given the proper open assembly time, pressure is applied. The most common method for applying pressure is with clamping beds; the pressure is applied with either a mechanical or hydraulic system. This results in a batch-type process, and the adhesive is allowed to cure at room temperature from 6 to 24 h. Some newer automated clamping systems include continuous hydraulic presses and radio-frequency curing to shorten the face gluing process from hours to minutes. Upon completion of the face bonding process, the adhesive is expected to have attained 90% or more of its bond strength. During the next few days, curing continues, but at a much slower rate.

The face bonding process is monitored by controls in the lumber planing, adhesive mixing, and adhesive spreading and clamping processes. Performance is evaluated by conducting shear tests on samples cut off as end trim from the finished glulam timber. Thus, the adhesive bonds are expected to develop nearly the full strength of the wood soon after manufacture.

### Finishing and Fabrication

After the glulam timber is removed from the clamping system, the wide faces are planed to remove the adhesive that has squeezed out between adjacent laminations and to smooth out any slight irregularities between the edges of adjacent laminations. As a result, the finished glulam timber is slightly narrower than nominal dimension lumber. The remaining two faces of the member can be lightly planed or sanded.

The appearance requirements of the beam dictate the additional finishing necessary at this point. Historically, three classifications of finishing have been included in the industry standard, AITC 110: Industrial, Architectural, and Premium (AITC 2001). Industrial appearance is generally applicable when appearance is not a primary concern, such as industrial plants and warehouses. Architectural appearance is suitable for most applications where appearance is an important requirement. Premium appearance is the highest classification. The primary difference among these classifications is the amount of knot holes and occasional planer skips that are permitted. A recently introduced classification, called Framing, consists of hit-and-miss planing and permits a significant amount of adhesive to remain on the surface. This finishing is intended for uses that require one member to have the same width as the lumber used in manufacture for framing into walls. These members are often covered in the finished structure.

The next step in the manufacturing process is fabrication, where the final cuts are made, holes are drilled, connectors are added, and a finish or sealer is applied, if specified. For various members, different degrees of prefabrication are done at this point. Trusses may be partially or fully

assembled. Moment splices can be fully fabricated, then disconnected for transportation and erection. End sealers, surface sealers, primer coats, and wrapping with waterproof paper or plastic all help to stabilize the moisture content of the glulam timber between the time it is manufactured and installed. The extent of protection necessary depends upon the end use and must be specified.

### Preservative Treatment

In instances where the moisture content of the finished glulam timber will approach or exceed 20% (in most exterior and some interior uses), the glulam timber should be preservative-treated following AITC 109 (AITC 2007b). Three main types of preservatives are available: creosote, oilborne, and waterborne. Creosote and oilborne preservatives are applied to the finished glulam timbers. Some light oil solvent treatments can be applied to the lumber prior to gluing, but the suitability must be verified with the manufacturer. Waterborne preservatives are best applied to the lumber prior to the laminating and manufacturing process because they can lead to excessive checking if applied to large finished glulam timbers.

## Structural Composite Lumber

Structural composite lumber (SCL) was developed in response to the increasing demand for high-quality lumber at a time when it was becoming difficult to obtain this type of lumber from the forest resource. Structural composite lumber products are characterized by smaller pieces of wood glued together into sizes common for solid-sawn lumber.

One type of SCL product is manufactured by laminating veneer with all plies parallel to the length. This product is called laminated veneer lumber (LVL) and consists of specially graded veneer. Another type of SCL product consists of strands of wood or strips of veneer glued together under high pressures and temperatures. Depending upon the component material, this product is called laminated strand lumber (LSL), parallel strand lumber (PSL), or oriented strand lumber (OSL). These types of SCL products can be manufactured from raw materials, such as aspen or other underutilized species, that are not commonly used for structural applications. Different widths of lumber can be ripped from SCL for various uses. Compared with similar size solid-sawn lumber, SCL often provides a stronger, more reliable structural member that can often span greater distances and has less dimensional change.

