10 Wood Composites

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A composite can be defined as two or more elements held together by a matrix. By this definition, what we call "solid wood" is a composite. Solid wood is a three-dimensional composite composed of cellulose, hemicelluloses and lignin (with smaller amounts of inorganics and extractives), held together by a lignin matrix. (See Chapter 3.)

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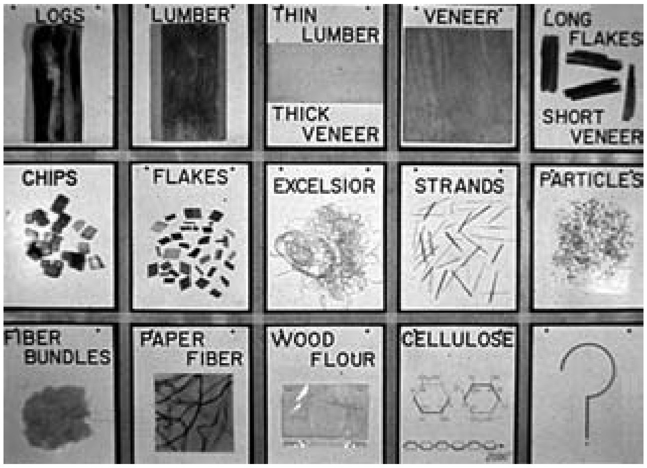

FIGURE 10.1 Basic wood elements, from largest to smallest (Mara 1979).

The advantages of developing wood composites are (1) to use smaller trees, (2) to use waste wood from other processing, (3) to remove defects, (4) to create more uniform components, (5) to develop composites that are stronger than the original solid wood, and (6) to be able to make composites of different shapes.

Historically, wood was used only in its solid form as large timbers or lumber. As the availability of large-diameter trees decreased (and the price increased) the wood industry looked to replace large-timber products and solid lumber with reconstituted wood products made using smaller-diameter trees and saw and pulp mill wastes. There has been a trend away from solid wood for some traditional applications toward smaller element sizes. Marra (1979) put together what he called "a periodic table of wood elements" (Figure 10.1), showing the breakdown of solid wood into composite components. With some modifications, this table still represents most of the types of elements used today to produce composite materials.

New composite products started with very thick laminates for glued laminated beams, to thin veneers for plywood, to strands for strandboard, to flakes for flakeboard, to particles for particleboard, and, finally, to fibers for fiberboard. As the size of the composite element gets smaller, it is possible to either remove defects (knots, cracks, checks, etc) or redistribute them to reduce their effect on product properties. Also, as the element size becomes smaller, the composite becomes more like a true material, i.e. consistent, uniform, continuous, predictable, and reproducible (Marra 1979). For many new fiber-based composite products, the use of fibers will become more common, and these fibers can come from many different agricultural sources.

Glued laminated beams were introduced in an auditorium using a casein adhesive in 1893 in Basel, Switzerland (Wood Handbook 1999). These early laminated beams created a new dimension in design away from the solid wood beam that had been used in construction for hundreds of years. Now it was possible to create a structure from solid wood with graceful lines, and a new structural element that was aesthetic as well as functional was introduced. This is a design element still very much in use today.

The modern plywood industry began around 1910, but the furniture industry had used veneers over solid wood for several hundred years beforethat. Overlaying thin sheets of wood or paper over another material created the "wood look" without actually using very much wood, if any, at all. Furniture designs using plywood were created using rather complex designs but were still limited to the bending properties of thin wood veneers. Today, very thin veneers are made, backed with a thermoplastic sheet that can be overlaid onto many different materials. The best known example of this technology is in the manufacture of business cards using these thin wood/thermoplastic laminated sheets.

The particleboard industry started in the 1940's, the hardboard industry around 1950, and the flakeboard and medium density fiberboard (MDF) industries in the early 1960s (Maloney 1996). In general, all of these products are produced in flat sheets and used in two-dimensional designs. It is possible, however, to produce all of these composites in three-dimensional products. Flakes and particles have been formed into pallets and packing materials using an adhesive and a rather simple mold.

10.1 TYPES OF COMPOSITES AND APPLICATIONS

The earliest composite structures were made of solid beams. Figure 10.2 shows an example of solid beam construction that was done about 200 years ago. Solid beam structures are still being built today but it is far more common to see smaller wood elements that are glued together in composite structures.

10.1.1 LAMINATED TIMBERS

Structural glued-laminated beams (glulam) can be made using thick, wide wood members and are used as structural elements in large, open buildings. Glulam is a structural product that consists of two or more layers of lumber glued together with the grain all going parallel to the length. Figure 10.3 shows a laminated beam being fitted into a steel plate that joins the beam to the ground. It can be formed straight or curved, depending on the desired application. Typically the laminates are 25 to 50 mm in thickness. Douglas fir, southern pine, hem-fir and spruce are common wood species used to make glulam in the United States (Wood Handbook 1999). Solid wood and glulam have a specific gravity of 0.4 to 0.8.

The biggest advantage of using glulam is that large beams can be made using small trees. In addition, lower quality wood can be used, thinner lumber can be dried much faster than large, thick beams, and a variety of curved shapes can be produced.

FIGURE 10.2 Old cabin built using solid wooden beams.

FIGURE 10.3 Large composite beam made from laminated lumber.

10.1.2 PLYWOOD

Thin veneers can be glued together for plywood, a material that is used as a structural underlayment in floors and roofs and in furniture manufacturing. There are two basic types of plywood: construction and decorative. Construction-grade plywood has traditionally been produced using softwoods such as Douglas-fir, southern pines, white fir, larch, and western hemlock, and comes in several grades based on the quality of each layer and the adhesive used. Decorative plywood is usually produced using softwoods for the back and inner layers, with a hardwood layer on the outer surface. Figure 10.4 shows a three-ply composite in which each layer is perpendicular to the layer above and below. The veneers can be produced either by peeling or slicing, and the grade of plywood depends on the defects on the two faces. Different thicknesses of plywood can be produced using multi-layers of veneers. Usually an odd number of layers is used, and the products have a specific density from about 0.4 to 0.8.

10.1.3 STRUCTURAL COMPOSITE LUMBER

Structural composite lumber (SCL) is manufactured by laminating strips of veneers or strands of wood glued parallel to the length. Figure 10.5 shows three types of SCL products: oriented strand

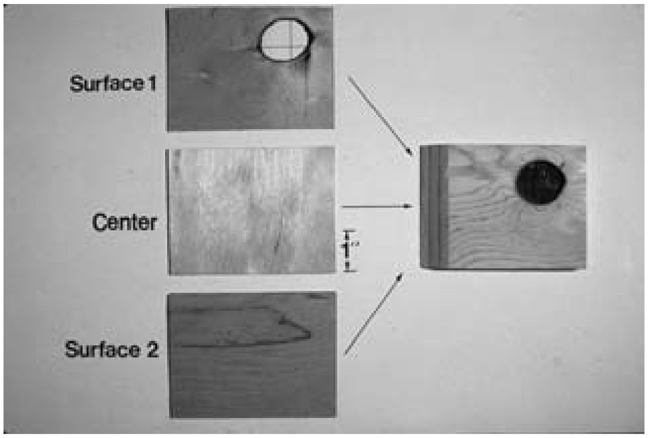

FIGURE 10.4 Thin veneers used to make plywood.

