WOOD AS AN ADHEREND

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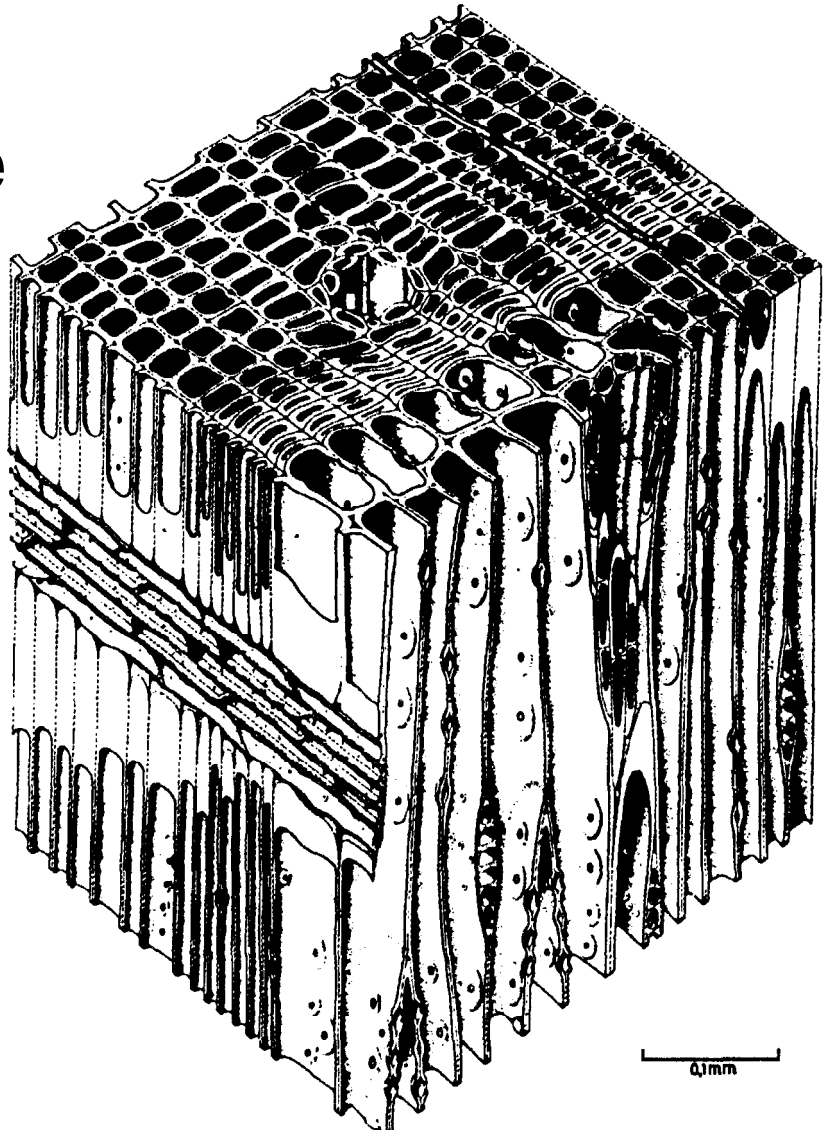

chapter 1
from
volume 7

Treatise on ADHESION and ADHESIVES

edited by
J. Dean Minford

Marcel Dekker, Inc.
New York 1991

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I. INTRODUCTION

Wood is a porous, permeable, hygroscopic, orthotropic, biological composite material of extreme chemical diversity and physical intricacy. Table 1.1 provides an overview of the may variables, including wood variables, that bear on the bonding and performance of wood in wood joints and wood-based materials. Of particular note is the fact that wood properties vary between species, between trees within a species, and even within a tree. Variability within a single species alone is enough to significantly challenge an adhesive to perform consistently and satisfactorily. In this chapter, we have attempted to describe wood and to explore how this complex biological material interacts with adhesives to affect the bonding process and the quality of the bonded joint or material. First, we will present a short review of the history connecting wood and adhesives.

The gluing of wood is ancient. No one knows where or when it began. We do know that early civilizations used mud, plant

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Table 1.1 Wood Bonding Variables

Resin	Wood	Process	Service
Type	Species	Adhesive spread	Strength
Viscosity	Species gravity	Adhesive distribution	Shear modulus
Tack	Moisture content	Relative humidity	Modulus of elasticity
Mole ratio of reactants	Plane of cut: radial, tangential, transverse, mix	Temperature	Creep
Filler	Heartwood versus sapwood	Open assembly time	Percentage of wood failure
Total solids	Juvenile versus mature wood	Closed assembly time	Failure type
Molecular weight distribution	Earlywood versus reaction wood	Pressure	Adhesive penetration
Solvent system	Grain angle	Gas-through	Dry versus wet
Age	Porosity	Press time	Temperature
pH	Surface roughness	Pretreatments	Finishing
Buffering	Drying damage	Posttreatments	Heat resistance
Cure rate	Machining damage	Adherend temperature	Hydrolysis resistance
Catalyst	Dirt		Swell-shrink resistance
Mixing	Contaminants		Ultraviolet resistance
	Chemical surface		Biological resistance : fungi, bacteria, insects, marine organisms
	Extractives		
	pH		
	Buffering capacity		

Errata (April 2004): This table was originally developed by Norm Kutscha for the Forest Products Research Society Gluing Technical Committee.

resins, beeswax, bitumen, and other naturally occurring substances for glue. Pottery and weapons bonded with resin have been discovered in grave sites almost 6000 years old (Stumbo 1965). Evidence has been found that lime-based plaster was used for bonding stone blades as long as 12,000 B.C. (Bower 1988). The use of fire for cooking undoubtedly led to the discovery that plant and animal proteins make sticky materials. Many of these naturally occurring materials were available to ancient peoples, including lime, egg white, and flour paste. With these primitive materials, wood bonding developed into a sophisticated art form. A love of luxury and a delight in beautiful surroundings evolved in the ruling families of ancient Egypt. They found wood to be an ideal material from which to fashion decorative furniture. But decorative woods were not abundant in that land of little rain. Ebony, teak, and rosewood were imported, no doubt at great expense, prompting craftsmen to learn to cut thin veneers to stretch supplies. Wall carvings in Thebes, dated about 1500 B.C., show thin wood veneers being glued to a plank of wood. A glue pot and brush, with the pot warming over a fire, suggest the glue was a hot animal glue (Knight and Wulpi 1927, referencing Wilkinson 1878). These veneers were glued to a core of ordinary material, which added strength and durability while conserving the supply of decorative but scarce and costly woods. Plywood, made by gluing together thin sheets or plies, was also well known. The people made table tops, chests, beds, and other furniture by gluing thin veneers to suitable core material. The decoration of furniture with inlays of precious stones, gold, and ivory, as well as the veneers of rare woods, was developed to a high artistic level in Egypt. We can appreciate the result of the Egyptians' gluing skill, for many beautifully veneered and inlaid wooden artifacts recovered from the tombs of the Pharaohs, and from other archeological excavations, survive to this day.

Undoubtedly the first articles of furniture were fashioned in one piece. Later, various parts were held together by leather thongs or wooden pegs. But the marriage of wooden parts with glued structural joints occurred at least as early as the eighth century B.C. An ornately decorated and intricately formed table recently discovered in a tomb, possibly that of the renowned King Midas, had been assembled with dowels and mortise and tenons joints (Simpson 1983). Although the table had failed under a heavy load of bronze pots, it demonstrates that artisans had discovered the structural advantages of adhesive-bonded joints for furniture (Darrow 1930).

After the Egyptian period, veneering continued as an art form in Greece and later in Rome. The ancient Greeks described a recipe for casein glue not unlike the recipes of the early twentieth century. The art suffered a setback with the fall of Rome and the

loss of interest in decorative arts. Only traces of the veneering art from this period can be found today.

Interest in gluing rekindled during the Renaissance. From the fifteenth to the middle of the nineteenth century, the art of veneering and development of intricate glued structural joints led to the creation of magnificent furniture and architectural woodwork in Italy, France, England, Holland, and Flanders, and finally in the United States. Distinctive periods of styling were known by the names of ruling sovereigns or patrons of the arts-de Medici, Elizabethan, Victorian, Queen Anne, and Louis XIV, XV, and XVI. Great master cabinetmakers rose to prominence one after another, and styles were distinguished by their names-Adam, Hepplewhite, Chippendale, and Sheraton. All the great masters worked with animal glue and, to lesser extent, with fish and casein glues, to create the forms of their imaginations in wood. The lasting grace and beauty of their creations are, in no small measure, a tribute to the performance of these glues (Pollen).

Other glues from natural sources were neither highly developed nor widely used until after the beginning of the twentieth century. Then, F. G. Perkins developed a vegetable glue (actually tapioca starch) from the roots of the cassava plant (Perkins 1912). This glue became so successful for cold pressing furniture parts, plywood, veneering, and other wood applications that the Perkins Company sold 230×10^6 lb of it in 1930 (Darrow 1930). The use of animal blood as a glue goes back many centuries-Aztec Indians mixed blood with mortar for building construction. Two developments spurred its widespread use in modern times. One was the discovery in about 1910 that blood could be dried in a soluble form, making it easier to preserve and handle. The other was the urgent need for a water-resistant glue for plywood for aircraft construction during World War I (Lambuth 1977). The war also spurred the development of water-resistant casein glues for the manufacture of laminated wood aircraft propellers (Truax 1930). A water-resistant, soybean-protein glue was possibly the last major development in glues of natural origin (as compared to synthetic resin adhesives) (Johnson 1923, Laucks and Davidson 1928). It became the major glue for interior softwood plywood with production of 34×10^6 lb annually in the 1930s. Combinations of blood albumin and soybean protein took advantage of the best properties of each material (Lambuth 1977); these combinations were used extensively for plywood until displaced by synthetic resins in the 1950s.

Until about 1930, the term glue accurately described the materials used to bond wood because all materials were derived from naturally occurring substances such as casein and collagen. These materials, their processing and use, and their performance with

different woods were carefully described by T. R. Truax (1929). At that time, furniture was the principal product manufactured by wood bonding. Softwood plywood was in its infancy, and it was suitable for only interior use because of the poor water-resistance of the vegetable-starch glues used in its manufacture.

With the development of synthetic resins, the term adhesive became a more appropriate word for the broad range of bonding agents that included synthetic resins as well as glues. The first important wood product made with the new synthetic resin adhesives was water-resistant plywood for airplane construction. But the impact of synthetic resin adhesives was not really felt until the early 1930s, when urea- and phenol-formaldehyde-bonded plywood began to be used in furniture and housing. World War II intensified the demand for water-resistant or waterproof bonded-wood products. During this time, adhesives based on the synthetic thermosetting resins-urea-formaldehyde, melamine-formaldehyde, phenol-formaldehyde, and resorcinol-formaldehyde-began to replace adhesives from natural resources. The emergence of commercial synthetic resin adhesives greatly expanded the variety of useful wood products that could be manufactured. In the early 1950s, adhesives based on thermoplastic vinyl acetate resin began to replace animal glue in furniture assembly. Two-polymer adhesives combining thermosetting and thermoplastic resins, such as polyvinyl-acetal/phenol-formaldehyde and nitrile rubber/phenol-formaldehyde resins, were developed that had the capability of bonding wood to metal. By the 1950s, the variety and number of synthetic resin adhesives and bonded-wood products mushroomed.

Practically all branches of the wood-using industry now use adhesives (White 1979). Adhesives and the industries they have spawned are responsible for new or improved products, dramatic improvements in the utilization of forest and mill residues, and conservation of timber supplies. New industries such as plywood, particleboard, flakeboard, and laminated-veneer lumber owe their very existence to synthetic resin adhesives. In the United States alone, these industries, which are entirely dependent on adhesives, annually produce :

21×10^9 ft^2 of structural panels (3/8-in.-thick basis).
10×10^9 ft^2 of nonstructural panels (3/8-in.-thick basis), excluding hardwood plywood.
104×10^6 ft^2 laminated-veneer lumber (1-1/2-in.-thick basis).

The United States also imports 3.1×10^9 ft^2 (surface measure) of hardwood and softwood plywood.

The development of these and other bonded-wood products and the growth of related industries over the years have resulted in

the consumption of huge amounts of synthetic resins. In 1986, the wood products industries consumed 1.4 kt of melamine-formaldehyde, 1.4 kt of isocyanate, 1.1 kt of poly(vinyl acetate), 3.6 kt of resorcinol-formaldehyde and phenol-resorcinol formaldehyde, 793 kt of phenol-formaldehyde, 745 kt of urea-formaldehyde, and 12 kt of mastic construction adhesive (Myers 1988). The total consumption of adhesives used in the forest products and construction industries was 2.37 billion pounds in 1988, and it is estimated that consumption will total more than 3 billion pounds by the year 2000 (Anonymous 1989).

II. WOOD CHARACTERISTICS INFLUENCING THE BONDING PROCESS AND BOND QUALITY

A. Physical Structure

Wood

There are two major types of wood: *softwood* (from needle-bearing trees) and hardwood (from broad-leaved trees). The terms softwood and hardwood are misnomers and have little to do with hardness or density. Many softwoods are actually much harder than many hardwoods.

When a tree is cut, often the most noticeable features on the end of the log are the light outer ring and the dark inner core. The outer ring, called the *sapwood*, consists of the cells that were actively growing or carrying on the life processes of the tree when it was cut. As the tree grew larger in diameter, cells closer to the center of the tree, which were no longer required for these activities, died and were converted to *heartwood*. This conversion entails both anatomical and chemical changes. The anatomical changes have minimal effect on strength, but they may reduce permeability, thus affecting bonding behavior. Chemically, stored food disappears and new chemicals are created. When these chemicals oxidize, the heartwood darkens, and the border between sapwood and heartwood becomes more evident. Heartwood formation is highly individualistic between species, even within trees of the same species. These changes, especially the chemical changes, account for much of the difficulty and unpredictability in the bonding of heartwood as we shall explain later.