Structural composite lumber is a growing segment of the engineered wood products industry. It is used as a replacement for lumber in various applications and in the manufacture of other engineered wood products, such as prefabricated wood I-joists, which take advantage of engineering design values that can be greater than those commonly assigned to sawn lumber.

### Laminated Veneer Lumber

Work in the 1940s on LVL targeted the production of high-strength parts for aircraft structures using Sitka spruce veneer. Research on LVL in the 1970s was aimed at defining the effects of processing variables for veneer up to 12.7 mm (1/2 in.) thick. Since the 1990s, production of LVL uses veneers 3.2 to 2.5 mm (1/8 to 1/10 in.) thick, which are hot pressed with phenol-formaldehyde adhesive into lengths from 2.4 to 18.3 m (8 to 60 ft) or more. Today LVL is commonly used as the flanges in composite I-joists.

Veneer for the manufacture of LVL must be carefully selected for the product to achieve the desired engineering properties. Veneers are often sorted using ultrasonic testing to ensure that the finished product will have the desired engineering properties.

End joints between individual veneers may be staggered along the product to minimize their effect on strength. These end joints may be butt joints, or the veneer ends may overlap for some distance to provide load transfer. Some producers provide structural end joints in the veneers using either scarf or fingerjoints. LVL may also be made in 2.4-m (8-ft) lengths, having no end joints in the veneer; longer pieces are then formed by end-jointing these pieces to create the desired length.

Sheets of LVL are commonly produced in 0.6- to 1.2-m (2- to 4-ft) widths in a thickness of 38 mm (1.5 in.). Continuous presses can be used to form a potentially endless sheet, which is cut to the desired length. Various widths of lumber can be manufactured at the plant or the retail facility.

### Parallel Strand Lumber

Parallel strand lumber (PSL) is defined as a composite of wood strand elements with wood fibers oriented primarily along the length of the member. The least dimension of the strands must not exceed 6.4 mm (0.25 in.), and the average length of the strands must be a minimum of 150 times the least dimension. PSL is a proprietary product, sold as Paral-lam®. It is often used for large beams and columns, typically as a replacement of solid-sawn lumber or glulam.

Parallel strand lumber is manufactured using veneer about 3 mm (1/8 in.) thick, which is then clipped into strands about 19 mm (3/4 in.) wide. These strands are commonly at least 0.6 m (24 in.) long. The manufacturing process was designed to use the material from roundup of the log in the veneer cutting operation as well as other less than full-width veneer (Fig. 11–15). Thus, the process can utilize waste material from a plywood or LVL operation. Species commonly used for PSL include Douglas-fir, southern pines, western hemlock, and yellow-poplar, but there are no restrictions on using other species.

The strands are coated with a waterproof structural adhesive, commonly phenol-resorcinol formaldehyde, and oriented in a press using special equipment to ensure proper

orientation and distribution. The pressing operation results in densification of the material, and the adhesive is cured using microwave technology. Billets larger than those of LVL are commonly produced; a typical size is 0.28 by 0.48 m (11 by 19 in.). This product can then be sawn into smaller pieces, if desired. As with LVL, a continuous press is used so that the length of the product is limited by handling restrictions.