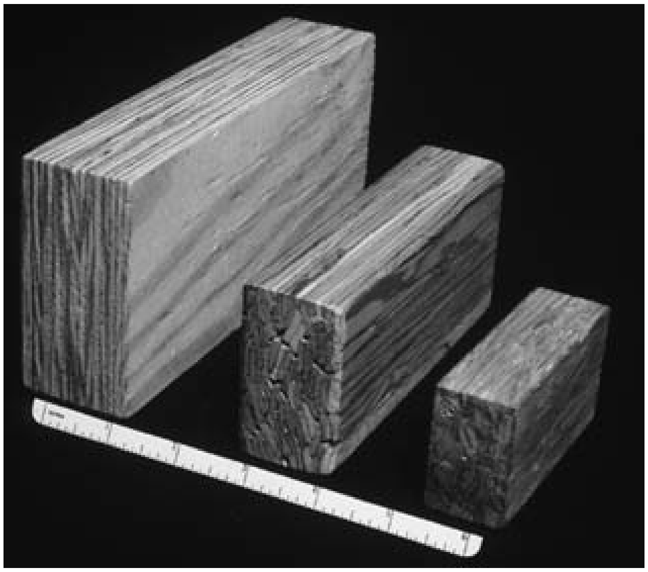

FIGURE 10.5 Three types of structural composite lumber (SCL). Left—Oriented strand lumber (OSL), center—Parallel strand lumber (PSL), right—Laminated veneer lumber (LVL).

lumber (OSL), parallel strand lumber (PSL) and laminated veneer lumber (LVL). Laminated strand lumber (LSL), oriented strand board (OSB) and OSL are produced using different lengths and sizes of strands. LSL uses strands that are about 0.3 m in length while OSB is produced from shorter strands. PSL is made from strands that are 3 mm thick, approximately 19 mm wide, and 0.6 m in length. Usually Douglas-fir, southern pines, western hemlock, and yellow-poplar are used, but other species are also used. LVL is produced from veneers that are approximately 2.5 to 3.2 mm thick and varying lengths. The major adhesives used to produce SCL products are phenol-formaldehyde or isocyanates. All of these SCL products are used as replacements for solid wood and have a specific gravity of 0.5 to 0.8.

10.1.4 COMPOSITE BEAMS

By combining several elements, composite structural beams can be produced. Figures 10.6, 10.7, and 10.8 show composite beams made from a variety of elements. Figure 10.6 shows an I-beam made of curved plywood sides and laminated plywood top and bottom. Figure 10.7 shows a comply beam made of a flakeboard center with plywood top and bottom. Figure 10.8 shows beams made of plywood, hardboard, flakeboard and oriented strandboard. Prefabricated I-beams are used by builders because they are lightweight, uniform, and easy to use; have increased dimensional stability; and meet codes and standards.

10.1.5 WAFER- AND FLAKEBOARD

Large, thin wafers or smaller flakes can be produced by several methods and used to produce a composite board. Wafers are almost as wide as they are long while flakes are much longer than they are wide. Wafers are also thicker than flakes. Figure 10.9 shows the flakes used to produce a construction grade flakeboard. These are used as the structural skin over wall and floor joists. Wafer- and flakeboard are made with a waterproof adhesive, such as phenol formaldehyde or an isocyanate, and usually have a specific gravity of between 0.6 and 0.8 (Wood Handbook 1999).

FIGURE 10.6 Composite laminated beam.

10.1.6 PARTICLEBOARD

Wood can be broken down into particles of various size and glued together to produce particleboard. Figure 10.10 shows representative particles and an example of an industrial particleboard. Particleboard has a specific gravity of between 0.6 and 0.8 and is usually produced from softwoods such as Douglas-fir, southern pines or other low-value wood sources (Maloney 1993).

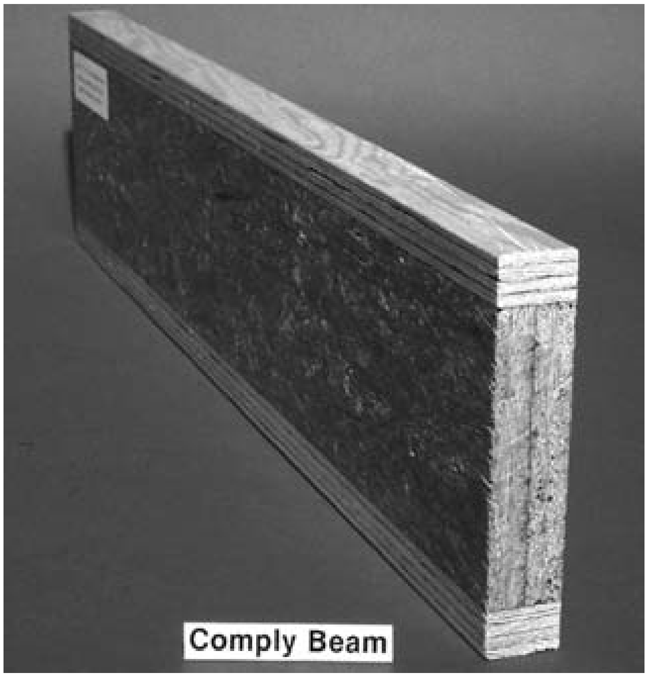

FIGURE 10.7 Comply beam.

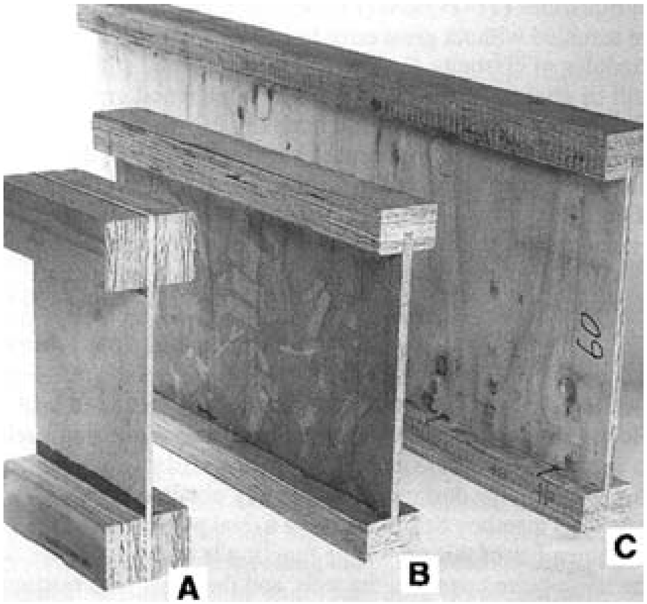

FIGURE 10.8 Composite I beams. A—plywood and hardboard, B—flakeboard and plywood, C—plywood and oriented strandboard.

10.1.7 FIBERBOARD

10.1.7.1 Isolation of Fibers

Wood can be broken down into fiber bundles and single fibers by grinding or refining. In the grinding process, the wood is mechanically broken down into fibers. In the refining process, wood chips are placed between one or two rotating plates in a wet environment and broken down into fibers. If the refining is done at high temperatures, the fibers tend to slip apart as a result of the softening of the lignin matrix between the fibers, and, consequently, the fibers will have a lignin-rich surface. If the refining is done at lower temperatures, the fibers tend to break apart and the surface is rich in carbohydrate polymers. Fiberboards can be formed using a wet-forming or a

FIGURE 10.9 Flakes used to make flakeboard.

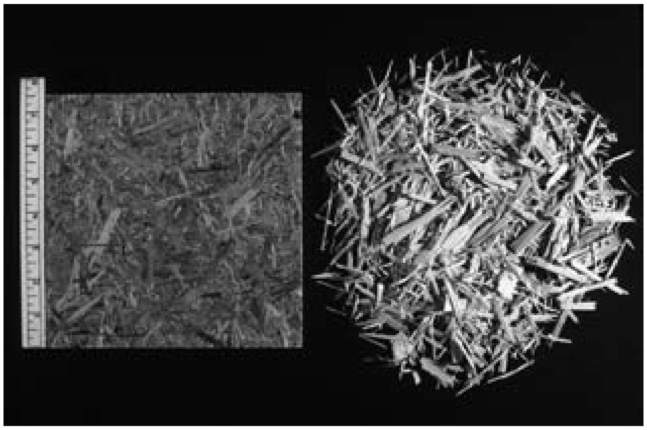

FIGURE 10.10 Particles used to make particleboard.

dry-forming process. In a wet-forming process, water is used to distribute the fibers into a mat, which is then pressed into a board. In many cases an adhesive is not used, and the lignin in the fibers serves as the adhesive. In the dry process, fibers from the refiner go through a dryer and a blowline, where the adhesive is applied, and then formed into a web, which is pressed into a board.