All wood is made of fibrous cells organized to perform the support and living functions of the plant. The cells are organized in annual growth increments or *growth rings*. Each ring is the result of 1 year of growth. The rings are usually prominent because of cyclical variation in color or porosity. These variations in turn are due to the formation of different types of cells and wood structure during

different parts of the growing season. Lighter colored (less dense) and more porous cell tissue, called the earlywood, forms early in the growing season. The porous earlywood cells are largely responsible for the movement of liquid and nutrients about the tree. Darker (more dense) and less porous cell tissue, called the latewood, forms later in the growing season. The latewood cells are largely responsible for supporting the tree (Figure 1.1).

The growth patterns of some species result in a large contrast between the earlywood and latewood densities. These woods are

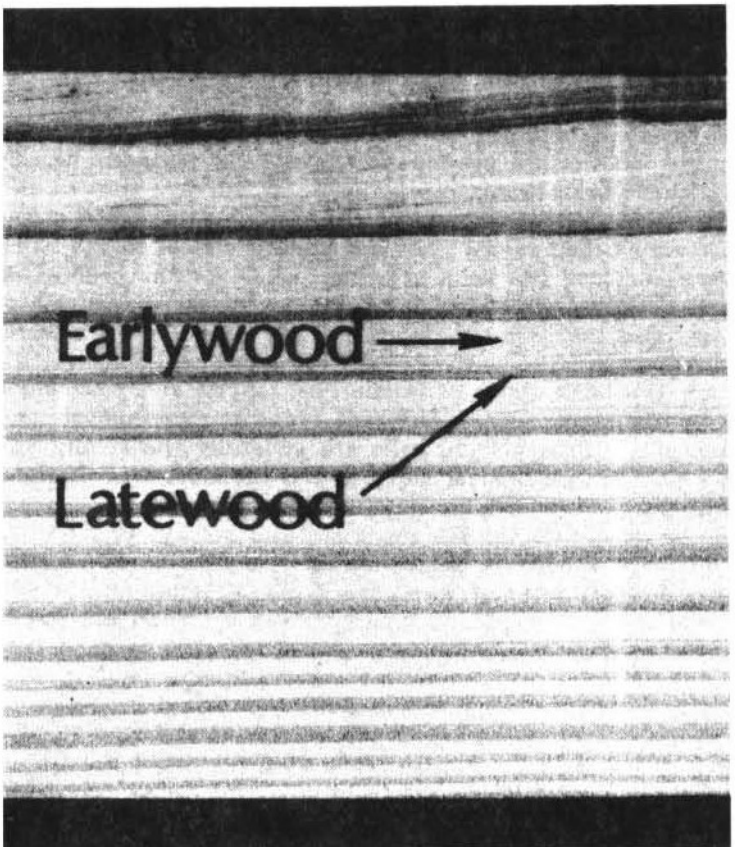


Figure 1.1 A longitudinal radial view of southern pine showing the dark, dense latewood and the light, less dense earlywood.

called coarse textured. Southern pines are an example of coarse-textured softwoods. Coarse-textured hardwoods, such as red oak, have a special name; they are called *ring-porous* woods. In other species, the growth pattern is less variable in density and porosity, and the wood is called uniform textured. White pine is a uniform-textured softwood. Uniform-textured hardwoods, such as basswood, also have a special name; they are called *diffuse-porous* woods.

Large differences between the earlywood and latewood porosity and density in some species like oak and southern pine often cause difficulty in bonding, as we will later discuss in detail.

Cells

Wood cells are microscopic, long, thin, hollow tubes, like soda straws with their ends pinched shut. The long axis of the majority of the cells is parallel to the longitudinal axis or grain direction of the tree trunk. Most longitudinal cells are either for support or for the movement of fluids in the living tree. However, small numbers of special cells either produce or store nutrients and chemicals. Some special cells are organized into tissue called *rays* that lie perpendicular to the longitudinal axis of the tree trunk and along its radii. The very broad rays of oak are plainly visible to the naked eye on every surface. Ray cells are responsible for the production and storage of amorphous materials of complex chemical nature. The rays are also the pathway for lateral movement of fluids in the tree.

There are two basic types of cells-prosenchyma and parenchyma. Softwoods and hardwoods have different types of prosenchyma and parenchyma cells. *Prosenchyma* cells are generally the strong woody cells responsible for mechanical support and the movement of fluids in the living tree. *Parenchyma* cells are responsible for the production of chemicals and for the movement and storage of food. The real differences between softwoods and hardwoods are in the size, shape, and diversity of these two types of cells.

The structure of softwoods is characterized by relatively few types of prosenchyma and parenchyma cells compared to hardwoods-a result of their lower position on the evolutionary scale (Figure 1.2). One type of prosenchyma cell, the longitudinal *tracheid.* constitutes approximately 90-94% of the volume of softwood wood. Tracheids perform both the support and fluid movement for the tree. Earlywood tracheids are generally of large diameter and thin walled. Earlywood cells are specifically adapted to moving fluids through large openings (bordered pits) that connect adjoining Cells. Latewood tracheids, which are generally smaller in diameter, are thicker walled, have smaller pits, and are specifically adapted for

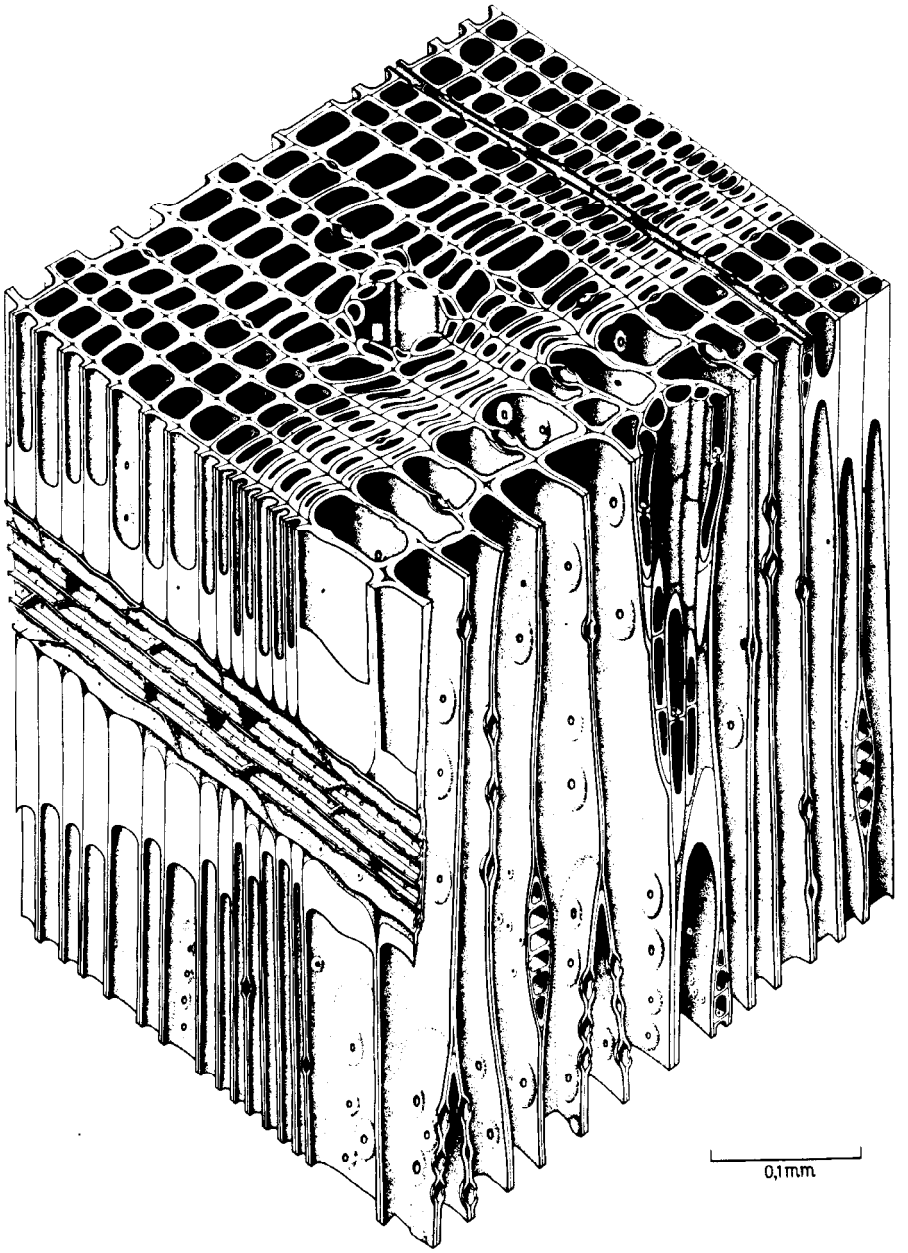


Figure 1.2 Gross structure of a typical softwood, showing relatively few types of cells and the preponderance of longitudinally (vertically) oriented cells called tracheids.

strength. The remaining 10% of a softwood consists of longitudinal parenchyma cells, ray tracheids, and ray parenchyma cells. Generally, parenchyma cells play a secondary strength role, but they are important for adhesive bonding as paths for adhesive penetration. Moreover, the chemicals contained by the cells affect adhesion and adhesive cure.

In comparison to softwoods, the structure of hardwoods is characterized by a greater diversity of cell types and functions (Figure 1.3). One notable difference is that specialized prosenchyma cells are responsible for mechanical support, and other specialized prosenchyma cells are responsible for fluid movement. Support is provided by two types of small-diameter thick-walled prosenchyma cells called *libriform fibers* and *fiber tracheids.* Fluid movement is provided by medium- to large-diameter, thin-walled, and open-ended cells called vessel *elements.* Normally, a number of vessel elements link end-to-end along the grain to form long tube-like structures known as vessels. The cavities of large vessels in oak and other species are large enough to see with the naked eye. Such large cavities obviously affect wood strength and adhesive flow when pressure is applied during bonding. Together the longitudinally oriented fibers and vessels constitute the major volume of cells (roughly 70-90%) in hardwoods. A number of other specialized longitudinal prosenchyma and parenchyma cells and ray prosenchyma and parenchyma cells constitute the remaining volume. As in the softwoods, some of these minor hardwood cell types have important chemical roles and secondary, though often minor, mechanical roles. Panshin and deZeeuw (1980) provide further information on wood anatomy.

Cell Wall

Under the microscope, the end of a piece of wood looks rather like a honeycomb (Figures 1.2 and 1.3). The walls of the honeycomb, the wood cell *walls,* are a framework of oriented long-chain cellulose molecules called elementary fibrils. These are grouped in bundles called microfibrils. In certain regions of the microfibrils, the elementary fibrils are highly aligned, tightly packed, and crystalline. In other regions they are less aligned, not packed, and noncrystalline. The cellulose chains in the noncrystalline regions of the microfibrils are interpenetrated and thereby stiffened by a heterogeneous and amorphous matrix of *lignin* that also binds the cells together. Spaces between the microfibrils are thought to be filled with a heterogeneous matrix of short-chain cellulose-like materials called *hemicellulose,* as well as lignin and other amorphous materials, air, and water. The exact relationships between cellulose, hemicellulose, and lignin in these regions are not entirely understood. Water is able to enter and leave these noncrystalline regions quite

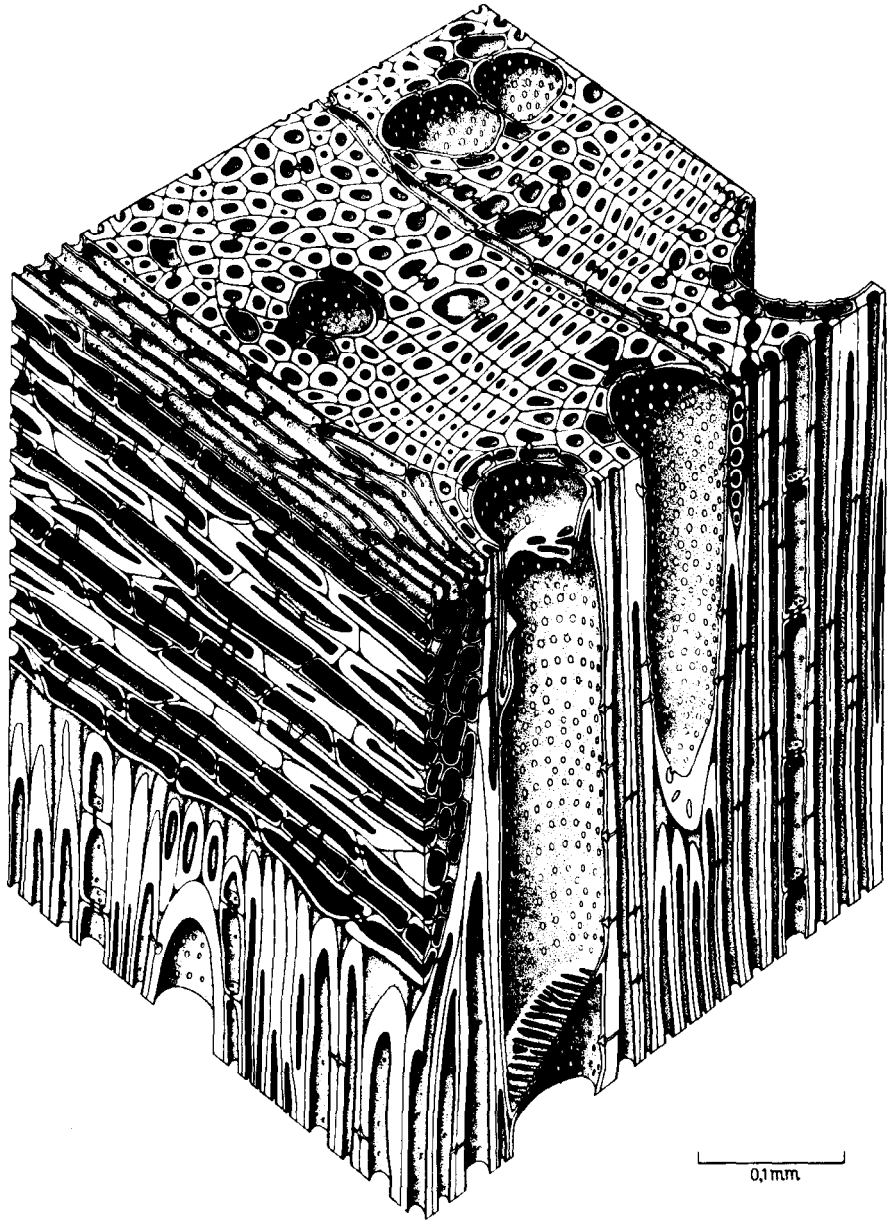


Figure 1.3 Gross structure of a typical hardwood, showing the greater variety of cell types when compared to the softwood in Figure 1.2. Also evident are the large-diameter vessels (vertically oriented) and the larger amount of horizontally oriented ray cells compared to the softwood.

freely; this accounts for the swelling and shrinking of wood in response to changes in relative humidity.