### Laminated Strand Lumber and Oriented Strand Lumber

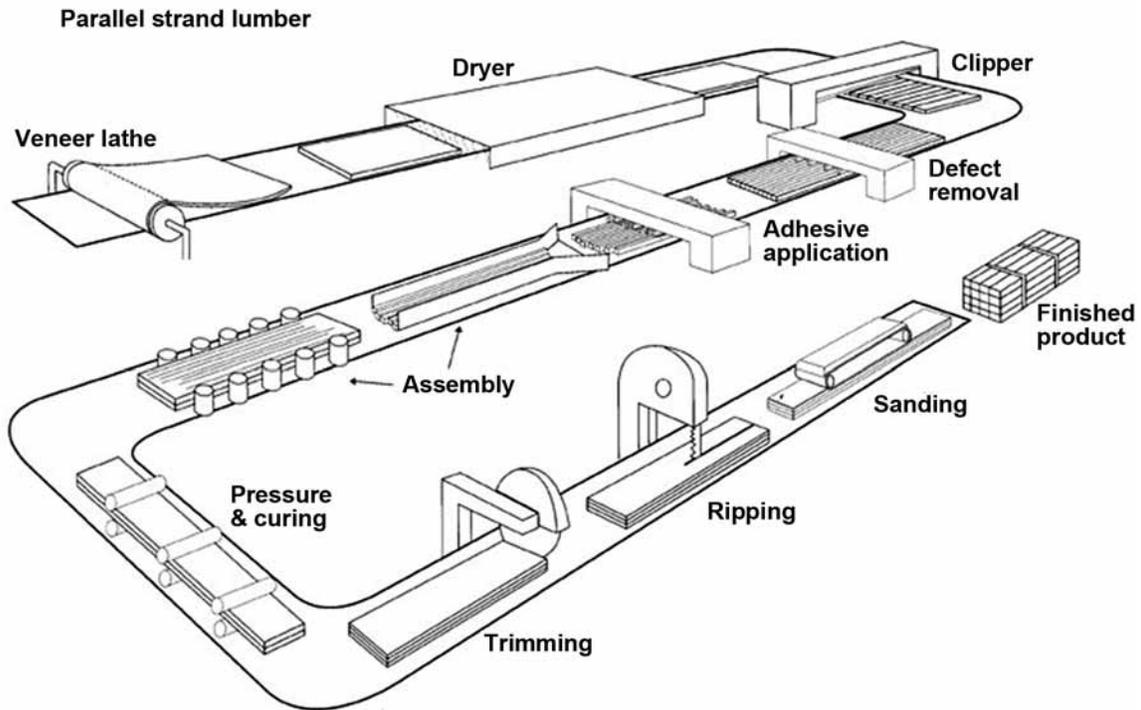
Laminated strand lumber (LSL) and oriented strand lumber (OSL) products are an extension of the technology used to produce oriented strandboard (OSB) structural panels. The products have more similarities than differences. The main difference is that the aspect ratio of strands used in LSL is higher than for OSB (AF&PA 2006). One type of LSL uses strands that are about 0.3 m (12 in.) long, which is somewhat longer than the strands commonly used for OSB. Waterproof adhesives are used in the manufacture of LSL. One type of product uses an isocyanate type of adhesive that is sprayed on the strands and cured by steam injection. This product needs a greater degree of alignment of the strands than does OSB and higher pressures, which result in increased densification. Both LSL and OSL are proprietary products; LSL is sold as TimberStrand®. Applications such as studs and millwork are common.

### Advantages and Uses

In contrast with sawn lumber, the strength-reducing characteristics of SCL are dispersed within the veneer or strands and have much less effect on strength properties. Thus, relatively high design values can be assigned to strength properties for both LVL and PSL. Whereas both LSL and OSL have somewhat lower design values, they have the advantage of being produced from a raw material that need not be in a log size large enough for peeling into veneer. All SCL products are made with structural adhesives and are dependent upon a minimum level of strength in these bonds.

All SCL products are made from veneers or strands that are dried to a moisture content that is slightly less than that for most service conditions. Thus, little change in moisture content will occur in many protected service conditions. When used indoors, this results in a product that is less likely to warp or shrink in service. However, the porous nature of both LVL and PSL means that these products can quickly absorb water unless they are provided with some protection.

All types of SCL products can be substituted for sawn lumber products in many applications. Laminated veneer lumber is used extensively for scaffold planks and in the flanges of prefabricated I-joists, which take advantage of the relatively high design properties. Both LVL and PSL beams are used as headers and major load-carrying elements in construction. The LSL and OSL products are used for band joists in



**Figure 11–15. Generalized process for manufacturing PSL.** (Courtesy of iLevel by Weyerhaeuser, Federal Way, Washington. Used by permission.)

floor construction and as substitutes for studs and rafters in wall and roof construction. Various types of SCL are also used in a number of nonstructural applications, such as the manufacture of windows and doors.