10.1.7.2 Low-Density Fiberboard (LDF)

Low-density fiberboards have a specific gravity of between 0.15 and 0.45, and are used for insulation and for light-weight cores for furniture. They are usually produced by a dry process that uses a ground wood fiber.

10.1.7.3 Medium-Density Fiberboard (MDF)

Medium-density fiberboard has a specific gravity of between 0.6 and 0.8 and is mainly used as a core for furniture. Figure 10.11 shows a MDF board with a melamine-paper overlay.

FIGURE 10.11 Thin veneer over medium-density fiberboard.

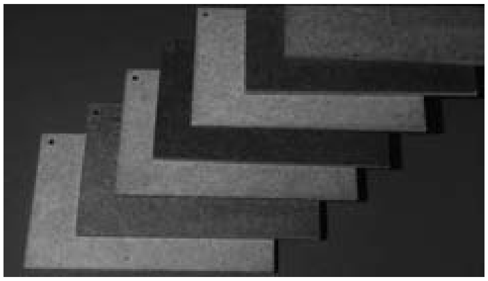

FIGURE 10.12 High-density hardboard.

10.1.7.4 High-Density Fiberboard (HDF)

High-density fiberboard has a specific gravity of between 0.85 and 1.2 and is used as an overlay on workbenches and floors, and for siding. It is produced both with and without wax and sizing agents. The wax is added to give the board water resistance. Figure 10.12 shows a few of the different types of high-density fiberboards.

10.1.8 OTHER TYPES OF COMPOSITES

There are a wide variety of composite products that can be made from wood. Figure 10.13 shows a few two- and three-dimensional composites made from a wide variety of wood elements. Sawdust, planer shavings, and bark have been used to produce composite boards. There are also a lot of wood-based composites that are a combination of wood and non-wood elements. Combinations of wood and inorganics, thermoplastics, fiberglass, metals, and other synthetic polymers have been produced; some are commercial, and some are still in the research phase. One commercially used product is a cement-bonded insulation panel for sound damping, which is based on thin wood shavings.

10.1.9 NANOCOMPOSITES

It has been mentioned that the small size of the wood element often has desirable consequences. This is particularly true for fibrous wood elements. The high stiffness and strength of wood is caused by the cellulose reinforcement in the wood cell wall. Thin cellulose micro-fibrils are the major constituent of wood and are aligned close to the axial direction of the fiber. The modulus of

FIGURE 10.13 Wide variety of flat and three-dimensional shaped composites.

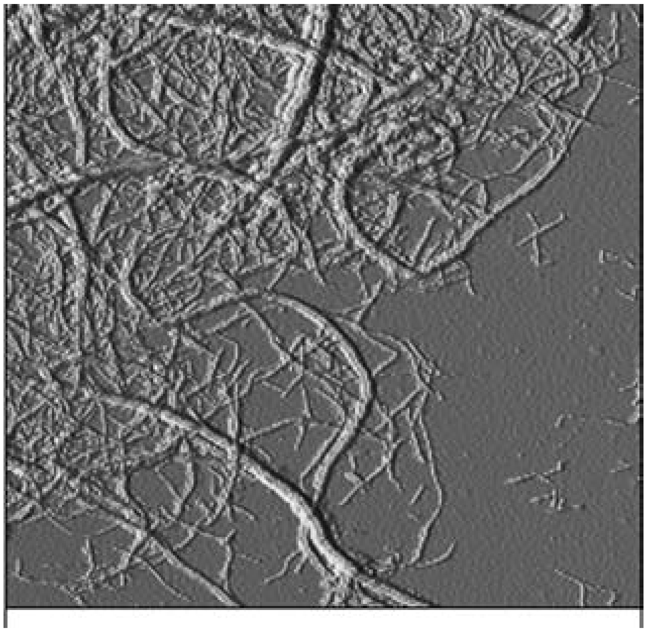

FIGURE 10.14 Atomic force microscopy image of cellulose microfibrils from wood pulp; the horizontal length of the complete image is 5 μm (image by Dr Shannon Notley, Royal Institute of Technology).

these micro-fibrils is in the order of 130 GPa, which is the same as for Kevlar® fibers. A vision for future wood composites is therefore high-performance materials and structures based on stiff and strong cellulose micro-fibrils. Research efforts are focusing on disintegration of very small micro-fibrils from the wood cell wall (see Figure 10.14). Another current research topic is the processing of micro-fibrils and polymers into new composite materials.

10.2 ADHESIVES

Adhesives are thoroughly covered in Chapter 9. In the context of wood composites, adhesive development is driven by adhesive cost-reduction, faster processing time, and specialized products

TABLE 10.1
Typical Choices of Structural Adhesives in Different Service Environments

Service Environment	Adhesive Type
Fully exterior (withstands long-term soaking and drying)	Phenol-formaldehyde Resorcinol-formaldehyde Phenol-resorcinol-formaldehyde Emulsion polymer/isocyanate Melamine-formaldehyde
Limited exterior (withstands short-term water soaking)	Melamine-urea-formaldehyde Isocyanate Epoxy
Interior (withstands short-term high humidity)	Urea-formaldehyde Casein

Source: Data from USDA, 1999.

where complex adhesive formulations are motivated. The basic chemicals most commonly used for wood adhesives and resins are formaldehyde, urea, melamine, phenol, resorcinol, and isocyanate. However, despite the apparent simplicity, in terms of families of chemicals, the formulations are highly complex mixtures of chemicals and additives. Various wood adhesives, along with their typical applications, are listed in Table 10.1.

Although the requirements for cheaper raw materials and reduced press times are the same in Europe and the United States, the emphasis on environmental issues appears to be stronger in Europe. This includes the effect of adhesives on wastewater and on gas emission during panel production. Formaldehyde emission is of significant importance. It is caused by residual un-reacted formaldehyde and by slow adhesive hydrolysis under hot/humid conditions. Modern adhesives show very low formaldehyde emission rates, in compliance with the strict E1 emission class (Pizzi and Mittal, 2003).

10.3 PRODUCTION, PROPERTIES, PERFORMANCE, AND APPLICATIONS

This section first describes laminated timbers (such as glulam) and structural composite lumber. These materials are primarily used in load-bearing building applications in the form of beams. The section then continues with wood composition boards such as plywood, flakeboard, particleboard and fiberboard. Finally, nanocomposites are presented as a concept for new materials with great potential for the future. The wood composition boards can be classified according to density, raw material form, and process type (see Figure 10.15).