Successive lamellae of microfibrils are laid down in waves from the middle to the end of the cell, each lamella with a slightly different orientation of the microfibrils. These lamellae surround. the central cavity or *lumen* of the cell. Distinct groups of lamellae or wall layers are distinguished by differences in the orientation of the microfibrils. The first layer, the primary *wall,* is very thin and consists of randomly oriented microfibrils. The primary wall provides the framework for the subsequent formation of the secondary wall. The secondary wall is formed of three distinct layers, the *S-1, S-2,* and *S-3* layers; each layer is much thicker than the primary wall (Figure 1.4). The secondary wall is the principal

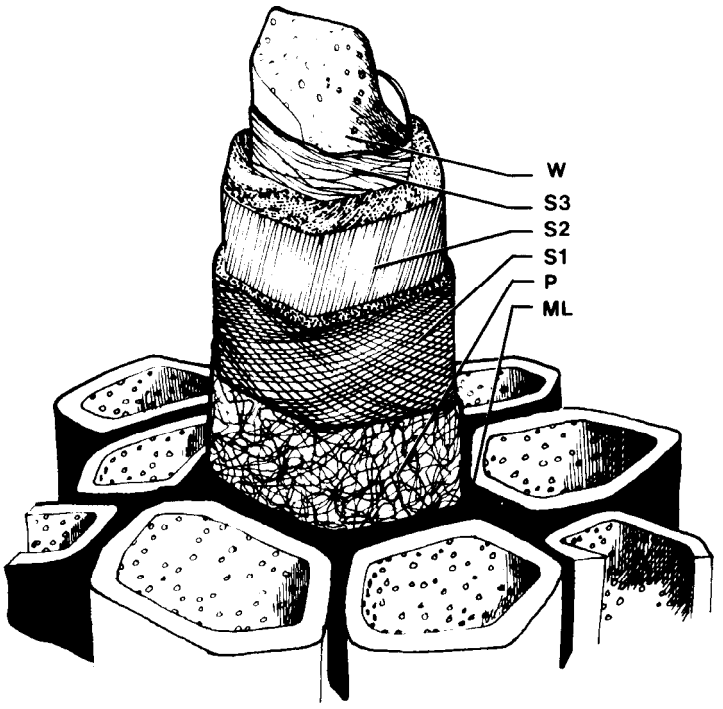


Figure 1.4 Schematic construction of the cell wall showing the middle lamella (ML) and primary wall (P), the S1 layer of the secondary wall, the dominant S2 of the secondary wall, the S3 layer, and the warty layer (W).

structural element of the wood cell. In the secondary wall, the microfibrils are aligned helically around the lumen. The angle and direction of the helices vary from layer to layer within the wall, and the thickness of the individual layers and the overall thickness of the cell wall vary with the type of cell. The properties of the cell are strongly influenced by the degree of orientation of the microfibrils and the proportions of the various layers in the cell wall. For example, the S-2 layer, whose microfibrils are oriented nearly parallel to the long axis of the cell, is responsible for resisting principal stresses in the living tree and for the longitudinal strength and stiffness of lumber cut from the tree. Latewood cells normally have very thick S-2 layers and thus are very resistant to stresses parallel to the long axis of the cell. Cell wall thickness variation and swelling and shrinking are principally, but not exclusively, due to thickness variation of the S-2 layer. The S-1 layer is important to resisting stresses perpendicular to the grain direction; the S-1 and S-3 layers, whose microfibrils lie at a large angle to the long axis, also restrain the swelling and shrinking of the S-2 layer, and thus of the wood as a whole. The secondary wall by virtue of its bulk largely determines the mechanical and physical properties of the wood.

B. Chemical Composition

Wood is made up of cell wall constituents and extraneous materials (Figure 1.5). The cell wall constituents that form the structural

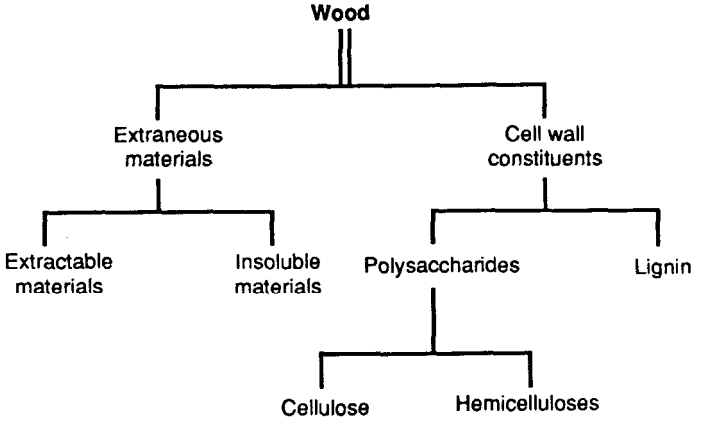


Figure 1.5 Chemical components of wood.

components of the wood cell wall are collectively called *wood substance.* Wood substance typically accounts for 95-98% of the weight of the wood, the remainder being extraneous organic and inorganic materials. The ratio of polysaccharides to lignin in the wood substance is roughly 3:1. The most abundant polysaccharide, cellulose, in the form of microfibrils, provides the framework for all plant tissues. Pettersen (1984) provides an extensive compilation of the chemical composition of woods from the entire world.

Cell Wall Constituents

Cellulose is an unbranched and highly oriented homopolymer formed of ß-D-glucose units linked by ß-1,4-glycosidic bonds to form long linear macromolecules. In nature, the cellulose polymer consists of 5000 to 10,000 repeating units and may consist of as many as 30,000 repeating glucose units. The physiochemical relationship between adjacent cellulose chains is not completely understood. X-ray diffraction evidence indicates large portions of cellulose exist as well-ordered parallel arrays of molecules held together by intermolecular hydrogen bonding. This portion of the cellulose is highly crystalline, whereas other parts are not well ordered and are amorphous. Each glucose unit has three hydroxyl units that are available for hydrogen bonding. Hydroxyl units in the amorphous regions are responsible for the great attraction of wood for water, and they provide the primary sites for adhesive bonding.

Cellulose is the principal structural component of wood. It constitutes roughly 42% of the wood in both softwoods and hardwoods. Anatomically, cellulose is most abundant in the S-2 layer and least abundant in the middle lamella. Pure wood cellulose is strong, very stiff, and fibrous, but it is unable to function alone in supporting the tree because the microfibrils in the noncrystalline regions buckle easily under compression because of their small diameter. The microfibrils are intimately associated with lignin and hemicellulose, which bond and support the cellulose microfibrils (Winnandy and Rowell 1984).

Lignin interpenetrates and rigidifies the cellulose microfibrillar framework, making certain plant tissues woody and thus able to resist compression forces. Lignin is a phenolic, highly branched three-dimensional heteropolymer formed by enzymatic polymerization of three elementary monomers-coumaryl, coniferyl, and sinapyl alcohols. These alcohols are linked by ether and carbon-carbon bonds to form structural units (Pettersen 1984). The structural components in the lignin polymer are referred to as guaiacyl, syringyl, and p-hydroxyphenyl units, respectively, from the three monomeric alcohols. Softwood lignins are distinguishable by the predominance of guaiacyl units in their composition, whereas hardwood lignins contain both syringyl and guaiacyl units. The ratio

of guaiacyl and syringyl units is an important measure of lignin characterization. The ratio varies with the type of cell and the location within the cell wall (Fergus and Goring 1970).

Lignin also has hydroxyl units available for the adsorption of water and adhesive bonding, although there are few compared to cellulose. In its native state, lignin is thermoplastic and softens at about 100°C. The temperature at which it softens, however, is strongly affected by moisture. The ability of the binding agent lignin to flow under heat and pressure accounts for many of the unique processing characteristics of wood, such as thermomechanical pulping, steam bending, and bonding of certain types of reconstituted panel products such as masonite.

Lignin constitutes 24-33% of the wood substance in softwoods and 16-24% in hardwoods. Anatomically, lignin content is most dense in the middle lamella, where it constitutes 60-90% of the wood substance. However, because of the great thickness of the secondary wall, most lignin is actually located in the secondary wall between the cellulose microfibrils. Lignin contributes to compression strength as a rigidifying and bulking agent. It also contributes to tensile and shear strength indirectly by protecting hydrophilic polysaccharidic materials that act as bonding agents between the cellulose microfibrils and between adjacent cells. Chemical removal of lignin greatly increases dry tensile strength but also greatly lowers wet strength of wood and fibers (Klauditz 1952). Lignin is considered to provide some measure of protection to the hydrophilic polysaccharides of wood substance from water.

The last major component of wood substance is a heterogeneous group of polysaccharides known as hemicellulose. Hemicelluloses complement the lignin fraction, so they constitute about 20-29% of the cell wall substance of softwoods and 29-37% of hardwoods. Collectively, the hemicelluloses are hydrophilic, thermoplastic, alkali-soluble, and heat-labile polysaccharides. Their function is less well understood than that of lignin. Unlike cellulose, which consists of one basic repeating unit, hemicelluloses are comprised of five different sugar monomers (glucose, mannose, galactose, xylose, and arabinose). For example, glucomannans are formed by polymerization of glucose and mannose. Xylans are formed by polymerization of xylose. The degrees of polymerization of the hemicellulose molecules are tens or hundreds of repeating units, instead of thousands of units as in cellulose. Branching may occur, as well as the addition of acetyl ester and uronic acid ester groups. Glucomannans are the predominant hemicellulose found in softwoods; xylans predominate in hardwoods. Both softwoods and hardwoods also contain small amounts of water-soluble pectic substances such as uronans, galactan, and arabinan.

Glucomannans have short branches and lie parallel to and in close association with the cellulose chains in the micrfibrils. Xylans are well distributed throughout the cell wall and appear to be located within the interstices and upon the surfaces of the cellulose microfibrils. They are well branched and apparently form a complex interpenetrating matrix material with lignin (Kerr and Goring 1975; Fengel and Wegener 1984; Bach-Tuyet, Hyama, and Nakano 1985). Pectic substances are found mainly in the middle lamella and primary wall. Pectic substances are thought to provide bonding between adjacent cells and to control the properties of the primary wall.

The thermal softening temperature of hemicellulose (about 60°C) is much lower than that of cellulose or lignin, and it is lowered further by the presence of water (Goring 1965). However, in the presence of lignin, hemicellulose flow is inhibited until the lignin softening temperature (about 100°C) is reached (Byrd 1979). Hemicelluloses are believed to act as bonding agents in paper formation from high-yield pulps, which contain large amounts of hemicellulose and lignin (Horn 1979). In a process called press drying, a wet pulp sheet is dried under heat and pressure to form paper with unusually high wet strength. The unusual properties of the press-dried paper are attributed to flow of both the hemicellulose and the lignin (Horn 1979, Byrd 1979). Hemicellulose flow is thought to be responsible for superior adhesion between fibers in press-dried paper. However, lignin is thought to flow and surround the hemicellulose bonds, protecting them from water (Horn 1979). Hemicellulose and lignan flow may also play important roles in solid-wood bonding (Young and others 1985). The relationships between cellulose, lignin, and hemicelluloses are discussed in depth by Mark (1967).

Wood is mildly acidic. The acidity arises from acetyl groups attached to the xylan but also from the absorption of cations of extraneous mineral substances (ash) and from the organic extractives (Rowell 1982a). Gray (1958) measured the pH of damp sawdust of 109 hardwood and 20 softwood species. Most species fell in the pH range of 3.0-6.0. Only one species, Parana pine, was alkaline, with a pH of 8.8.

Extraneous Materials

Extraneous materials are organic or mineral substances found in the cell wall and cell lumen. These materials usually account for up to 5% of the dry weight of unextracted wood. However, in some species or in certain locations within the tree, they may constitute as much as or more than 30% of the weight of the wood. The organic substances are a mixture of compounds with diverse chemical

properties. They are called extractives because they can be removed (extracted) from wood by fairly gentle procedures, such as bathing with hot water, alcohol, benzene, or ether. The extraction procedure is a convenient way to group these materials, as outlined in Table 1.2. Each group includes several classes of materials; each class may include many different compounds, and some materials overlap in terms of their solubility. More can be learned of specific extractives in various textbooks on the subject (Hillis 1962, Pettersen 1984, Fengel and Wegener 1984).

Many unique properties of various species of wood are due to their different extractives. Even in very small quantities, some extractives impart strong resistance to decay and insects. The chemical uses of various species of wood, as in pulp and paper making, syrup production, and naval stores, are all totally based on, or strongly influenced by, extractive materials. Extractives are almost totally responsible for the color, odor, or smell of a given species of wood. The abrasiveness of inorganic extraneous materials, such as silica, dulls cutting tools and adversely affects the machineability of the wood, even though the extraneous material is present in small quantities.