### Standards and Specifications

The ASTM D 5456 (ASTM 2008b) standard provides methods to develop design properties for SCL products as well as requirements for quality assurance during production. Each manufacturer of SCL products is responsible for developing the required information on properties and ensuring that the minimum levels of quality are maintained during production. An independent inspection agency is required to monitor the quality assurance program.

Unlike lumber, no standard grades or design stresses have been established for SCL. Each manufacturer may have unique design properties and procedures. Thus, the designer should consult information provided by the manufacturer.

## Wood–Nonwood Composite Materials

Wood may be combined with inorganic materials and with plastics to produce composite products with unique properties. Wood–nonwood composites typically contain wood elements suspended in a matrix material (for example in fiber-reinforced gypsum board, or in thermoplastic material), in which the proportion of wood elements may account for less than 60% of product mass.

The primary impetus for developing such products has come from one or more of the following research and development goals:

- Develop “green” or “environmentally benign” products with enhanced sustainability.
- Reduce material costs by combining a lower cost material (acting as a filler or extender) with an expensive material.
- Develop products that can utilize recycled materials and be recyclable in themselves.
- Produce composite products that exhibit specific properties that are superior to those of the component materials alone (for example, increased strength-to-weight ratio, improved abrasion resistance, enhance resistance to fire, decay, and insects).

Composites made from wood and other non-wood materials create enormous opportunities to match product performance to end-use requirements. The following discussion includes the most common type of wood–nonwood composites: inorganic-bonded and wood–thermoplastic composites.

### Inorganic-Bonded Composite Materials

Inorganic-bonded wood composites have a long and varied history that started with commercial production in Austria in 1914. They are now used in many countries in the world, mostly in panel form. Applications include panel products, siding, roofing tiles, and precast building members.

## Chapter 11 Wood-Based Composite Materials

Inorganic-bonded wood composites are molded products or boards that contain between 10% and 70% by weight wood particles or fibers and conversely 90% to 30% inorganic binder. Acceptable properties of an inorganic-bonded wood composite can be obtained only when the wood particles are fully encased, and the binder is a continuous matrix material. This differs considerably from conventional wood-based composites, where flakes or particles are “spot welded” by a binder applied as a finely distributed spray or powder. Because of this difference and because hardened inorganic binders have a higher density than most thermosetting resins, the required amount of inorganic binder per unit volume of composite material is much higher than that of resin-bonded wood composites. The properties of inorganic-bonded wood composites are significantly influenced by the amount and type of the inorganic binder and the wood element as well as the density of the composites.

Inorganic-bonded composites include gypsum-bonded, cement-bonded, and ceramic-bonded composites. Magnesia and Portland cement are the most common cement binders. Gypsum and magnesia cement are sensitive to moisture, and their use is generally restricted to interior applications. Composites bonded with Portland cement are more durable than those bonded with gypsum or magnesia cement and are used in both interior and exterior applications. Inorganic-bonded composites are made by blending wood elements with inorganic materials in the presence of water and allowing the inorganic material to cure or “set up” to make a rigid composite. Some inorganic-bonded composites are very resistant to deterioration by decay fungi, insects, and vermin. Most have appreciable fire resistance.

An advantage of inorganic-bonded composites is that their manufacture is adaptable to either end of the cost and technology spectrum. This is facilitated by the fact that no heat is required to cure the inorganic material. This versatility makes inorganic-bonded composites ideally suited to a variety of lignocellulosic materials. With a very small capital investment, satisfactory inorganic-bonded lignocellulosic composite building materials can be produced on a small scale using mostly unskilled labor. If the market for such composites increases, technology can be introduced to increase manufacturing throughput. The labor force can be trained concurrently with the gradual introduction of more sophisticated technology.