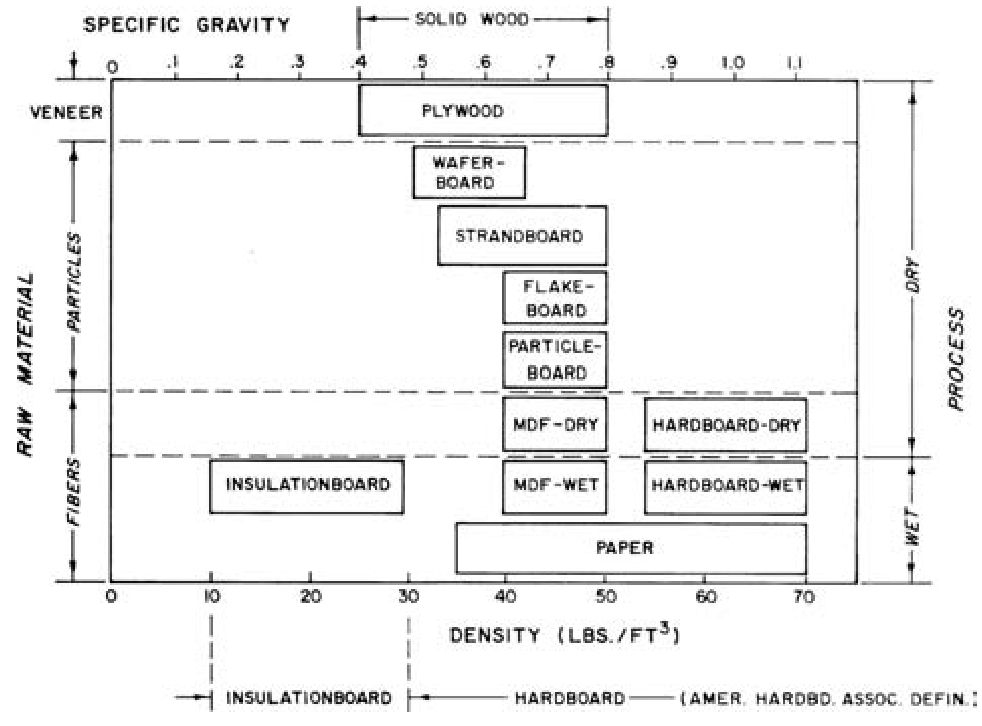

FIGURE 10.15 Classification of wood composite board materials by particle size, density and processing principle (Suchsland and Woodson 1986).

TABLE 10.2
Design Values for Douglas Fir

Design Values	Bending (MPa)	Transverse Compression (MPa)	Shear Stress (MPa)	Modulus of Elasticity (GPa)
Glulam	16.6	4.5	1.1	12.4
Sawn timber	9.3	4.3	0.6	11.0

Source: Adapted from Schniewind 1989.

10.3.1 GLUED LAMINATED TIMBER

Glued laminated timber (glulam) was first used about a hundred years ago with casein as an adhesive system. During the second World War, improved-durability adhesives were developed (e.g., phenol-resorcinol), and glulam was used in aircraft.Later it was also used as framing members for buildings (churches, schools, sports centers, airports, etc.), bridges, truck beds, and marine construction.

Glued laminated timber is currently used for construction members and typically consists of at least four laminations of wood, bonded together with adhesives. The grain direction is parallel to the direction of the construction member. The laminations are typically 45 mm (1.5–2 in.) in thickness and can be end-joined by finger-joints or bonded edge-to-edge to increase the width of the member. In the case of curved beams, laminations are often thinner. The center part of the member may be of lower quality wood. Dried wood is used, typically at 12% moisture content. For indoor applications, the customers thus experience considerable dimensional stability, and the extent of drying cracks is lower as compared to solid wood elements. In addition, the higher strength values for the dry state apply. Selective placement of wood laminations leads to distributed locations of knots and other weak spots. Design values for glulam and sawn timber based on Douglas fir are compared in Table 10.2. The design values for failure stress in bending and in shear are much higher for glulam than for sawn timber.

Phenol resorcinol adhesives are commonly used in the manufacture of glued laminated timber. Melamine-formaldehyde is used where light-colored joints are desired. Very large glulam beams are fabricated industrially. Beams of 60 m in length and 2000 × 215 mm in cross-section have been made. The fire resistance is significant due to the carbonization rate of approximately 40 mm/hr (see Chapter 6).

Glulam members are produced industrially under strict control procedures. The manufacturing requires great care with respect to the milling of finger joints, adhesive preparation and application, pressing conditions, etc. Random extraction of test pieces for strength and durability testing is used to maintain product quality.

Glulam is produced from strength-graded quality timbersuch as spruce. The timber is dried, planed, and finger-jointed (see Figure 10.16). Adhesive bonding is carried out under pressure. Two different types of bonding are used industrially: high-frequency bonding and hot press bonding.

10.3.2 STRUCTURAL COMPOSITE LUMBER (LVL, PSL, LSL)

Structural composite lumber is often referred to as SCL. Product examples include laminated veneer lumber (LVL), parallel strand lumber (PSL), and laminated strand lumber (LSL). PSL is made from 3-mm thickness veneers cut to 100–300 mm in length and 20 mm in width. Adhesive is applied, and blocks are pressed under high pressure in a continuous process. Beams of desired dimensions are cut from the blocks. LSL is similar to PSL; however, long and slender strands are cut directly from whole logs, in special machines equipped with rotating knives.

LVL is closely related to plywood and is produced in larger quantities than PSL and LSL. Veneers 3 mm in thickness are adhesively bonded together under pressure into thick boards. Typical

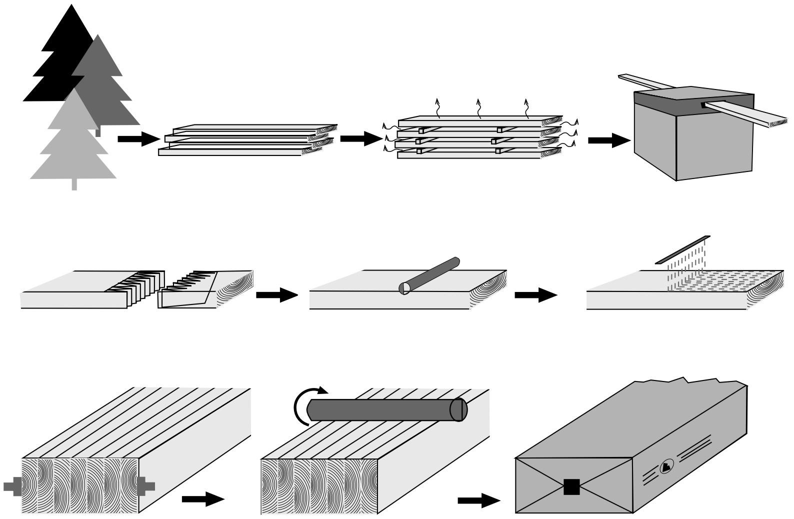

FIGURE 10.16 Sketch of procedure for glulam fabrication. The wood is cut, dried, sorted, fingerjointed, and planed; adhesive is applied; the glulam is pressed and the adhesive cured; final planing is carried out; and the product is packaged (courtesy of the Swedish Glulam Manufacturers Association, www.limtra.se).

thicknesses are 21–75 mm. In contrast with plywood, all veneer is typically oriented in one direction, although certain qualities have some cross-wise oriented layers. Construction members in the form of beams are cut from the LVL-boards. A typical beam width is 45 mm, and beam height is normally 200–400 mm, although up to 900 mm exists. Applications include roof and floor joists, lintels, framework studs, etc. LVL with crosswise veneer is often used for load-bearing panels. There are five main steps in the LVL manufacturing process (in some companies, green or dried veneer is purchased, thereby skipping the first two or three steps):

1. Logs are debarked and then cut to length.
2. Logs are peeled to veneer sheets.
3. Veneer is dried and graded.
4. Veneer sheets are glued, laid up, and pressed.
5. Billets are sawn to required size.

The basic idea behind SCL is similar to that for glulam. Thin layer constituents reduce the probability of large, localized defects. For this reason, average strength is increased and scatter in mechanical properties is reduced. Veneer or strands are dried so that the products have a moisture content of around 12% or lower to provide dimensional stability. An important argument in favor of SCL is that construction elements remain straight after equilibrium moisture conditions have been reached. Mechanical properties of LVL based on Scandinavian pine or spruce are summarized in Table 10.3.