Table 1.2 Major Groups of Extractable Materials

Group by method of extraction	Individual or classes of compounds
Steam distillable	Terpenes, including sesquiterpenes, diterpenes, triterpenes, tetraterpenes, and polyterpenes Phenols, hydrocarbons, and lignans
Alcohol-benzene or ether extractable	Fatty acids, including unsaturated and saturated fatty acids Fats and oils, waxes, resins, resin acids, and sterols
Alcohol extractable	Coloring matter, including flavonoids and anthocyanins Phlobaphenes, tannins, and stilbenes
Water extractable	Carbohydrates, including monosaccharides, starch and pectic materials Proteins, alkaloids, and inorganic materials

With regard to wood as an adherend, extractives are extremely important because of their often undesirable and unpredictable effect upon adhesive bonding. As indicated in Table 1.2, innumerable opportunities exist for chemical reactions between extraneous materials and the atmosphere, and between these materials and adhesives or other chemicals that may contact the materials at the wood surface. The pH, buffering capacity, and acid content of the wood can be strongly affected by the type and amount of extractives. The setting or curing reactions of some adhesives have been reported to be sensitive to these factors.

Woods that are very acidic, such as the oaks, Douglas fir, and kapur, are sometimes difficult to bond with adhesives that are sensitive to extractives. Mizumachi (1973) studied the effects of 18 species of wood with varying amounts and types of extractive contents upon the activation energy of the urea-formaldehyde curing reaction. The resin cured with an activation energy of 29 kcal/mol. When wood flour of the various species was added to the resin, the activation energies of the filled resin ranged from 26 to 63 kcal/mol. Wood flours, including red and white lauan, apitong, and sugi, had virtually no effect on the reaction. However, wood flours such as septir (38 kcal/mol), kapur (39 kcal/mol), and dellania (63 kcal/mol) had strong effects. Similarly, extractives obtained from pressure refining a group of five hardwoods and loblolly pine decreased the gel time of a urea-formaldehyde resin when added in small amounts. The addition of about 6-9% of alcohol-soluble fractions shortened gel time by as much as 70%. Water-soluble fractions had a lesser, although still strong, effect (Slay, Short, and Wright 1980).

Extractives that are insoluble in the adhesive-solvent system may cause more adhesion problems than extractives that are soluble. For example, Narayanamurti, Gupta, and Verna (1962) found that the extractives of teak (*Tectona grandis*) that are insoluble in water, although soluble in alcohol/benzene, adversely affected the setting of water-based animal and urea-formaldehyde adhesives. The extractives of acacia that are soluble in hot water did not interfere with either animal glue or urea-formaldehyde.

Gardner (1965) describes an interesting test ascribed to Sanderman, Dietrichs, and Puth (1960) for compatibility between a finish and various extractives. A paper chromatogram of a solution of the extractives is made and then coated with finish. The spots of the chromatogram are observed for signs of failure. Specific types of interference, such as interference with drying, discoloration, or cracking, can then be associated with specific types of extractives. The same technique might be used to detect effects of extractives upon the curing behavior of adhesives.

From the physical standpoint, heavy concentrations of extractives can physically block an adhesive from the intimate molecular contact with the wood substance that is necessary to form a strong, durable bond. These interactions will be discussed in more detail later in the chapter.

C. Physical Properties

Density

Wood substance normally accounts for most of the weight of wood in service, followed by water and extraneous materials. Wood substance, that is, cellulose, hemicellulose, and lignin, has a density of about 93.6 lb/ft^3, regardless of the species. But wood is a porous material, so the void volume, and consequently the amount of wood substance, varies with the anatomy of species, the growth rate of the tree, and even the position of the wood within a tree. Wood is also hygroscopic (see next section), and so its density also varies with the environment. Because water is less dense (62.4 lb/ft^3) than wood substance, wood density decreases as the moisture content increases. For example, increasing the moisture content from 8% to 28% decreases specific gravity from 0.54 to 0.44. Wood density is the weight of wood substance, extractives, and water per unit volume. It is usually expressed in pounds per cubic foot (grams per cubic centimeter). Specific gravity is the ratio of the density of the wood to the density of a standard substance, usually water. Specific gravity is usually determined by measuring the volume at a given moisture content (e.g., green, 12%) and the oven-dry weight. The extractive content is not usually a major contributor to density. However, in some cases, extractives do constitute up to 30% or more of the dry weight of wood.

When dry, the least and most dense woods weigh about 2.3 and 89 lb/ft^3, respectively, which translate to specific gravities of 0.04 and 1.42. Among the familiar woods, balsa weighs 10 lb/ft^3 (specific gravity 0.16) and oak about 44 lb/ft^3 (specific gravity 0.75). Most commercial species fall within the range of 19-50 lb/ft^3 (specific gravity 0.30-0.80). Not surprisingly, density or specific gravity is the best single indicator of the mechanical properties of wood. This relationship is discussed in detail later in this section. As applied to adhesive bonding, the strength of adhesive-bonded joints is strongly dependent upon the wood density, as is discussed further in Section VI.

The challenge presented in bonding extremely low-density wood, like balsa, is to prevent overpenetration of the wood by the adhesive. Overpenetration produces an adhesive-starved, and thus

weak, joint. Fortunately, very strong joints are not required to exceed the strength of very low-density wood. At the opposite end of the scale, very dense wood may be stronger than the adhesive. However, low porosity and permeability and increased amounts of extractives in the very heavy woods may be more important. These characteristics limit mechanical adhesion and the ability of the adhesive to penetrate the wood surface and to make intimate molecular contact over a large surface area. In addition, high extractives content in dense woods increases the opportunities for interference with wetting and cure.

Even if the average specific gravity of a wood is well within the range of gravity for easy bonding, the disparity between earlywood and latewood densities in a coarse-textured wood can make bonding difficult. The southern pines provide a good example. The average specific gravities of the southern pines range from 0.51 to 0.59, which is well within the range of density that can be readily bonded. However, southern pines are often difficult to bond well. Their wood presents two problems. First, the wood contains high levels of oleoresinous extractive materials. Second, the earlywood is very low in specific gravity (about 0.3), and thus it is very porous and conducive to overpenetration by the adhesive. The latewood, on the other hand, is very high in specific gravity (about 0.8), and thus it is nonporous and nonconducive to penetration and adhesion, Similar difficulties are often experienced in bonding coarse-textured hardwoods such as ash and oak, which are ring-porous.

In spite of these interacting factors, density is the best single indicator of the mechanical properties, swelling and shrinking behavior, and difficulty of bonding that can be expected of a wood, and of the probable durability of the bonded joints and wood products.

Hygroscopicity

In the living tree, wood holds water as *free water* in the cell lumen and as *bound water* within the cell wall. Free water, which occurs in the lumens of sapwood and to some extent in the heartwood cells of the living tree, may range from 30% of the oven-dry weight of the wood in the heartwood and up to 250% of wood weight in the sapwood. When a tree is cut and converted to wood products, the free water is removed by air or kiln drying; once removed, free water will never return unless the wood is soaked in water. The bound water in the cell wall is attracted to the free hydroxyl groups of the cellulose, hemicellulose, and lignin, where it is adsorbed in mono- or polymolecular layers between the microfibrils and other submicroscopic spaces in the cell wall. At normal service temperatures

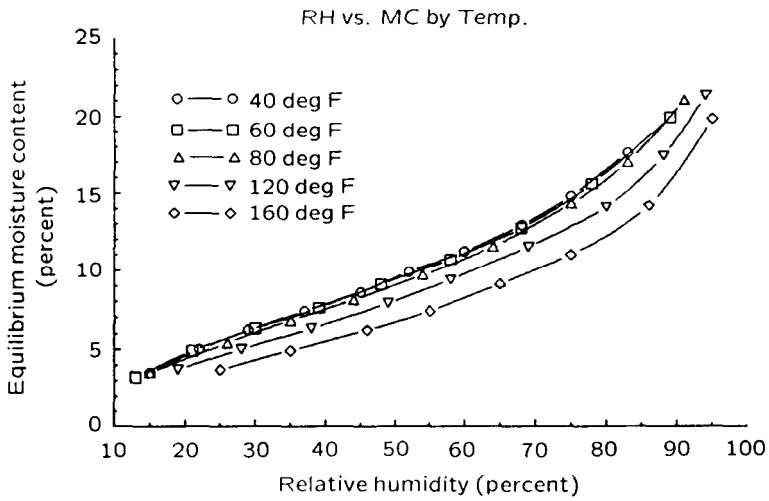


Figure 1.6 The relationship of the moisture content (MC) of wood at equilibrium with the humidity (RH) and temperature of the surrounding air.

and humidities, the bound or hygroscopic water in wood is always in balance, or at least tending toward a balance, with the environment. This balance is called the *equilibrium moisture content* (EMC) (Figure 1.6). In theory, the attraction of the hydroxyl units for the water is balanced by the force required to separate or push apart the cellulose microfibrils. Increasing the temperature decreases the amount of moisture adsorbed, and consequently the EMC. at a given relative humidity. Bound water has the most influence and is of the greatest concern with regard to wood as an adherend.

When the relative humidity is zero, the EMC is zero. This is often referred to as the *ovendry moisture content.* At the other extreme, when the relative vapor pressure is 1, the EMC reaches the *fiber saturation* point. At this point, the cell wall is fully saturated. The actual moisture content at the fiber saturation point varies with species, tree, temperature, and pressure, in the range of about 26-34% of the oven-dry weight of the wood. This is a critical point. Below the fiber saturation point, wood swells and shrinks ; significant changes in mechanical properties occur as the moisture content changes. The addition of water above the fiber saturation point (by soaking in water), on the other hand, does not affect the mechanical properties of wood.

In typical service environments, wood naturally maintains a moisture content between 5 and 20% of the oven-dry weight of the wood. The actual value is determined by the surrounding temperature and relative humidity. If the environment remains constant, the wood will reach EMC. However, most service environments vary continually, so there are always slight changes in wood moisture content. Short-term changes, such as daily fluctuation of humidity, only affect the wood surface. Seasonal changes may affect the moisture content in the core of a wood member, but the greater the thickness, the slower the moisture content change in the core of the member. The EMC in the core of a large member may only change slightly in response to long-term seasonal changes in the environment. Coatings such as paint, varnish, and lacquer can also dampen the hygroscopic response of wood. Changes of the bound water level in the cell wall (moisture content) affect the density, dimensional stability, and mechanical properties of wood, and not surprisingly, the bonding process and bond performance. Moisture content and density may exert an interactive effect on adhesive bonding; however, this effect is probably not of practical significance compared to their separate effects. The effects of both density and hygroscopicity on bonding and bonded products are discussed in Sections V and VI.

Anisotropy

Wood is an anisotropic material. Its physical and mechanical properties differ in the three principal directions relative to the trunk of the tree (Figure 1.7a):

Longitudinal: Parallel to tree trunk and parallel to long axis of longitudinally oriented cells (tracheids and fiber tracheids).
Radial: Perpendicular to longitudinal direction and parallel to radius of trunk and wood rays.
Tangential: Perpendicular to longitudinal direction and parallel to growth rings.

The properties of wood are also often referred to an orthotropic plane such as the tangential/radial (TR), longitudinal/radial (LR), and longitudinal/tangential (LT) planes shown in Figure 1.7b.

Part of the explanation for the anisotropy of wood is the elongated shape of the majority of wood cells, and their orientation in the longitudinal or *grain direction* of the wood. But anisotropy is manifest at all levels of wood structure. The cell wall is also anisotropic. In the dominant layer of the cell wall, the S-2 layer, the cellulose chains and the microfibrils are predominately oriented in the longitudinal direction of the cell itself.

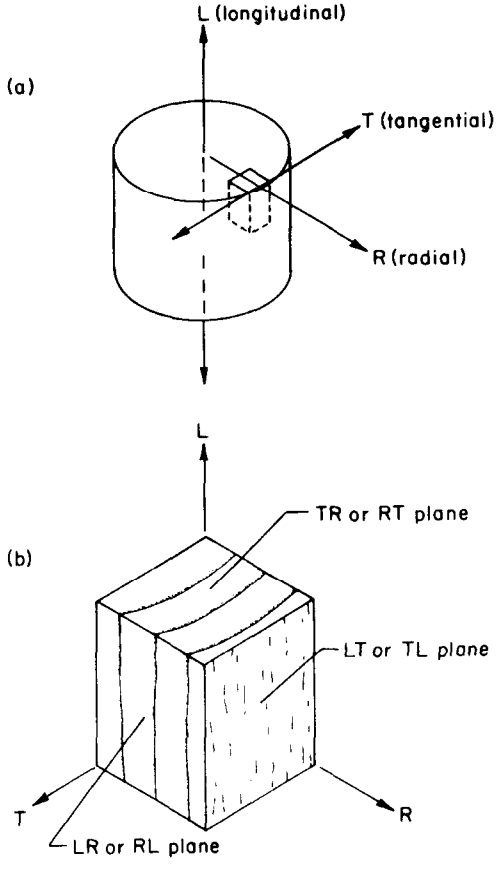


Figure 1.7 The pseudo-orthotropic structure of wood in relation (a) to the tree and (b) to the grain direction and growth rings.

The properties of wood differ in each principal direction, much as with fiber-reinforced plastic composite materials. The properties also vary as a function of the angle between the principal directions. With regard to adhesive bonding and performance, differences and variations in permeability, swelling and shrinking, and strength are of the greatest significance.

Porosity and Permeability. In the context of anistropy, these terms refer to the macro- and microscopic pathways by which a

liquid or vapor passes through a piece of wood. Stamm (1964b) says that wood is highly porous, but not very permeable. This is because the cell lumens, which largely account for high porosity, are discrete. The void volume or porosity of commercial woods ranges from 45 up to 80% of the total wood volume, but the pits and smaller cell wall voids provide poor communication between the larger voids (lumens).

The formation of high-quality joints is dependent on the porosity or macroscopic pathways that allow a liquid adhesive to penetrate several cells below the surface. Penetration, in many instances, seems to be a requirement for high-performance joints. First, penetration allows the adhesive to repair damaged cells; second, it also diffuses the stress concentration between the wood and the adhesive at the interface; third, it increases mechanical interlocking and surface area for bonding.