### Gypsum-Bonded Composite Materials

Paper-faced gypsum boards have been widely used since the 1950s for the interior lining of walls and ceilings. They are commonly called drywall because they often replaced wet plaster systems. These panels are critical for good fire ratings in walls and ceilings. Paper-faced gypsum boards also find use as exterior wall sheathing. Gypsum sheathing panels are primarily used in commercial construction, usually over steel studding, and are distinguished from gypsum dry-

wall by their water repellent additives in the paper facings and gypsum core. The facings of drywall and of gypsum sheathing panels are adhered to the gypsum core, providing the panels with impact resistance, and bending strength and stiffness. The paper facings of gypsum panels are derived from recycled paper fiber.

An alternative to adhered facings is to incorporate lignocellulosic fiber (typically recycled paper fiber) in the gypsum core to make what are termed fiber-reinforced gypsum panels. In the production process, a paste of gypsum and water is mixed with the recycled paper fiber and extruded into a panel without facings. Shortly after formation, the panel is dried in an oven. Bonding occurs between the gypsum and the fiber as hydrate crystals form.

Fiber-reinforced gypsum panels are typically stronger and more resistant to abrasion and indentation than paper-faced drywall panels and also have a moderate fastener-holding capability. They are marketed for use as interior finish panels (drywall). Additives can provide a moderate degree of water resistance, for use as sheathing panels, floor underlayment, roof underlayment, or tile-backer board.

### Cement-Bonded Composite Materials

The properties of cement-bonded composites are influenced by wood element characteristics (species, size, geometry, chemical composition), cement type, wood–water–cement ratio, environmental temperature, and cure time (Jorge and others 2004). They are heavier than conventional wood-based composites but lighter than concrete. Therefore they can replace concrete in construction, specifically in applications that are not subjected to loads. Wood–cement composites provide an option for using wood residues, or even agricultural residues. However, species selection can be important because many species contain sugars and extractives that retard the cure of cement (Bowyer and others 2007).

### *Magnesia-Cement-Bonded Composite Materials*

Fewer boards bonded with magnesia cement have been produced than Portland-cement-bonded panels, mainly because of price. However, magnesia cement does offer some manufacturing advantages over Portland cement. First, the various sugars in lignocellulosics do not have as much effect on the curing and bonding. Second, magnesia cement is more tolerant of high water content during production. This opens up possibilities to use lignocellulosics not amenable to Portland cement composites, without leaching or other modification, and to use alternative manufacturing processes and products. Although composites bonded with magnesia cement are considered water sensitive, they are much less so than gypsum-bonded composites.

One successful application of magnesia cement is a low-density panel made for interior ceiling and wall applications. In the production of this panel product, wood wool (excelsior) is laid out in a low-density mat. The mat is then sprayed



**Figure 11–16. Commercial cement-bonded composite panel.** (Courtesy of Ty-Mawr Lime Ltd., UK. Used by permission.)

with an aqueous solution of magnesia cement, pressed, and cut into panels (Fig. 11–16).

Other processes have been suggested for manufacturing magnesia-cement-bonded composites. For example, a slurry of magnesia cement, water, and lignocellulosic fiber may be sprayed onto existing structures as fireproofing. Extrusion into a pipe-type profile or other profiles is also possible.

#### ***Portland-Cement-Bonded Composite Materials***

The most widely used cement-bonded composites are those bonded with Portland cement. Portland cement, when combined with water, reacts in a process called hydration to solidify into a solid stone-like mass and bind aggregate materials. Successfully marketed Portland-cement-bonded composites consist of both low-density products made with excelsior and high-density products made with particles and fibers.

Low-density products may be used as interior ceiling and wall panels in commercial buildings. In addition to the advantages described for low-density magnesia-bonded composites, low-density composites bonded with Portland cement offer sound control and can be decorative. In some parts of the world, these panels function as complete wall and roof decking systems. The exterior of the panels is coated with stucco, and the interior is plastered. High-density panels can be used as flooring, roof sheathing, fire doors, load-bearing walls, and cement forms. Fairly complex shapes, such as decorative roofing tiles or non-pressure pipes, can be molded or extruded.