10.3.3 PLYWOOD

Plywood consists of thin veneer wood layers (plies) bonded together by an adhesive into sheet form. Typically, each ply is placed perpendicular to the preceding ply to increase in-plane dimensional stability. The outside plies are called faces, and the inner plies are cores. The core may be lumber, particleboard, or veneer. The panel thickness range is typically 1.6–76 mm. Its history is very old, even Greek and Roman civilizations used plywood-like materials. Hardwood plywood is primarily used for decorative purposes whereas softwood plywood finds applications in the building industry. Competition from oriented strand-board (OSB) is strong. Compared with solid wood, its mechanical

TABLE 10.3
Design Values for LVL (Scandinavian Pine or Spruce) According to Euronorm (EC5)

Calculations of Stress Values	MPa
Bending edgewise	51
Tension parallel to grain	42
Tension transverse to grain	0.6
Compression parallel to grain	42
Compression transverse to grain, edgewise	9
Shear edgewise	6
Calculations of Deformation	
Modulus of elasticity	14000
Shear modulus	960

properties are more isotropic in the plane, and the resistance to splitting is greater. Plywood can cover large areas with a minimum amount of wood since thinner sections are possible. Plywood properties depend on the adhesive used (durability), ply stacking, and quality of veneer. Since plywood is often subjected to bending, the face and back plies are particularly critical to performance.

After debarking, logs are often prepared for the veneer cutting procedure by softening in hot water. The veneer is produced from rotary cutting of blocks on a lathe. The veneer of highest quality is produced initially, then the extent of knots increases as the block diameter decreases. The veneer side pressed against the knife is the tight side, whereas lathe checks occur on the knife side creating a “loose” side. The veneer goes into a dryer to reduce the moisture content and produce flat and pliable veneer. Dried veneer is graded and stacked according to width and grade. Grade A veneers have the fewest defects and Grade D the most. Phenol-formaldehyde adhesives dominate the plywood industry although urea and melamine adhesives are also used. The adhesive is sprayed, roller-coated, curtain-coated, or foamed. Today, the plies are laid up by machine, although core materials may be placed by hand. Cold pressing is often used to flatten the sheet. Hot pressing takes place in multi-opening presses. A typical pressure is 1.2–1.4 MPa and the temperature is 100–165°C, depending on the adhesive. Complete curing is essential to ensure chemical stability and low emissions. Grading of the finished panels then takes place. Typical properties for sheathing-grade plywood are presented in Table 10.4.

TABLE 10.4
Property Values for Sheathing-Grade Plywood

Property	Value
Linear hygroscopic expansion (30%–90%RH)	0.15%
Linear thermal expansion	6.1×10^{-6} m/mK (3.4×10^{-6} in/in°F)
Flexure	
Strength	21–48 MPa (3000–7000 lb/in^2)
Modulus of elasticity	6.9–13 GPa ($1–1.9 \times 10^6$ lb/in^2)
Tensile strength	10–28 MPa (1500–4000 lb/in^2)
Compressive strength	21–35 MPa (3000–5000 lb/in^2)
Edgewise shear	
Shear strength	4.1–7.6 MPa (600–1100 lb/in^2)
Shear modulus	470–760 MPa ($68–110 \times 10^3$ lb/in^2)

Source: Adapted from Youngquist, 1999.

In principle, the lay-up of plywood (grain direction and stacking sequence of veneer layers) can be tailored for specific applications. If the requirements, in terms of maximum deformation due to moisture and mechanical loads, are known, the plywood lay-up can be optimized. Lay-up optimization can be performed by the use of laminate plate theory, which has been described in the context of wood composites (Bodig and Jayne 1993).

10.3.4 PARTICLEBOARD

Particleboard is a result of the need to utilize large quantities of sawdust at sawmills. It is primarily used in panel form, although it is possible to produce I-beams, corrugations or even compression–molded, three-dimensional objects. Wood particles are bonded using synthetic adhesives and pressed into sheets. Although the mechanical performance is limited as a result of the inherent weakness of materials composed of particles, high performance flakeboard materials based on oriented fibrous strands were developed from the particleboard concept.

Typically, particleboard consists of a lower density core of coarse particles and outer, higher-density layers of finer particles. This distribution of density and particle size is important with respect to board performance. Many applications involve bending loads, where a high-density skin and a low-density core are advantageous. The particleboard panel functions as a sandwich structure and the ratio of bending stiffness to weight becomes high. Particleboard is mainly used for furniture, in flooring, and as panels.

In a modern particleboard plant, production is by continuous pressing (see outline in Figure 10.17). Such a line may have an annual production capacity of 400,000 m^3. The raw material is typically sawdust from sawmills, although sawmill chips may also be ingredients. Saw dust is used increasingly, and recycled wood is in some countries becoming more common. Where roundwood is used, mobile chippers are convenient to use. Hammer-milling ensures proper particle size and can also be used to process over-sized particles from screening. Oscillating screens allow dry particle screening into core and surface fractions and oversized particles. Drying is carried out in a single-pass drum dryer, where the temperature of the drying gases declines with decreasing moisture content of particles. Flakes are then gravity-fed to resin blenders from dosing bins. Urea-formaldehyde resins are most common, although melamine enhanced resins are often used in applications where exposure to moisture is common.

The forming unit is a key machine, since the structure (and cost) of the final board can be controlled at this stage. Proportions between surface and core flakes can be adjusted. Also, the amount of fine particles in the core can be increased to improve internal bond strength (out-of-plane tensile strength). A conveyor brings the flakes from the forming to the prepress unit. A fine spray of water is added to facilitate heat transfer in the pressing operation. A gentle initial press is applied to the loose fiber mat. The prepressing operation provides increased density and strength and reduces spring-back.

Modern continuous presses can have a length of 35 m and are equipped with cooling zones. This reduces temperature and steam pressure of entrapped moisture, provides a more even moisture distribution, and reduces the risk for board blisters. The final moisture content can be higher; a typical value is 7–8%. This is close to the equilibrium value for many applications, and the risk for warping is thus reduced. Board thicknesses are typically 3–38 mm.

10.3.5 FLAKEBOARD

Flakeboard is a term that also includes waferboard (WB) and oriented strandboard (OSB). They are structural panels produced from wafers obtained from logs. The first waferboard plant was opened in 1963 by MacMillan Bloedel in Saskatchewan, Canada. Aspen was the raw material, and the wafers were randomly oriented. In the late 1980s, most wafers were oriented, resulting in oriented waferboard (OWB). Long and narrow strands are now used in OSB, which typically have 3 or 5 layers. The orientation distribution may be tailored to the application. OWB and OSB compete