Hardening of many adhesives is dependent on the permeability or microscopic pathways for removal of adhesive solvents or liquid carriers. Most adhesives used with wood have water or other liquid carriers, and many adhesives release water of condensation as they cure. The water must be removed from the bondline in a timely fashion for nonchemically curing adhesives such as poly-(vinyl acetate). The water must be removed at just the right time with respect to the chemical curing reaction of adhesives, such as urea-formaldehyde, to develop the best joint.

Water and other liquids move through wood in three ways: (1) as vapor in the lumens under a vapor pressure gradient, (2) as adsorbed moisture in the cell walls under a moisture content gradient (but in effect a relative vapor pressure gradient), and (3) as capillary-entrained water in the cell-lumen/pit system under a liquid surface tension gradient.

One can easily visualize that water and other liquids move most rapidly in the grain direction either as liquid or vapor because the majority of long, hollow cells are oriented that way. In fact, the cell lumens are capillary tubes capable of drawing liquids into the wood interior. The force exerted by surface tension in tubes the size of cell lumens and pits is theoretically strong enough to lift a column of water 390 ft against gravity (Tarkow 1981). The size of the tracheid in softwoods or vessel lumens in hardwoods and the presence or absence of blockages in the heartwood of hardwoods have a considerable effect on the movement of water and, in particular, on the penetration of adhesives into the wood structure.

In the tangential and radial directions, pathways into the wood structure are few and indirect. The magnitude of anisotropy in porosity and permeability can be extreme. The ratios of longitudinal to tangential or radial permeability can be as great as 1

million to 1 (Comstock 1970). When a liquid or vapor reaches a cell wall, it must diffuse through the wall or pass through the pits. Many large pits on the radial cell walls assist movement in the tangential direction. Even so, passage is interrupted 50 times more often in the tangential direction than in the longitudinal direction. The pits sometimes close during drying of the wood, and this makes penetration by water or adhesives even more difficult in the tangential direction. Movement in the radial direction is further restricted because pits on the tangential cell wall are smaller and infrequent. This forces radial movement by diffusion or circuitous flow along a longitudinal-tangential path. Density and extractives primarily reduce permeability by reducing the void volume of the wood through which the liquid or vapor can pass.

The anisotropic aspects of porosity have several effects on the flow of adhesives during bonding. First, they affect how and where the adhesive moves after spreading, and when pressure is applied during bonding. Stamm (1973) found that water at atmospheric pressure penetrated white oak and loblolly pine more than 25 times faster in the grain direction than laterally. We have previously mentioned that woods of high porosity provide the potential for robbing or starving the joint of adhesive. The fact that wood on the end grain is most porous explains in part the weakness of end-grain to end-grain adhesive bonds. On the radial and tangential surfaces, porosity is much reduced. Sufficient pressure can be applied to achieve a thin, uniform bondline without forcing all the adhesive out of the bondline, although there may still be large differences between earlywood and latewood. Very porous woods or high-density woods with zones of high porosity, like the oaks and southern pines, are often difficult to bond even on the radial and tangential surfaces because capillarity and bonding pressure draw or force adhesive away from the bondline, leaving the joint in an adhesive-starved condition in those regions.

Anisotropic permeability also affects the rate of loss of water or other liquid carriers from an adhesive. Some adhesives are quite sensitive to the relationship between the liquid carrier content and the cross-linking reaction. If the carrier is removed too rapidly, the adhesive molecules will not have the mobility necessary for optimum cross-linking. If the carrier is removed too slowly, full cure may not be achieved (Moult 1977, Pillar 1966). Thus, differences between the radial and tangential surface permeabilities and between earlywood and latewood permeabilities may account for some variability in bond quality that occurs between radial and tangential surfaces and in coarse-textured woods that are likely to exhibit large differences in the permeability between earlywood and latewood.

Swelling and Shrinking. Between the oven-dry moisture content and the fiber saturation point, wood swells or shrinks depending on whether it is gaining or losing moisture. Longitudinal shrinkage amounts to only 0.1-0.3%, but it can have a strong effect because of the high longitudinal modulus. Longitudinal shrinkage is significantly greater in veneers with cross-grain, in reaction wood, and in juvenile wood than in normal straight-grain wood. Even small differences in longitudinal shrinkage can have significant effects upon the performance of certain types of bonded products. Lateral shrinkage (radial and tangential) is much greater. Lateral shrinkage varies greatly between species, with density, and between the radial and tangential directions within a given species (Table 1.3). In common U.S. woods, the tangential shrinkage ranges from about 4.5 to 12.5% over the range of moisture content from the fiber saturation point to oven dry. The radial shrinkage ranges from about 2.0 to 8.5% over the same range. Generally, tangential shrinkage is two times greater than radial shrinkage;

Table 1.3 Tangential and Radial Shrinkage from Fiber Saturation to Oven-Dry Condition for Selected Species

Species	Shrinkage (%)		Tangential/ radial
	Tangential	Radial	
Southern magnolia	6.6	5.4	1.2
Yellow birch	9.2	7.2	1.3
Eastern redcedar	4.7	3.1	1.5
Douglas fir	7.8	5.0	1.6
Redwood	4.4	2.6	1.7
Hard maple	9.5	4.9	1.9
Red oak	8.9	4.2	2.1
American beech	11.0	5.1	2.2
Western hemlock	6.8	3.0	2.3
American elm	9.5	4.2	2.3
White pine	6.0	2.3	2.6
Black willow	8.1	2.6	3.1

however, the ratio varies from 1.2 to 3.3 depending on species (Forest Products Laboratory 1987, Noack and Schwab 1973). These differences are thought to be due to the restraint of ray cells on swelling and shrinking of the longitudinal cells in the radial direction. The lower density earlywood also has a lower tendency to swell and shrink (swell-shrink coefficient) compared to the latewood. Swelling in the tangential direction is dominated by the higher swelling and shrinking latewood, which forces the earlywood to move as the latewood moves. In the radial direction, however, the lower swelling and shrinking earlywood can act independently, thus minimizing radial movement.

When wood swells and shrinks, stresses develop that can rupture the adhesive bond or the wood, whichever is weaker. Stresses develop because the dimensional changes are anisotropic. Woods with low tangential (T) and radial (R) shrinkage coefficients and low T/R ratios (Table 1.3) are more stable and less likely to warp, crack, or delaminate when moisture content changes after bonding or later in service. The T/R anisotropy of swelling and shrinking is a critical factor in the performance of most adhesively bonded joints in furniture construction. Anisotropy must also be considered in the selection and machining of lumber for edge-glued panels. The T/R ratios of <1.6, 1.6-2.0, and >2.0 are considered favorable, normal, and unfavorable, respectively, from a technological view (Noack, Schwab, and Bartz 1973).

Actually, adhesive bonding can be used to overcome some problems caused by anisotropy, or even to take advantage of anisotropy, as illustrated by the following examples. First, lumber can be dried free of strength-reducing checks; large, solid beams cannot. However, large beams can be made free of checks by bonding together pieces of carefully dried, check-free lumber. Second, T/R anisotropy of swelling and shrinking is very small compared to T/L and R/L anisotropy. These last ratios may be as high as 100:1. Wood products manufacturers take advantage of this fact to create dimensionally stable wood panels. Cross-banded furniture panels, plywood, and structural flakeboards are dimensionally stable in the plane of the board because lateral swelling and shrinking of the components is restricted by adjoining components. The grain directions of adjoining lumber, veneer, or flakes are by design or chance at an angle, often a right angle, to each other. Thus, lateral movement of each piece of lumber, veneer, or flake is restrained through the adhesive bond by the low longitudinal movement and high stiffness of its neighbor. As a result, movement in the plane of the panel is not much greater than movement of solid wood in the longitudinal direction.

D. Mechanical Properties

Wood strength and other mechanical properties are extremely variable between species, within a species, within a given tree, and in different directions within the tree. In this section, we will outline the mechanical properties of greatest importance to wood as an adherend and discuss their variability.

Strength

Fibers and Clear Wood. Strength is usually of most concern. The strength of individual wood fibers varies widely. Fibers are extremely strong in the longitudinal direction, with tensile strengths in the range of 40,000-140,000 lb/in.^{2} based on the type of cell and wood species (Mark 1967). Wood, for many reasons, is not that strong, but in the longitudinal direction, the strength of clear straight-grained lumber parallel to the grain ranges from 10,000 lb/in.^{2} to as high as 20,000 lb/in.^{2}.

An adhesive bond would require similar strengths to join wood fibers or lumber pieces end to end (a tensile butt joint). Neither people nor nature has devised an adhesive capable of such strength. In a simplistic way, the stress on the adhesive bond in a tensile butt joint is equal to the force applied at the ends of a fiber or wood member divided by the area of the bond (Figure 1.8a). Obviously, a larger bond area would reduce the stress. Unfortunately, the bond area of the end of a fiber or piece of lumber is limited to the diameter of the fiber or the transverse dimensions of the lumber. However, this problem can be overcome by overlapping and bonding fibers or members to form joints that are stressed in shear instead of tension. The bond area on the side of the fiber or member can be easily increased by increasing the amount of overlap. Thus, the same force can be transmitted from one fiber or member to another at a much lower bond stress (Figure 1.8b.c). This explains why both people and nature rely on large, lateral, shear bond areas (lap joints). (Notice the overlapping shear joints between fibers in Figure 8c.)

This example explains why the shear strength of wood parallel to the grain (Figure 1.9a,b) is particularly important. Tension strength perpendicular to the grain (Figure 1.9c-f) is important because significant tensile stress perpendicular to the grain arises in most shear-type joints, and when wood shrinks after bonding. Shear strength perpendicular to the grain, or “rolling shear” (Figure 1.9g,h), is important in plywood and certain types of assembly joints where the adherends are bonded with their grain directions at an angle to each other. The term rolling shear arises from the tendency of the cells to roll under this type of loading. Rolling-shear strength has not

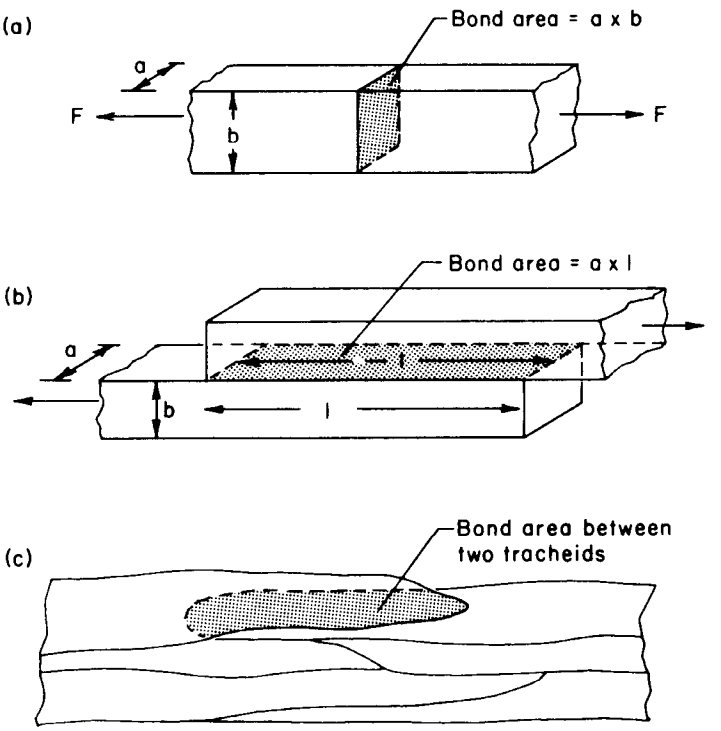


Figure 1.8 Adhesive bond areas of different types of joints: (a) the fixed maximum area of a tensile butt joint, (b) the easily increased or adjustable shear bond area of a lap joint, and (c) the large shear bond area formed by the overlap between the tapered ends of the two wood tracheids. Note that the bond area of the butt joint is limited by the cross-sectional area, but the bond area of the lap joint is limited only by the length of the overlap.

been measured for individual fibers, but rolling-shear strength values are undoubtedly much lower than the longitudinal fiber strength values. Representative shear parallel to the grain, tension perpendicular to the grain, and rolling-shear strength values of various solid woods are given in Table 1.4.

Compression strength perpendicular to the grain is important during processing the wood surface for bonding and when applying pressure during bonding. Pressure from dull or improperly

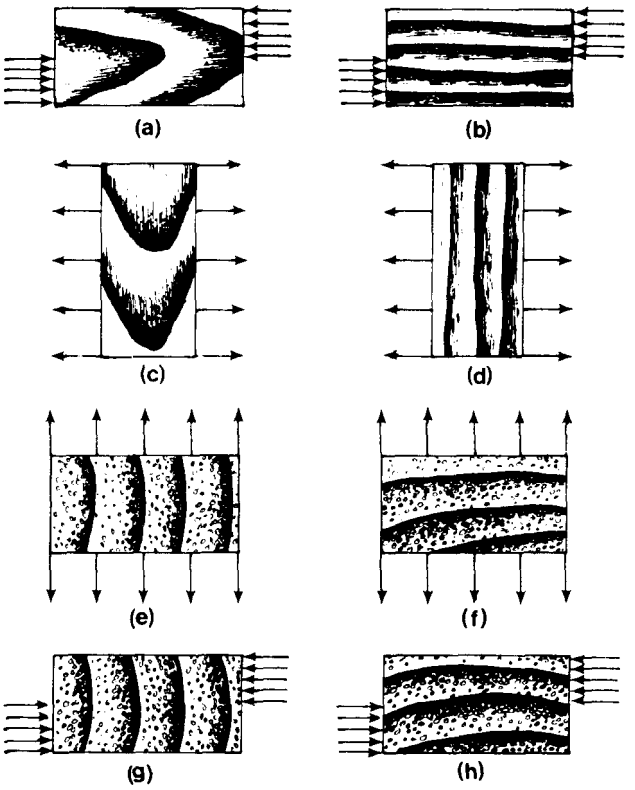


Figure 1.9 Shear and tension modes of loading wood in relation to its orthotropic structure: (a) shear in the longitudinal direction on the LR plane, (b) shear in the tangential direction on the LT plane, (c and e) tension perpendicular to the grain on the LR (or RL) plane, (d and f) tension perpendicular to the grain on the LT (or TL) plane, (g) shear in the radial direction on the RL plane (rolling shear), and (h) shear in the tangential direction on the TL plane (rolling shear).

sharpened cutters, from abrasive planing, and from feed rolls or pressure bars can exceed the strength of the wood and cause permanent and irreparable damage. Excessive pressure during bonding can also cause permanent damage that weakens the surface and detracts from the strength and durability of the bonded joint.