The largest volume of cement-bonded wood-based composite materials manufactured in North America is fiber-cement siding. Fiber-cement siding incorporates delignified wood fiber into a Portland cement matrix.

#### ***Problems and Solutions of Cement-Bonded Composite Materials***

The use of cement for wood-based composites involves limitations and tradeoffs. Embrittlement of the lignocellulosic component is known to occur and is caused by the alkaline environment provided by the cement matrix. In addition, hemicellulose, starch, sugar, tannins, and lignin, each to a varying degree, affect the cure rate and ultimate strength of these composites. To make strong and durable composites, measures must be taken to ensure long-term stability of the lignocellulosic in the cement matrix. To overcome these problems, various schemes have been developed. The most common is leaching, whereby the lignocellulosic is soaked in water for 1 or 2 days to extract some of the detrimental components. However, in some parts of the world, the water containing the leachate is difficult to dispose of. Low water-cement ratios are helpful, as is the use of curing accelerators like calcium carbonate. Conversely, low-alkali cements have been developed, but they are not readily available throughout the world. Two other strategies involve the use of natural pozzolans and carbon dioxide treatment.

**Pozzolans**—Pozzolans are defined as siliceous or siliceous and aluminous materials that can react chemically with calcium hydroxide (slaked lime) at normal temperatures in the presence of water to form cement compounds. Some common pozzolanic materials include volcanic ash, fly ash, rice husk ash, and condensed silica fume. All these materials can react with lime at normal temperatures to make a natural water-resistant cement.

In general, when pozzolans are blended with Portland cement, they increase the strength of the cement but slow the cure time. More importantly, pozzolans decrease the alkalinity of the product.

**Carbon Dioxide Treatment**—In the manufacture of a cement-bonded lignocellulosic composite, the cement hydration process normally requires from 8 to 24 h to develop sufficient board strength and cohesiveness to permit the release of consolidation pressure. By exposing the cement to carbon dioxide, the initial hardening stage can be reduced to less than 5 min. This phenomenon results from the chemical reaction of carbon dioxide with calcium hydroxide to form calcium carbonate and water.

Reduction of initial cure time of the cement-bonded lignocellulosic composite is not the only advantage of using carbon dioxide injection. Certain species of wood have various amounts of sugars and tannins that interfere with the hydration or setting of Portland cement. Research has shown that the use of carbon dioxide injection reduces the likelihood that these compounds will inhibit the hydration process,

thus allowing the use of a wider range of species. In addition, research has demonstrated that composites treated with carbon dioxide can be twice as stiff and strong as untreated composites (Geimer and others 1992). Finally, carbon-dioxide-treated composites do not experience efflorescence (migration of calcium hydroxide to surface of material), so the appearance of the surface of the final product is not changed over time.

### Ceramic-Bonded Composite Materials

In the last few years a new class of inorganic binders, non-sintered ceramic inorganic binders, has been developed. These non-sintered ceramic binders are formed by an acid–base aqueous reaction between a divalent or trivalent oxide and an acid phosphate or phosphoric acid. The reaction slurry hardens rapidly, but the rate of setting can be controlled. With suitable selection of oxides and acid-phosphates, a range of binders may be produced. Recent research suggests that phosphates may be used as adhesives, cements, or surface augmentation materials to manufacture wood-based composites (Jeong and Wagh 2003, Wagh and Jeong 2003).

As adhesives, the reaction slurry resulting from the acid–base reaction may be used as an adhesive similar to the current polymer resins. Thus, phosphate adhesives can be used to coat individual fibers and form a composite by binding the fibers to each other. The adhesives will behave much like current polymer resins and may be used with existing equipment. The binder content is typically 15% to 20 % by weight.

As a cement, phosphate binders can be used to produce bulk composites. When conventional cement is used in fiber-based products, typical cement loading is approximately 30% or higher; phosphate cements may be used in a similar manner. The slurry formed by the acid–base reaction may be mixed with fiber or any other extender to produce solid composites (Jeong and Wagh 2003).