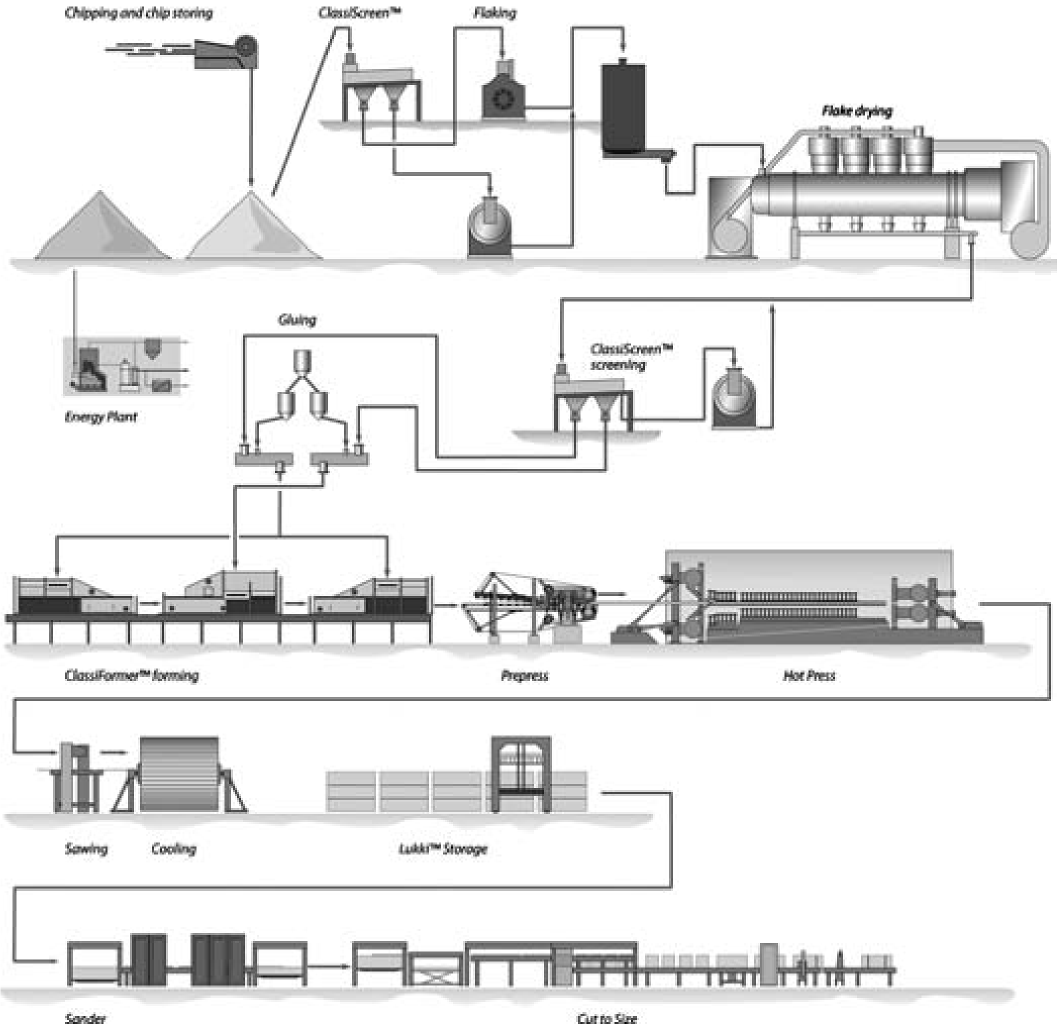

FIGURE 10.17 Outline of a modern particleboard factory for continuous pressing (courtesy of Metso Panelboard).

with plywood in applications such as single-layer flooring, sheathing, and underlayment in lightweight structures. Pines, firs and spruce are used, as well as aspen.

Manufacturing begins with logs, which are debarked and cut to 2.5-m lengths. The waferizer slices the logs into wafers typically 38 mm wide by 76 to 150 mm long by 7 mm thick. The wafers are dried in rotary drum dryers to moisture levels below 10 percent. Screening and separation takes place, and the wafers are stored. Resin, wax, and additives are mechanically mixed in a blender. Phenol-formaldehyde and isocyanates dominate as resins. In the forming step, the wafers are metered out on a moving screen system. In WB production, wafers fall randomly whereas in OSB production, wafers are mechanically oriented in one direction. Forming heads can form distinct layers oriented perpendicularly with respect to each other. The mat is trimmed and sent to either a multi-opening press or a continuous belt press. Curing takes place at elevated temperatures. In some newly developed processes, boards are cooled prior to trimming and packaging.

Typical properties of OSB are presented in Table 10.5. Plywood and OSB are competing materials for wood structural panels, a term used in the building codes. The structural performance

TABLE 10.5
Property Values for Sheathing-Grade Oriented Strandboard

Property	Value
Linear hygroscopic expansion (30%–90%RH)	0.15%
Linear thermal expansion	6.1×10^{-6} m/mK (3.4×10^{-6} in/in°F)
Flexure	
Strength	21–28 MPa (3000–4000 lb/in^2)
Modulus of elasticity	4.8–8.3 GPa ($0.7–1.2 \times 10^6$ lb/in^2)
Tensile strength	6.9–10.3 MPa (1000–1500 lb/in^2)
Compressive strength	10–17 MPa (1500–2500 lb/in^2)
Edgewise shear	
Shear strength	6.9–10.3 MPa (1000–1500 lb/in^2)
Shear modulus	1.2–2.0 GPa ($180–290 \times 10^3$ lb/in^2)

Source: Data from Forest Products Lab at www.fpl.fs.fed.us.

of the two materials is equal in general terms. They share the same exposure durability classifications, performance standards, and span ratings. Both are applied on roofs, walls, and flooring.

One limitation with OSB is edge swelling. Although the edges are coated during transport, subsequent cutting causes limitations in high humidity applications. One advantage, however, is that OSB is more consistent than plywood. Soft spots caused by overlapping knots do not exist, nor do knot holes at edges, and delamination does not take place. Since one OSB sheet may consist of 50 strands, properties are homogeneous, and there are only minor stiffness variations with location in the panel. Through-thickness shear strength is approximately twice as high with OSB. OSB is increasing its market share as a result of its lower cost as compared with plywood. Since OSB is a newer product than OSB, there is also a steady improvement in processing methods, quality control, and performance.

10.3.6 FIBERBOARD

Fiberboards are based on wood or other lignocellulosic fibers held together by an adhesive bond, either by using the inherent adhesive properties of the wood polymers or by adding an adhesive. The boards are in the form of sheet materials, typically less than 25 mm in thickness. Two steps are required in the manufacture of fiberboard. The first is the disintegration of larger wood elements into fibers, and the second is the formation of a sheet or board structure. The disintegration step essentially consists of two major substeps: the reduction of logs to chips and then the conversion of chips to pulp fibers in a refiner or defibrator. Chips are produced in chippers, such as rotating disk chippers, equipped with highly specialized knives which determine the geometry of the chips.

The pulping step is a mechanical process that takes place at elevated temperatures. Increased temperature is critical since it significantly reduces power consumption. There are three basic methods, the Masonite steam explosion process, and the atmospheric or pressurized disk refining processes. Although the board production can take place in both wet and dry processes, environmental issues warrant the dry process. A simple sketch of wet and dry fiberboard process steps is shown in Figure 10.18.

In the wet process, a dilute water suspension of fibers is used to form the mat on Fourdrinier machines (Low-Density Fiberboard or softboard). In the dry process, air-felting machines are used to form the board. Chemical additives, such as binders for adhesion or sizing for reduced water absorption, are, in the wet process, added to the water suspension and precipitated onto the fibers by pH-reduction. In the dry process, spraying and/or mechanical mixing is used for the dispersion of adhesives and additives.

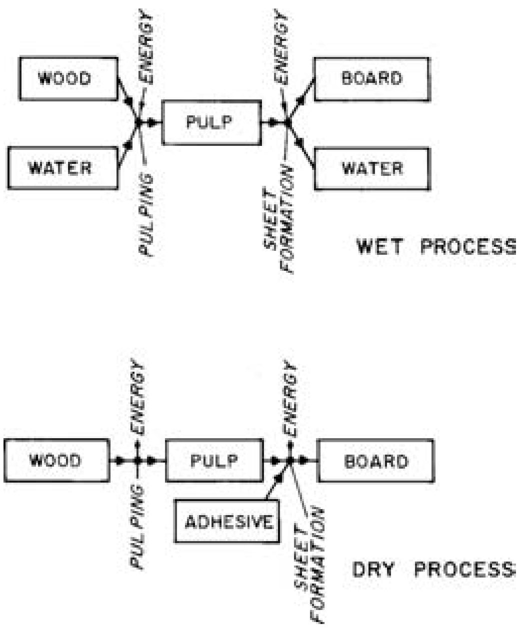

FIGURE 10.18 Sketch of principal steps in wet and dry fiberboard processes (Suchsland and Woodson 1986).

Low-density fiberboards are dried from the wet state, and the integrity of the board is ensured by fiber-fiber bonding caused primarily by hydrogen bonding. Hot pressing is used for the other types of fiberboards. During pressing, the water content is reduced, the mat is densified and fiber-fiber bonding develops by binder curing or solidification of plasticized lignin. With S1S boards (smooth on one side), a screen is placed between the mat bottom and the press in order to facilitate removal of water and steam. The screen pattern is embossed on the finished board. S2S boards (smooth on two sides) are produced from dry-formed mats or dried wet-formed mats.