Table 1.4 Strength of Selected Woods at 12% Moisture Content under Various Types of Loading

Species	Strength values (lb/in.^{2})		
	Shear parallel to grain	Tension perpendicular to grain	Rolling shear
Ash spp.	2232-2815		782–1308[a]
Quaking aspen	850	260	
Beech spp.	2090-2360		625–1038[a]
Yellow birch	1880	920	
Black cherry	1700	560	
Sugar maple	2330	–	
Red oak	1780	800	
White oak	2000	800	
Black walnut	1370	690	
Yellow poplar	1190	540	
Port orford cedar	1370	720	325[b]
Western redcedar	990	220	194[b]
Coast Douglas-fir	1130	340	
Balsam fir	944	180	216[b]
Subalpine fir	1070	–	208[b]
White fir	1100	300	
Western hemlock	1290	340	
Pine spp.	1265-1592		256-569[a]
Loblolly pine	1390	470	
Ponderosa pine	1130	420	
Sugar pine	1130	500	293[b]
Western white pine	1040	–	297[b]
Redwood	1110	250	
Black spruce	1230	550	273[b]
Englemann spruce	1200	350	
White spruce	970	430	259[b]
Red spruce	1290	350	259[b]
Sitka spruce	1150	370	252[c]

[a]Kollman and Cote (1968).
[b]Bendtsen (1976).
[c]Munthe and Ethington (1968).

Species Differences. Based on the data in Table 1.4, shear strengths parallel to the grain range from about 1000 to 3000 lb/in.^{2}, whereas tension strengths perpendicular to the grain range from about 200 to 1000 lb/in.^{2} The importance of the rolling-shear strength of wood has only recently been recognized so little data are available, but the rolling-shear strength for a given species is apparently in the same range as the tension strength perpendicular to the grain.

Based on tests of some 50 species, the coefficient of variation for wood strengths are 14% for shear parallel to the grain and 25% for tension perpendicular to the grain at a given moisture content (Forest Products Laboratory 1987). Of course, many factors affect the strength of wood in service, so the variation of individual pieces of wood of a given species may be higher than these values. Among the most important factors are density, moisture, temperature, and growth characteristics, such as knots and other grain deviations.

Density Effect. The strength of clear, straight-grain, defect-free wood can be approximated by the relationship

$$S = KG^n$$

where S is a property such as shear strength, K and n are constants for that property, and G is the specific gravity. The exponential factor n ranges from 0.55 to 2.25, depending on the property, on whether the wood is a softwood or a hardwood, and on the wood moisture content. As an example, the Wood Handbook (Forest Products Laboratory 1987) provides the following general relationships for the shear strength parallel to the grain of softwoods and hardwoods :

$S = 2430G^{0.86}$ for softwoods

$S = 3200G^{1.15}$ for hardwoods

The fact that n exceeds 1.0 means that the strength increases faster than would be expected from the simple increase in the amount of wood substance. The explanation for this increase must lie in the changing ratios of the three major cell wall constituents and the changing ratios of the three secondary cell-wall layers. For a given species, the specific gravity, shear plane (LR compared to LT), moisture content, and extractive content are major causes of variation in the relationship of specific gravity to mechanical property.

High levels of extractives distort the relationship between specific gravity and mechanical properties. For example, in an unpublished experiment conducted by one of the authors, a specimen of western larch wood was found to have a dry specific gravity of

0.55. Based on this density, the relationship of density to specific gravity predicts a modulus of rupture of 13,665 lb/in.^{2}; however, the measured value was only 6048 lb/in.^{2} Hot-water extraction revealed that 30% of the dry weight of the wood consisted of extractives. The dry specific gravity of the wood after extraction or, in other words, the specific gravity based primarily on the amount of wood substance was only 0.36. The predicted modulus of rupture based on the extractive-free density was 8757 lb/in^2, much closer to the observed value. Wood with high extractive content may actually be stronger in compression and hardness perpendicular to the grain than expected for its density, but lower than normal in bending, tension, and other strength properties.

Moisture Content Effect. Air- and kiln-dried wood are hygroscopic Adsorption of water and other polar liquids expands the intermolecular spaces and reduces direct hydrogen bonding within the cell wall. These actions plasticize the wood and reduce its strength. Between the oven-dry condition and the moisture content at which all the intermolecular spaces are fully expanded (*fiber saturation point*), the strength decreases by 40-60% depending on the property and the species of wood. The sensitivity of the strength property to moisture content varies with the species and property, as shown in Figure 1.10. The relationship can be described by the equation (Forest Products Laboratory 1987) :

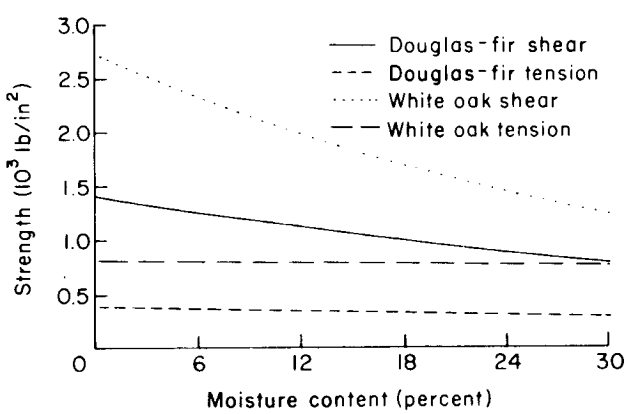


Figure 1.10 The temporary effect of wood moisture content on shear strength parallel to the grain and tensile strength perpendicular to the grain.

$$P = P_{12}\left(\frac{P_{12}}{P_g}\right)^{(12 - M)/(M_p - 12)}$$

where P is strength at the desired moisture content, P_{12} is strength at 12% moisture content, P_g is strength of wood above the fiber saturation point, M_p is moisture content approximating the fiber saturation point below which strength begins to change, and M is moisture content for which the strength is to be determined.

Values for P_{12} and P are tabulated for most commercial North American woods in the Wood Handbook (Forest Products Laboratory 1987) and in ASTM D 2555 (ASTM 1989a). The relationship between strength and moisture content is temporary and largely reversible within normal service temperatures and the expected service environment of most wood products.

Temperature Effect. Temperature has temporary and permanent effects on strength. The temporary effects are reversible and linear in the range between at least -70 and 150°C as long as the moisture content is constant. Increasing moisture content increases the rate of change of strength with temperature (Figure 1.11). For example, increasing the service temperature from 20 to 50°C will cause the following reductions in shear and tensile strengths (Forest Products Laboratory 1987) :

Strength property	Moisture content (%)	Strength loss (%)
Shear parallel to the grain	Above fiber saturation point	25
Tension perpendicular to the grain	4-6	10
	11-16	20

As mentioned previously, elevated temperatures have a measurable and permanent effect on strength. The permanent effect follows the Arrhenius time-temperature relationship (Stamm 1964b) :

$$\log_{10} t = A + B/T$$

where t is aging time, T aging temperature in degrees Kelvin, A material constant, and B temperature coefficient. Experimental results suggest that if wood is kept dry, it will lose about 25% of its original strength in about 2500 years. This is borne out by the condition of dry wood artifacts discovered in Egyption tombs. The thermal/chemical changes wrought by short-term exposures to higher temperatures are cumulative and are not recoverable. The same 25%

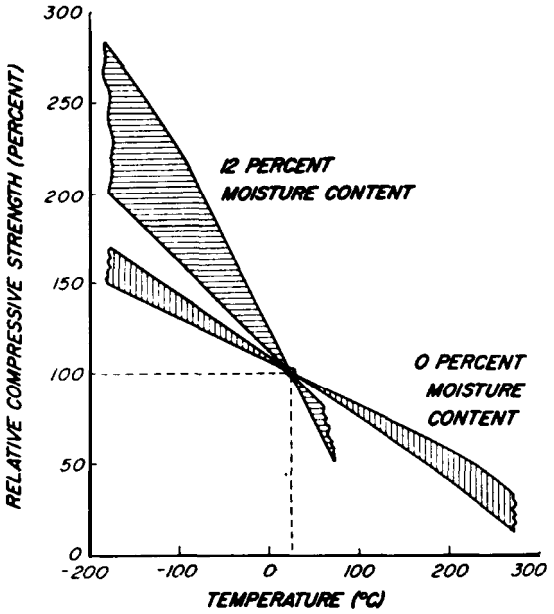


Figure 1.11 The temporary effect of temperature on the compression strength parallel to the grain at two moisture contents relative to the strength at 20°C.

loss will occur within only 1000 to 2000 days of aging at 100°C and in only 1-2 days of aging at 170°C.

Moisture accelerates cellulose hydrolysis at elevated temperatures. The moisture content of the wood, particularly if it is high, increases the temperature coefficient by at least 10 times. Wet wood will lose 25% of its original strength in 80-400 years at 20°C. The same loss will occur in 100-2000 days at 60°C, and in only 2-4 days at 100°C (Millett and Gillespie 1978). Equations for the time to lose 25% of the original shear strength of two species are as follows (Millett and Gillespie 1978) :

	Condition	
Species	Oven-dry	Soaked
Hard maple	$\log_{10} t = -17.308 + 7614/T$	$\log_{10} t = -15.185 + 5758/T$
White pine	$\log_{10} t = -16.222 + 7268/T$	$\log_{10} t = -16.145 + 6246/T$

Effect of Grain and Growth–Ring Angle Effect. Aside from the obvious effect of a large knot or knothole, the direction of loading with respect to the grain angle and the growth-ring direction probably has the most pronounced effect on mechanical properties. That the strength of wood differs in various directions of the grain is common knowledge. For example, we know that wood can be split quite easily along the grain, but we must laboriously chop or saw it across the grain. As children we are taught to hold a baseball bat with the trademark (tangential face) up as it strikes the ball because the bat is less likely to break than if held the other way. These are familiar effects of the anisotropic mechanical properties of wood.

The outstanding effects of wood anisotropy are due to large differences between the :

1. Elastic modulus and strength in the longitudinal direction, and the elastic moduli and strengths in the tangential and radial directions.
2. Rolling-shear modulus and strength, and the shear moduli and strengths in the longitudinal/tangential and longitudinal/radial directions.
3. Lateral contractions in the radial and tangential directions under longitudinal load, and the longitudinal contraction under either tangential or radial loading.

The general relationships of the major mechanical properties of wood in the different directions are shown in Table 1.5. In the table, the tensile modulus along the grain is in the range of 13-20 times higher than that of properties across the grain. Kollman and Cote (1968) summarized the properties for a group of 7 softwoods and 14 hardwoods from several sources. Their summary shows that the difference between the longitudinal and tangential directions is on the order of 10-25 times, whereas the difference between longitudinal and radial directions is on the order of 5-20 times. In some species, the longitudinal properties may be less than 10 times or greater than 40 times the lateral property. However, these strengths are for clear wood; the differences are considerably smaller when comparing lumber with typical defects, such as knots, that greatly reduce the longitudinal strength. The longitudinal shear strength is about 30 times higher than the shear strength in the tangential and radial directions (Table 1.5). As a general rule, the directional differences in the mechanical properties of hardwoods are somewhat smaller than these differences in softwoods. The smaller difference in hardwoods is thought to be due to the effects of the greater volume of rays (Schniewind 1980); rays presumably increase properties in the radial direction with some sacrifice of properties in the tangential and longitudinal directions.

Table 1.5 Representative Mechanical Properties of Wood in the Three Principal Directions

	Strength (lb/in.^{2})	Elastic modulus (lb/in.^{2})	Contraction/elongation[a]		
			Longitudinal	Radial	Tangential[b]
Tensile load direction					
Longitudinal	15,000	2,000,000	–	0.30	0.45
Radial	470	150,000	0.04	–	0.40
Tangential	420	100,000	0.03	0.40	–
Plane of shear failure					
Longitudinal/radial	1,370	120,000			
Longitudinal/tangential	1,430	150,000			
Radial/tangential	350	15,000			

[a]Poisson's ratio.
[b]Direction of contraction.

Both modulus and strength differences between the radial and tangential directions are much smaller, generally not exceeding 1.5 times in North American woods. Strength of the longitudinal/tangential (LT) plane is often higher. Data from a Canadian source, which lists both LT and longitudinal/radial (LR) shear strengths, offer the opportunity to compare these differences (Forest Products Laboratories of Canada 1956). Table 1.6 shows the average percentage of difference between the strengths in the LT and LR planes for a group of 21 softwood and a group of 32 hardwood species. In most species, the strength in the LT plane is higher than that in the LR plane, and the difference between LT and LR strengths is less than 10%. In contrast, the tensile modulus when load is applied in the radial direction is usually higher than that when load is applied in the tangential direction (Table 1.5). This is due to two factors. The first factor is the reinforcement in the radial direction by the ray cells, which are oriented radially instead of longitudinally. The second factor is the additional bending of the cell walls in the tangential direction stemming from the staggered position of cells in adjacent rows. The ratio of lateral contraction to elongation in the direction of an applied tensile load (Poisson's ratio) is large (0.30 to 0.45) when load is applied parallel to the grain, but quite small (0.03 to 0.04) when load is applied perpendicular to the grain.