Phosphate binders may also be used for coating wood-based composite panels to enhance surface properties. The phosphate slurry is very smooth; thin (<1 mm) coatings can be applied, suitable for providing fire or water resistance.

### Wood–Thermoplastic Composite Materials

In North America and Europe, wood elements have been combined with thermoplastics for several decades. However, it is only in the past decade that wood–thermoplastic composites have become a widely recognized commercial product in construction, automotive, furniture, and other consumer applications (Oksman Niska and Sain 2008). Commercialization in North America has been primarily due to penetration into the construction industry, first as decking and window profiles, followed by railing, siding, and roofing. Interior molding applications are also receiving attention. The automotive industry in Europe has been a leader

in using wood–thermoplastic composites for interior panel parts and is leading the way in developing furniture applications. Manufacturers in Asia are targeting the furniture industry, in addition to interior construction applications. Continued research and development will expand the available markets and each application will penetrate the global marketplace.

### Materials

Broadly defined, a thermoplastic softens when heated and hardens when cooled. Thermoplastics selected for use with wood generally melt or soften at or below the thermal degradation temperature of the wood element, normally 200 to 220 °C (392 to 428 °F). These thermoplastics include polypropylene, polystyrene, vinyls, and low- and high-density polyethylenes.

The term wood–thermoplastic composites is broad, and the class of materials can include fibers derived from wood or other natural sources. Geographical location often dictates the raw material choice. In North America, wood is the most common raw material, in Europe natural fibers such as jute, hemp, and kenaf are preferred, while rice hull flour and bamboo fiber are typical in Asia. The wood is incorporated as either fiber bundles with low aspect ratio (wood flour) or as single fibers with higher aspect ratio (wood fiber). Wood flour is processed commercially, often from post-industrial materials such as planer shavings, chips, and sawdust. Several grades are available depending upon wood species and particle size. Wood fibers, although more difficult to process than wood flour, can lead to superior composite properties and act more as a reinforcement than as a filler. A wide variety of wood fibers are available from both virgin and recycled resources.

Other materials can be added to affect processing and product performance of wood–thermoplastic composites. These additives can improve bonding between the thermoplastic and wood component (for example, coupling agents), product performance (impact modifiers, ultraviolet (UV) light stabilizers, flame retardants), and processability (lubricants).

Wood–thermoplastic composites are of two main types. In the first type, the wood element serves as a reinforcing agent or filler in a continuous thermoplastic matrix. In the second type, the thermoplastic serves as a binder to the wood elements much like conventional wood-based composites. The presence or absence of a continuous thermoplastic matrix may also determine the processability of the composite material. In general, if the matrix is continuous, conventional thermoplastic processing equipment may be used to process composites; however, if the matrix is not continuous, other processes may be required. For the purpose of discussion, we present two scenarios—composites with high and low thermoplastic content.

### Composite Materials with High Thermoplastic Content

The vast majority of commercially available wood–thermoplastic composites have high thermoplastic content. In composites with high thermoplastic content, the thermoplastic component is a continuous matrix and the wood element serves as a reinforcement or filler. The wood content is typically less than 60% by weight. In the great majority of reinforced thermoplastic composites available commercially, inorganic materials (for example, glass, clays, and minerals) are used as reinforcements or fillers. Wood-based materials offer some advantages over inorganic materials: they are lighter, much less abrasive, and renewable. Wood elements reinforce the thermoplastic by stiffening and strengthening and can improve thermal stability of the product compared with that of unfilled material.

The manufacture of thermoplastic composites is usually a two-step process. The raw materials are first mixed together in one step, and the composite blend is then formed into a product in the second step. The combination of these steps is called in-line processing, and the result is a single processing step that converts raw materials to end products. In-line processing can be very difficult because of control demands and processing trade-offs. As a result, it is often easier and more economical to separate the processing into a compounding step and a forming step (Clemons 2002).