10.3.6.1 Low-Density Fiberboard (Insulation Board)

Low-density fiberboards originate from the need to utilize paper byproducts. Oversize fiber bundles (screenings) were removed from groundwood pulp and used in board production about a hundred years ago. Agricultural byproducts are also used (sisal, flax, bagasse). A typical density is around 300 kg/m^3. The major application areas are as insulating layers in exterior products (sheathing, roof insulation), interior products (building boards, ceiling tiles, and sound absorption boards) and industrial products (mobile homes, and in the automotive and furniture industries).

Waxes may be added to low-density fiberboards to improve water resistance. Strength is often somewhat reduced with wax addition as a result of weakened fiber-fiber bonding. For the same purpose, asphalt is used in structural insulation board. Asphalt somewhat increases strength but obviously darkens the board color. In the wet process, wax or asphalt is added in emulsion form and is precipitated using alum. Starch can be added to increase strength but also tends to attract rodents.

The typical properties of low-density insulation boards are presented in Table 10.6. In-plane tensile strength is typically 10% of hardboard values, and out-of plane compression strength may be only 1% of hardboard values, because of the low density. Mechanical properties are often not critical for insulation boards. However, insulation sheathing may require a tensile strength of 2 MPa. Typical values for thermal conductivity are in the range 0.055 to 0.069 $Wm^{-1}K^{-1}$.

TABLE 10.6
Property Values for Low-Density Fiberboard (Insulation-Board)

Property	Values
Density	0.17–0.28 g/cm^3
Flexural strength	1.0–2.7 MPa (142–384 lb/in^2)
Modulus of elasticity (flexure)	80–400 MPa (11400–56900 lb/in^2)
Tensile strength parallel to surface	0.5–1.6 MPa (71–228 lb/in^2)
Out-of-plane tensile strength	0.07–0.17 MPa (10–26 lb/in^2)
Water absorption (24-hr immersion at 20°C)	30–100 w/o
Maximum thickness swelling	12–20%
Linear expansion, from 50–97% RH, 20°C	0.5%
Sound absorption of acoustical board (522 Hz)	50–85%

Source: Adapted from Kollman, 1975.

10.3.6.2 Medium-Density Fiberboard (MDF)

Today, MDF board production is predominantly by the dry process. In many countries, the MDF board market is expanding at the expense of particleboard and high-density fiberboard. Fibers are primarily produced in a pressurized disk refiner. Typical conditions are a pressure of 7–8 bars and a temperature of 170°C. The objective is to disintegrate the chips into individual fibers. The adhesives technology is based on a lignin-rich fiber surface obtained by fiber separation at the middle lamellae. After the refiner step, the furnish is dried to around 4% moisture content. Typically, a urea-formaldehyde adhesive in water solution is then mechanically blended with the fibers. Another alternative, used commercially, is to mix the adhesive with fibers in the transportation line leading from the refiner. A small amount of wax (0.25–1.5%) is often used to improve water resistance. The furnish is then formed into a loose mat, which may be as thick as 300 mm, depending on the final thickness of the board. Recently, continuous pressing has been increasingly used because of the higher productivity as compared with multi-opening presses. Typical press temperatures are in the range 160–210°C.

MDF boards show a significant density gradient through their thickness. The modulus of elasticity in bending correlates strongly with surface layer density (Suchsland et al 1979). Table 10.7 shows property requirements of MDF for interior use. In Table 10.8, the range of data found in eight commercial fiberboards is presented. Considerable variation is apparent. Note also that the density range for MDF extends down toward 500 kg/m^2.

In Europe, MDF tends to be used in indoor applications. In the United States, outdoor applications are also numerous. PF adhesives are often used when requirements for moisture resistance are higher. Another alternative, intermediate in moisture stability, is hybrid adhesives based on urea,

TABLE 10.7
Requirements for Medium-Density Fiberboard for Interior Use

Thickness (in)	Flexural Strength (MPa)	Modulus of Elasticity (MPa)	Internal Bond (Out-of-Plane Strength) (MPa)	Linear Expansion (%)
13/16 and below	20	2000	0.62	0.3
7/8 and above	19	1720	0.55	0.3

Source: Adapted from Schniewind, 1989.

TABLE 10.8
Property Data for Eight Commercial Medium-Density Fiberboards

Mill No	Density	Flexural Strength	Modulus of Elasticity	Internal Bond (Out-of-Plane Strength)	Residual Thickness Swelling
1	0.73 (g/cm^3)	4.84×10^3 lb/in^2	466×10^3 lb/in^2	125×10^3 lb/in^2	4.36%
2	0.90	4.93	576	136	1.61
3	0.79	3.37	432	282	2.48
4	0.82	5.70	635	121	2.83
5	0.95	3.57	517	133	5.45
6	0.80	5.28	578	103	4.52
7	0.77	5.42	572	179	3.18
8	0.71	5.11	858	158	3.03

Source: Adapted from Suchsland, 1979.

melamine and formaldehyde. MDF applications include furniture, cupboards, doors, flooring etc. MDF boards for indoor use are often painted and light fiber color is desirable, with correspondingly low press temperatures. Higher post-treatment temperatures improve moisture stability, due to hemicellulose degradation, but fiber and board colors become darker.

10.3.6.3 High-Density Fiberboard (HDF, Hardboard)

Wet processes for fiberboard production are decreasing in importance because of environmental issues. Instead, many HDF fiberboard materials are produced from the dry MDF process. The board density is higher, typically above 800–900 kg/m^3. Applications include exterior siding, interior wall paneling, household and commercial furniture, and industrial and commercial products. Hardboard is increasingly used in the expanding laminate flooring market where a hardboard sheet is used as a backing for the laminate top layer.

Hardboard dimensional and quality requirements are described in ANSI Standards ANSI/AHA A135.4-1995 Basic Hardboard, ANSI/AHA A135.5-1995 Prefinished Hardboard Panelling, and ANSI/AHA A135.6-1998 Hardboard Siding. The Basic Hardboard standard uses thickness and physical properties for classification. The objective is to facilitate the selection of the product for the customer. The other two standards focus on two particular applications, paneling and siding. The products are classified according to specific properties.

Hardboard properties vary considerably for different types of boards, both in average value and in the distribution of data. Important parameters are raw materials, tempering, additives, and density. Internal bond (strength perpendicular to the surface) correlates strongly with specific gravity, see Figure 10.19. Higher density also increases modulus (Suchsland and Woodson 1986). The correlation between density and modulus is not so strong, probably due to the through-thickness distribution of density. In a bending test, the apparent modulus depends strongly on density distribution rather than on average density. Typical property data for hardboards are presented in Table 10.9.

10.3.7 NANOCOMPOSITES

An important principle of engineered wood products is to reduce variability in the material structure by the creation of new materials where particles, fibers, flakes, strands, veneer or thin boards are adhesively bonded. The probability for concentrated regions of knots, cracks, oriented spiral grain, compression wood, juvenile wood and other defects is therefore very small. The smaller the repeating wood element is, the better the homogeneity and the smaller the variability in properties. Porosity and wood element shape complicates the picture, but as a general principle the statement is valid.