Table 1.6 Differences in Strength Between the Tangential-Longitudinal and Radial-Longitudinal Planes

	Difference (%)		Differences (number)			Plane with higher strength (number)		
	Range	Mean	Over 10%	Over 20%	Over 30%	Tangen-tial	Radial	No change
21 Softwoods								
Shear parallel to grain	0–12.1	4.1	2	0	0	7	10	4
Tension perpendicular to grain	0–32.2	12.4	14	2	1	17	2	2
32 Hardwoods								
Shear parallel to grain	0.6–35.4	10.0	16	2	1	28	4	0
Tension perpendicular to grain	0.9–36.9	18.7	27	16	5	31	1	0

The differences in strength and elastic properties such as those summarized in Tables 1.5 and 1.6 are responsible for much of the stress that develops in adhesively bonded joints and materials as the wood swells and shrinks. Changing the grain direction by 90° with respect to the applied load direction reduces shear strength by 60-80% and tensile strength by 93-96%. These large differences in properties between orientations parallel and perpendicular to the grain have already been described (Table 1.5). However, loads are often applied at angles between 0 and 90° to the grain direction because of the growth patterns, the way the board was cut, or the design of the bonded joint or product. Strengths at these intermediate angles follow a continuous function (Figure 1.12) often described by a Hankinson-type relationship (Forest Products Laboratory 1987) :

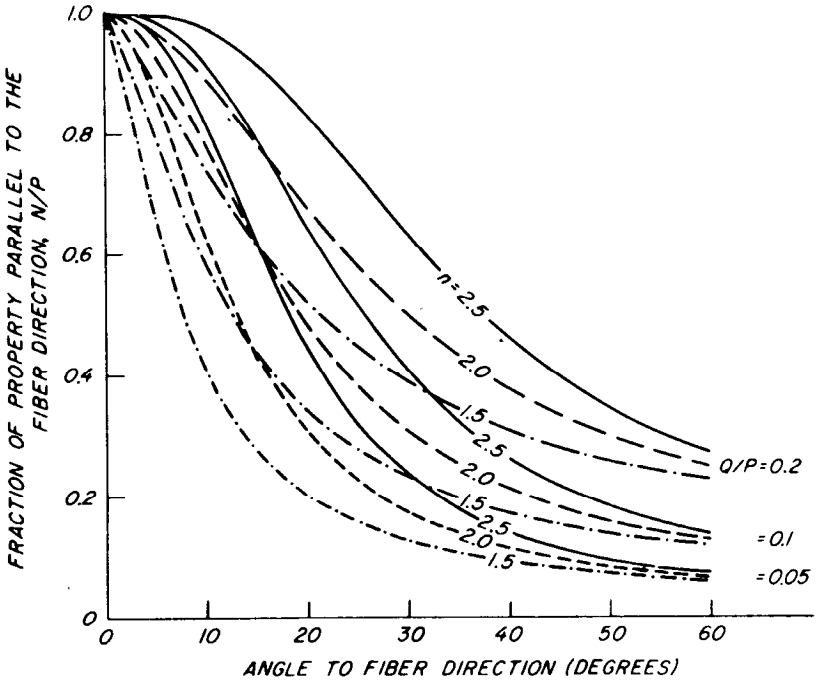


Figure 1.12 The effect of grain angle on mechanical properties of wood according to the Hankinson-type formula. Q/P is the ratio of the mechanical property across the grain (Q) to that parallel to the grain (P) ; it is an empirically determined constant.

$$N = \frac{PQ}{P \sin^n \theta + Q \sin^n \theta}$$

where N is strength, P is strength parallel to the grain, Q is strength perpendicular to the grain, n is an empirically determined constant between 1.5 and 2, and θ is the angle between the load and fiber directions. Generally, the ratios between strength values parallel and perpendicular to the grain range from 0.04 to 0.07 for tension and from 0.20 to 0.45 for shear, although shear behavior has not been thoroughly studied (see Table 1.4).

Fracture

Wood is a fibrous, laminar, anisotropic material. Cracks initiate and propagate easily in planes parallel to the fibers, but with great difficulty in the plane perpendicular to the fibers. In planes parallel to the fibers, the actual values of fracture toughness for wood parallel to the fibers range from 50 to 1000 J/m^2, and perpendicular, from about 10 to 30 kJ/m^2. These values are comparable to artificial fiber composites (Jeronimidis 1976). The fracture toughness across the grain is 10^4 J/m^2; comparable on a weight basis with the energy consumed during crack propagation in ductile metals (Gordon and Jeronimidis 1974).

Locus of Fracture. The modes of wood fracture most important to adhesive bonding and bond performance are shear parallel to the grain and tension perpendicular to the grain, or a combination of these. Transverse tensile fractures are common in earlywood cells but less common in latewood cells. In some instances, the damage resulting from excessive compression stress is important to performance. In most cases, however, fracture in service will actually occur in shear or tension.

At the molecular level, Porter (1964) found that fracture occurs in the amorphous, water-accessible regions rather than in the crystalline cellulose regions of the cell wall. At the microscopic level, wood fractures in different locations depend on the type of cell, direction of load, temperature, moisture content, speed of test, grain angle, pH of adhesive, pH of wood, aging of wood, and, in the case of adhesively bonded wood, penetration of adhesive.

At the microscopic level, there are three types of fracture: transwall, intrawall, and intercellular. A longitudinal *transwall* crack passes through the cell wall and across the cell lumen (Figure 1.13a). A longitudinal *intrawall* crack travels within the cell wall and around the lumen (Figure 1.13b). An *intercellular* crack occurs when hot and wet wood is fractured (Figure 1.13c). Transverse transwall cracks (Figure 1.13d) may also occur. These characteristic types

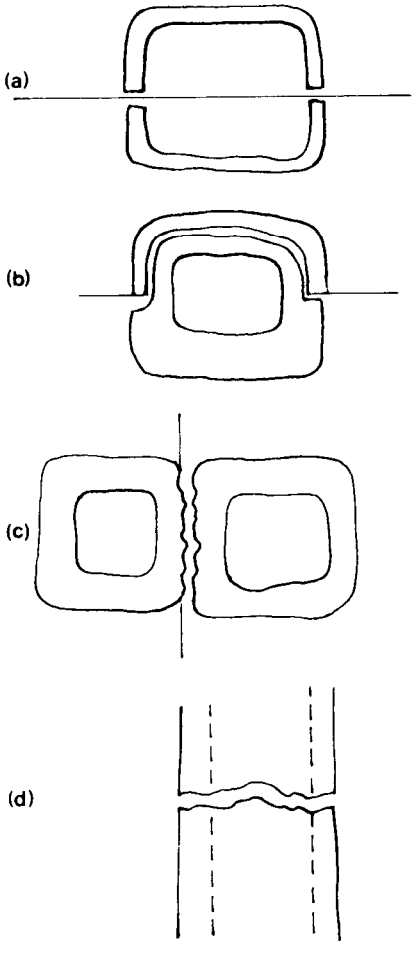


Figure 1.13 Schematic diagrams of typical loci of fracture in wood, (a) longitudinal transwall, (b) intrawall, (c) intercellular, and (d) transverse transwall.

of failure have been observed not only in solid wood but also in wood particles bonded with droplets of adhesive and in bonds formed by continuous films of adhesive between solid wood surfaces (Wilson and Krahmer 1976, Koran and Vasishth 1972).

Transwall failures are characteristic of thin-walled cells, such as the earlywood tracheids in softwoods and vessel and parenchyma

cells in hardwoods (Figure 1.14a). In these cells, the transwall fracture breaks the relatively thin layer of fibrils and leaves a smooth surface or a surface with only short fibril ends exposed (Figure 1.14b). When transwall failure occurs in combined shear and tension, the crack path follows the helical winding of the S-2 layer in a combined shear and tension failure (Figure 1.14c). Longitudinal transwall fracture of thick-walled cells is unusual but extremely fibrous (Figure 1.14d). Transwall fracture in the LT plane occurs preferentially in the first earlywood cells of a given growth ring in ring-porous hardwoods like oak and in coarse-textured softwoods like the southern pines. A mixture of transwall and intrawall fractures is more likely in the LR and intermediate planes as a result of the alternating bands of high- and low-density cells. Rarely, transverse transwall failure occurs at the tips of splinters where the stress concentrates in a few cells.

Intrawall failures are more characteristic of small-diameter, thick-walled cells, such as the latewood cells of softwoods and fibers of hardwoods. In these cells, which have a very strong S-2 layer, the crack tends to follow a weak plane within the cell wall or plane of stress concentration, such as between the S-1 and S-2 layers of the secondary wall, rather than breaking the fibrils (Figure 1.15). The fractured surfaces show the helical windings of the secondary wall layer through which the crack passes, or else these surfaces show the random fibril orientation of the primary wall (Figure 1.15b). Flaps of primary wall and S-1 layer are often present (Figure 1.15al.

When the wood is wet or hot, or when the load is applied very slowly, the intrawall crack may pass through the middle lamella/primary wall region, creating an intercellular fracture. When the wood is dry or cold, or when the load is applied rapidly, the intrawall crack will more likely pass through the S-1/S-2 region (Borgin 1971). The type of machining and conditions during machining also affect the crack path and the type of surface. For example, planing usually produces a longitudinal transwall fracture, exposing the cellulose-rich S-2 layer of the cell wall directly to the adhesive. On the other hand, lathe peeling of hot wet wood, as in veneer manufacture, tends to produce an intercellular fracture, exposing the lignin-rich middle lamella/primary wall region.

Transverse Fracture and Crack-Arrest Mechanisms. The great toughness of wood perpendicular to the grain is explained in part by the Cook-Gordon crack-arrest mechanism (Cook and Gordon 1964). This mechanism is operable in materials that are very strong in one direction but have perpendicular planes of weakness. Fiber reinforced plastic composites and wood are such materials. Wood, for example, is at least 20-30 times as strong in tension parallel to the grain as it is in tension perpendicular to the grain. Practical evidence of the difference can be found in the case of splitting

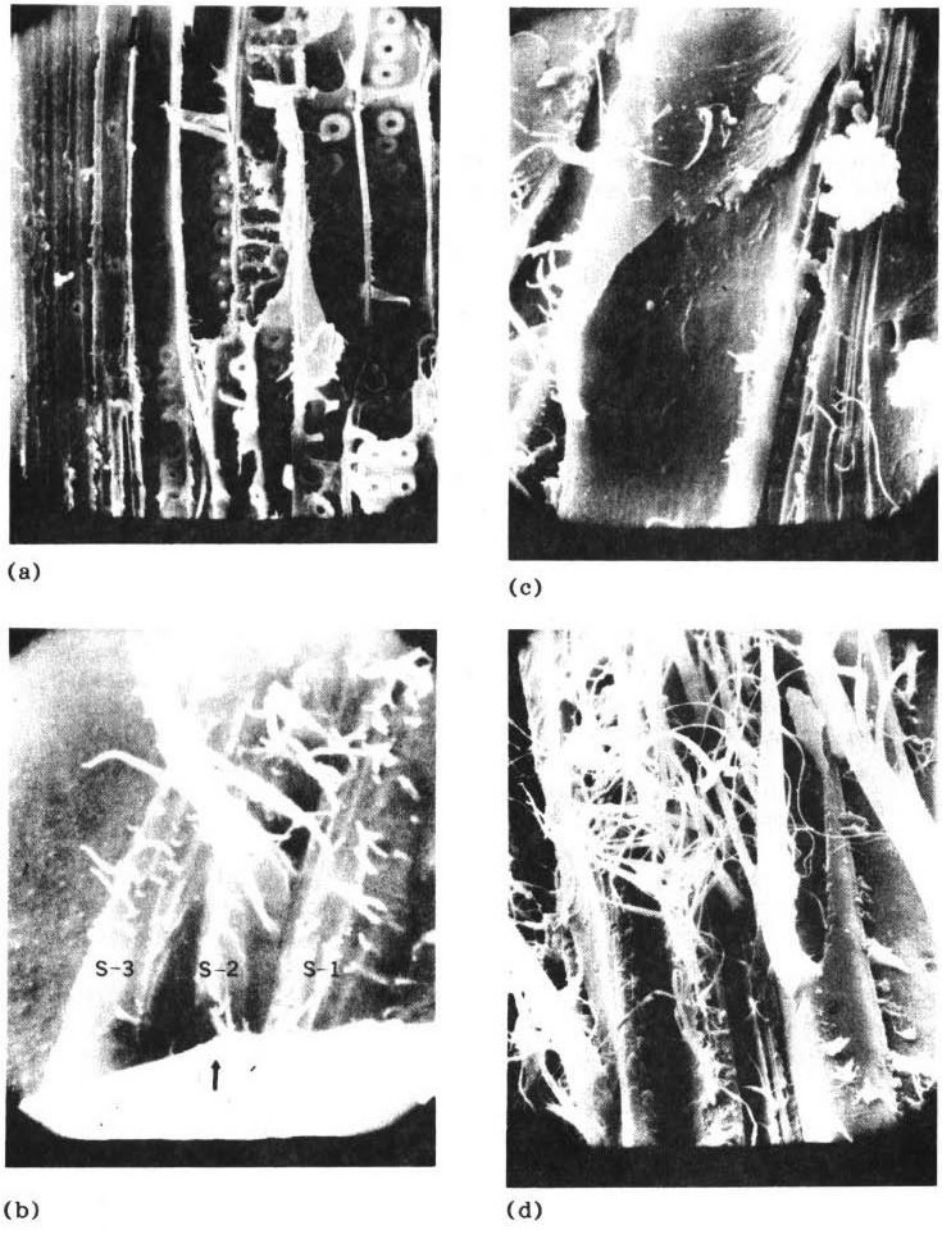


Figure 1.14 Scanning electron micrographs of typical transwall fractures in wood: (a) longitudinal fracture of thin-walled cells in shear parallel to the grain or in tension perpendicular to the grain, (b) transwall shear fracture of thin-walled cells showing relatively non-fibrous surface, (c) combined shear and tension fracture of a thin-walled cell, and (d) atypical transwall fracture of thick-walled cells showing extremely fibrous failure.

along the grain as compared to the toughness across the grain. When such materials are pulled in the strong direction, a crack tries to grow perpendicular to the direction of this primary stress. Secondary stresses arise in the vicinity of a flaw or crack. Some of these stresses act perpendicular to the strong direction; that is, they act in the weak direction. Although the secondary stresses are much smaller than the primary stress, they are sufficient to fail the wood in tension perpendicular to the grain (in the LT or LR plane), thus forming a secondary crack. The formation of secondary cracks consumes a great deal of energy and diverts the primary crack (Figure 1.16a). Secondary cracks are also responsible for the typical splintery fracture of tough wood in tension parallel to the grain and in bending (Figure 1.16b).