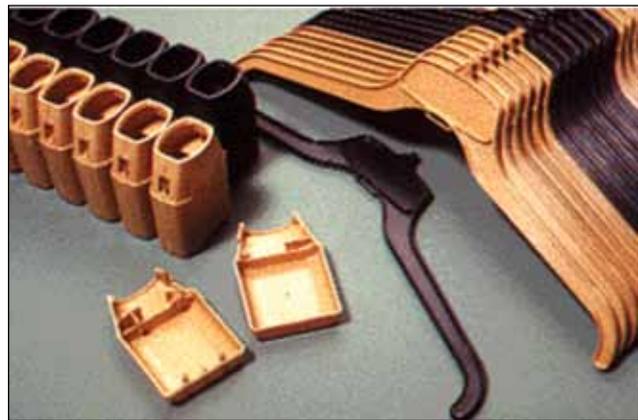
Compounding is the feeding and dispersing of the wood element in a molten thermoplastic to produce a homogeneous material. Various additives are added and moisture is removed during compounding. Compounding may be accomplished using either batch mixers (for example, internal and thermokinetic mixers) or continuous mixers (for example, extruders and kneaders).

The compounded material can be immediately pressed or shaped into an end product while still in its molten state or pelletized into small, regular pellets for future reheating and forming. The most common types of product-forming methods for wood–thermoplastic composites involve forcing molten material through a die (sheet or profile extrusion) or into a cold mold (injection molding), or pressing in calenders (calendering) or between mold halves (thermoforming and compression molding). Most wood–thermoplastic composites in North America are formed using profile extrusion. Products such as decking, siding, railings, and window profiles readily lend themselves to extrusion through a two-dimensional die (Fig. 11–17). Injection-molded applications such as consumer household goods and furniture parts are gaining importance (Fig. 11–18). Thermoforming or compression molding is the forming method of choice for the automotive industry.

Several factors must be considered when processing wood with thermoplastics. Moisture can disrupt many thermoplastic processes, resulting in poor surface quality, voids, and unacceptable parts. Either materials must be



**Figure 11–17. Extruded wood–thermoplastic composites being evaluated for a siding application (Clemons and Stark 2007).**



**Figure 11–18. Injection-molded wood–thermoplastic composites in a variety of shapes and forms.**

pre-dried or vented equipment must be used to remove moisture. The low thermal degradation temperature of wood must also be considered. As a general rule, melt temperatures should be kept below 200 °C (392 °F), except for short periods. Higher temperatures can result in the release of volatiles, discoloration, odor, and embrittlement of the wood component. Although processing wood flour in thermoplastics is relatively easy, the low bulk density and difficulty of dispersing fibrous materials in thermoplastics is more difficult. More intensive mixing and the use of special feeding equipment may be necessary to handle longer fibers.

### Composite Materials with Low Thermoplastic Content

In composites with low thermoplastic content, the thermoplastic component is not continuous, acting more as a binder for the fiber much the same way as binders in conventional wood-based composites. Thermoplastic content is typically

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less than 30% by weight. In their simplest form, lignocellulosic particles or fibers can be dry-blended with thermoplastic granules, flakes, or fibers and pressed into panel products. An alternative is to use the thermoplastic in the form of a textile fiber. The thermoplastic textile fiber enables a variety of lignocellulosics to be incorporated into a low-density, non-woven, textile-like mat. The mat may be a product in itself, or it may be consolidated into a high-density product.

Because the thermoplastic component remains molten when hot, different pressing strategies must be used than when thermosetting binders are used. Two options have been developed to accommodate these types of composites. In the first, the material is placed in the hot press at ambient temperature. The press then closes and consolidates the material, and heat is used to melt the thermoplastic component, which flows around the lignocellulosic component. The press is then cooled, “freezing” the thermoplastic so that the composite can be removed from the press. Alternatively, the material can be first heated in an oven or hot press. The hot material is then transferred to a cool press where it is quickly consolidated and cooled to make a rigid panel. Some commercial nonstructural wood–thermoplastic composite panels are made in this way.

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