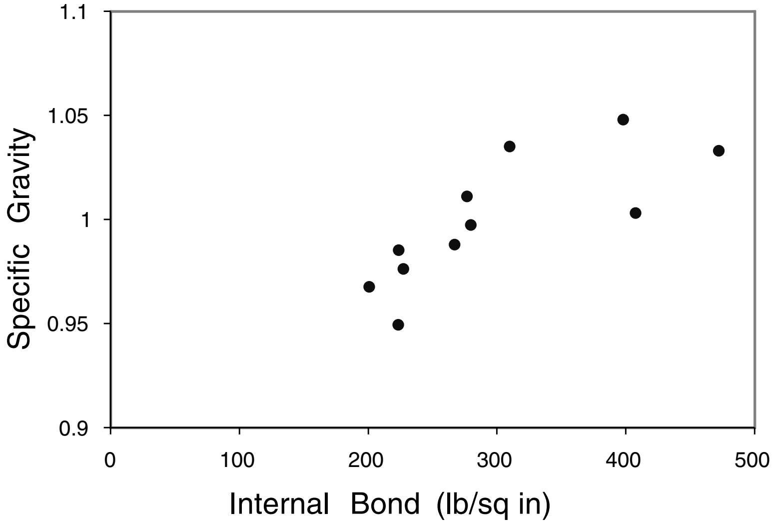

FIGURE 10.19 Effect of density on internal bond strength of fiberboard (data from Suchsland and Woodson 1986).

The smallest load-bearing element in wood is the cellulose fibril. Wood derives its strength and stiffness from cellulose. Lignin provides moisture stability, and hemicelluloses bond cellulose fibrils together, but the intrinsic mechanical performance comes from the cellulose fibrils. They are strongly aligned at an angle close to the axial direction of the wood cells. The Young's modulus of the cellulose unit cell is 134 GPa, a value similar to that of Kevlar® fibers. The reason for this high value is that the cellulose chains are densely packed, and, as they are deformed, strong covalent bonds of high energy take the load.

Cellulose microfibrils of 30 nm in diameter and a few microns in length can be disintegrated from wood pulp fibers using a mechanical milling procedure. It is also possible to take pulp fibers, subject them to acid hydrolysis, and then disintegration will take place in conventional mixing equipment used in plastics processing. The performance of injection molded cellulose fiber thermoplastics can be significantly improved by the use of microfibrils (Boldizar et al. 1987). Rubber polyurethanes have been reinforced with cellulose microfibrils, and strength, as well as strain to failure, increased substantially. The reason is the inherently high performance of the

TABLE 10.9
Property Data for Hardboard

Class	Thickness (in)	Water Absorption (w/o)	Thickness Swelling (%)	Flexural Strength (MPa)	Tensile Strength (MPa)	Internal Bond (out-of-Plane Strength) (MPa)
Tempered	1/8	25	20			
	3/16			41	21	0.9
	3/8	10	9			
Standard	1/8	35	25			
	3/16			31	15	0.6
	3/8	15	10			

Source: Adapted from Schniewind, 1989.

cellulose but also the small scale of the reinforcement. As with other wood composites, mechanisms of failure, such as microcracking and debonding, are delayed to higher stresses and strains. The reason is that small-scale reinforcements also cause damage at a very small scale, which is less detrimental to material performance. Cellulose microfibrils also show interesting properties as a material of their own. If a water suspension of cellulose microfibrils is dried, it forms a hard and tough material, similar to ivory in character. The reason is millions of strong hydrogen bonds forming between the cellulose entities.

The ultimate wood composite would have a high content of cellulose microfibrils oriented in the main direction of loading. Strength and stiffness would be competing with high performance composites used in the aerospace industry. Lightweight sandwich structures could be produced by introducing porosity, for instance through foam cores where the material primarily consists of cellulose.

The wood nanocomposite scheme presented by Yano et al. (2001) is an example of the potential. Veneer layers are subjected to chemical treatment so that significant parts of lignins and hemicelluloses are removed. The veneer is then impregnated with phenol-formaldehyde, compressed, and cured. The resulting wood composite has a Young's modulus of 40 GPa. This is more than twice the value for any commercial wood material or wood composite.

10.4 CONCLUSIONS

Wood composites constitute a wide variety of materials, such as glulam and laminated veneer lumber used in beams, as well as board materials such as particleboard, fiberboard and oriented strand board. Waste-wood and smaller trees can be used in wood composites, strength is increased since defects are removed, and structural shape can be designed. The scale of the wood element, its orientation, and material density are important factors controlling performance.

In laminated timber, plywood, and structural composite lumber, the wood element is cut, for instance by rotary cutting in the case of veneer. Adhesives are applied and the material is pressed and cured. Large standardized elements and continuous production can provide large-scale advantages. Dimensional stability and small variability in properties are selling points in the competition with other materials. Properties may be tailored by the choice of adhesive and, for example, by the design of grain direction in veneer lay-up.

In wafer- and flakeboard, particleboard, and fiberboard, economy depends strongly on the cost of raw materials and their disintegration. Sawdust and recycled wood are therefore increasingly used. Larger scale processing is also a trend, as well as dry processing. Board materials have layered structure. Particleboard and fiberboard typically have higher density in surface layers. This produces an advantageous sandwich structure so that mechanical performance per weight is improved. In addition, wood elements may be oriented, such as in oriented strandboard, so that performance is improved in given directions. The adhesive is an important and sometimes costly constituent, which often controls moisture sensitivity and ultimate properties.

For future developments, there is a need for new methods of breaking wood down into uniform furnish. Such processes must consume less energy, provide high yields, allow mixed species, and give improved performance or reduced cost. In this context, biotechnology is of interest, since enzymatic degradation takes place in water and at ambient temperature.

Optimization of structural shape, in combination with variations in material and material compositions, has great potential for components in building systems. I-beams with different materials in the flange and in the web are simple examples already in existance, although the concept may be brought much further. For example, lightweight structures subjected to bending can be produced through the use of sandwich structures with low-density cores and high-density skins. Such structures are of interest in a more industrialized production of housing, where large sections of the building are prefabricated in factories.

REFERENCES

Bodig, J. and Jayne, B.A. (1993). *Mechanics of Wood and Wood Composites*. Krieger Publishing Co., Melbourne, FL.

Boldizar A., Klason C., Kubat J., Näslund P., and Saha P. (1987). Prehydrolyzed cellulose as a reinforcing filler for thermoplastics. *Int. J. Polym. Mater.* (11):229.

Pizzi, A. and Mittal K.L. (2003). *Handbook of Adhesives Technology* (2nd ed.). Marcel Dekker, New York.

Kollman, F.F. (1975). *Principles of Wood Science and Technology: Wood Base Materials Manufacture and Properties*. Springer-Verlag, New York.

Maloney, T.M. (1996). The family of wood composite materials. *For. Prod. J.* 46(2):19–26.

Maloney, T.M. (1993). *Modern Particleboard and Dry-Processed Fiberboard Manufacture*. Miller-Freeman, Inc., San Francisco, CA.

Marra, G. (1979). Overview of wood as a material. *J. Educ. Modules for Mater. Sci. Eng.* 1(4):699–710.

Schniewind, A.P. (1989). *Concise Encyclopedia of Wood and Wood-Based Materials.* The MIT Press, Cambridge, MA.

Suchsland, O. and Woodson, G.E. (1986). Fiberboard manufacturing practices in the United States. *Agricultural Handbook 640*. Department of Agriculture. Washington, D.C.

Suchsland, O., Lyon, D.E., and Short, P.E. (1979). Selected properties of commercial medium-density fiberboards. *Fo. Prod. J*. 29(9):45–49.

USDA, Forest Service. (1999). Wood as an engineering material. General Technical Report FPL-GTR-113. *Wood Handbook*. USDA, Forest Service, Forest Products Laboratory.

Yano H., Hirose A., Collins P.J., and Yazaki Y. (2001). Effects of the removal of matrix substances as a pretreatment in the production of high strength resin impregnated wood based materials. *J. Mater. Sci. Lett.* (20):1125.

Youngquist, J.A. (1999). Wood-based composites and panel products. Chap. 10 in USDA, Forest Service. Wood as an engineering material. General Technical Report FPL-GTR-113. *Wood Handbook*. USDA, Forest Service, Forest Products Laboratory.