The other energy-consuming mechanism that opposes crack growth across the fibers is explained by Mark (1967) and Jeronimidis (1976). As a wood fiber elongates, the S-2 layer separates from the S-1 layer (intrawall fracture). After separation, The S-2 cylinder (the closed-end cylinder, formed of the helically wound S-2 and S-3 layers) twists and buckles inward. The twisting-buckling action allows the S-2 cylinder to elongate up to 18% before the cell finally ruptures. During this stage of elongation, energy is consumed by microcracking between the S-1 and S-2 layers and between microfibrils within the S-2 layer.

Fracture Along the Grain. Fracture of wood in a plane parallel to the grain (LR or LT plane), is dominated by the type of cell and the orientation of the growth rings (Johnson 1973). However, the two large energy-consuming mechanisms that are active during crack growth perpendicular to the grain do not act against a crack traveling along the grain. Cracks traveling in a plane parallel to the grain easily pass through or around cells (transwall and intrawall fractures). In this orientation, the strength of wood in the plane perpendicular to the direction of crack growth is greater than the strength in the plane of crack growth. This is just the opposite condition necessary for operation of the Cook-Gordon crack-arrest mechanism. Less energy consumption is also required because there is no buckling and twisting elongation of the S-2 cylinder. Fracture toughness in these planes is therefore greatly reduced. Since the crack-arrest mechanism also tends to force fracture along the grain, the fracture toughness of these weak planes, the LR and LT planes, is of primary importance to the performance of adhesive bonds in wood.

Modulus

The same major factors that affect wood strength-density, grain angle, moisture content, and temperature-have analogous effects

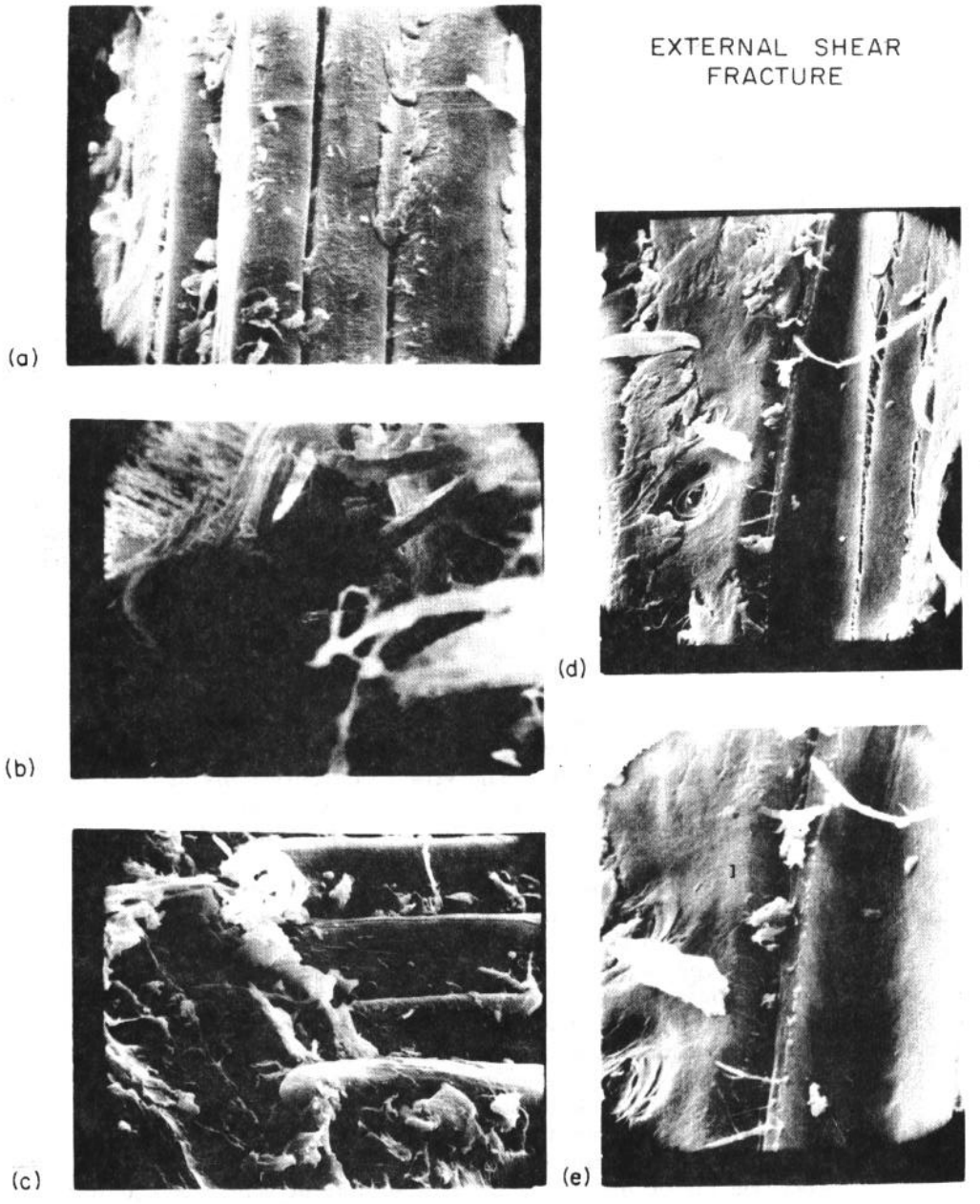


Figure 1.15 intra fracture: (a, c, d, e) Typical shear parallel to the grain or tension perpendicular to the grain fracture of thick-walled cells, (b) atypical logitudinal intrawall fracture between the S-1 and S-2 layers of a thick-walled cell.

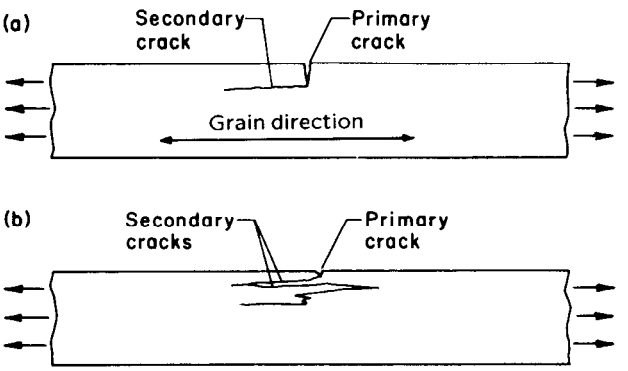


Figure 1.16 (a) Crack-stopping mechanism in wood stressed parallel to the grain or in bending, through the formation of a secondary crack in a weak plane ahead of the primary crack and at right angles to the direction of travel of the primary crack, and (b) typical splintery fracture of tough wood caused by secondary crack formation.

upon the elastic properties of wood. These properties, especially the modulus of the wood, affect stress concentrations in the vicinity of the bonded joint. The stress concentrations arise from the external loads during bonding and in service, and from the internal stresses that arise from swelling and shinking of the wood in service.

In bonding solid wood, the higher the modulus or resistance of the wood to deformation, the greater must be the force applied to the joint to affect a uniformly thin bondline. Likewise, the higher the modulus, the higher the springback stresses in the joint when the bonding pressure is released. The same principles hold for reconstituted panel materials The stiffer the wood flakes or particles, the more force required to compress the unbonded mat to the disired thickness and density, and the greater the tendency of those particles to spring back after pressing. These springback forces subtract from the strength of the adhesive bond in both solid wood joints and in reconstituted materials (Figure 1.17).

Geometric discontinuities occur at the ends of solid wood joints, and at the ends and edges of each flake or particle in reconstituted materials. When loads are applied to bonded joints, the higher the modulus of the wood, the greater the concentration of stress at each discontinuity. Failure initiates at these stress concentrations while the average stress level in the joint is well below

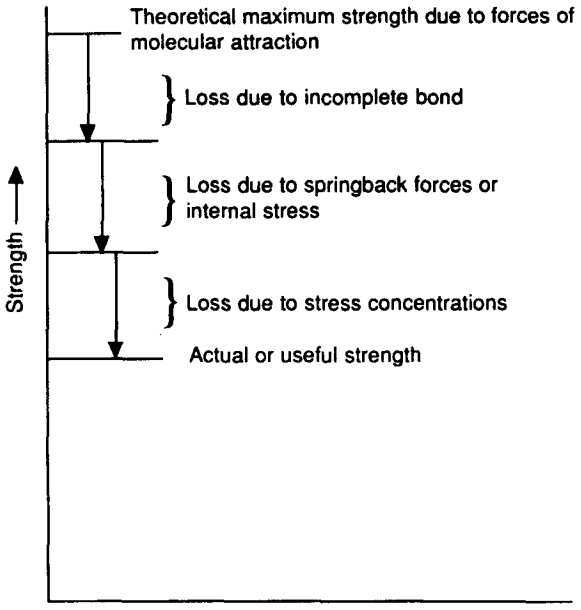


Figure 1.17 Schematic diagram of the maximum potential bond strength and the factors that reduce to the maximum effective bond strength, including internal stress and stress concentrations.

the strength of the adhesive. These relationships are discussed in more detail under the design of joints in Section VI.

The modulus of the wood is also an important factor controlling the magnitude of swelling and shrinking stresses that arise in solid wood and in bonded joints and materials. The effects of modulus are also discussed in Section VI.

Swelling and Shrinking Stresses

Wood can generate stress when it swells or shrinks if it is restrained (Perkitny and Kingston 1972). The restraint might be from an external load or from an adjacent wood member, or from differential shrinkage. As wood shrinks, the amount of stress that it can generate is limited by the tensile strength of the wood in the direction of the stress (Table 1.4). As the wood swells, the stress is limited by the swelling stress generated by voidless wood substance (1.44 specific gravity). Theoretically, this stress is 25,000 lb/in.^{2}, but the maximum that has been measured experimentally is

11,000 lb/in.^{2} (Tarkow and Turner 1958). Between these extremes, the stress that develops during swelling or shrinking is determined by the composition and construction of the cell wall, the wood structure, the degree of restraint, and the amount of moisture change. In swelling, whether the wood is absorbing water as liquid or as vapor also affects stress.

Swelling. The swelling stress exerted by wood correlates with several physical and mechanical properties of the wood. However, confounding factors include the increasing plasticity of the cell wall substance and the tendency of the cell wall to buckle into the lumen as the moisture content increases. Several researchers have measured swelling pressure (Kingston and Perkitny 1972, Kanno and Ishimura 1988). However, to our knowledge, a satisfactory model for predicting swelling stress has not been developed.

Density is a major factor in swelling. Kingston and Perkitny (1972) measured swelling stresses under complete uniaxial restraint for 46 species. A plot of their data as a function of density shows a reasonably strong relationship (Figure 1.18). Somewhat higher variability at higher densities is probably due to increasing variability in factors such as the cell wall structure and the type and amount of extractives. As a general rule, common commercial woods

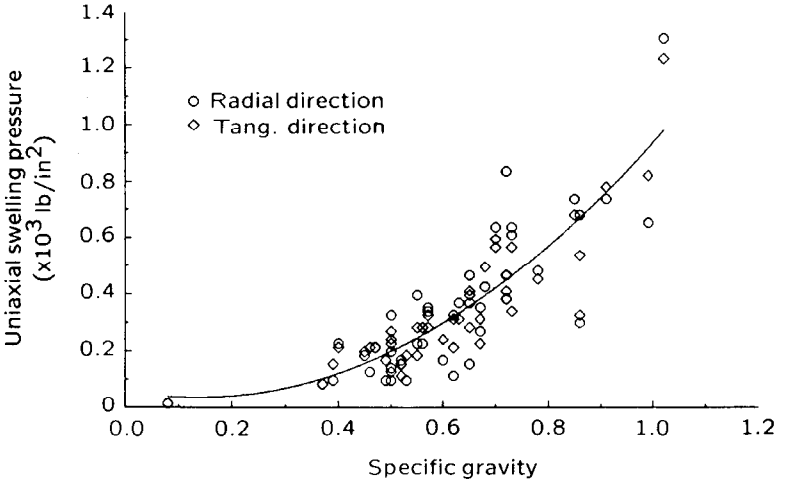


Figure 1.18 The dependence of maximum swelling pressure under uniaxial restraint upon the density of the wood.

with densities in the range of 0.4–0.8 g/cm^2 are apparently capable of generating lateral swelling stress in the range of 100-600 lb/in.^{2} after about 100 min of soaking. After about 100 min, plastic deformation and buckling of the cell walls begin. During the next 1000–5000 min, the swelling stress decreases by as much as 30–50%, even as moisture content continues to increase.

At lower moisture contents before buckling occurs, the swelling stress is also a function of the ratio of tangential to radial swelling (T/R ratio, Table 1.3), the Poisson's ratio, and the ratio of modulus of wood to modulus of restraining body (Kanno and Ishimura 1988). Under uniaxial restraint, Kanno and Ishimura found that swelling pressure was greater in the radial direction than in the tangential direction. If wood is restrained in both lateral directions, the swelling stress, for a given moisture content increase, increases from 20 to 40%, with larger increases occurring in denser wood and under greater restraint (Kanno and Ishimura 1988). Under both uniaxial and biaxial restraint, the swelling stress increases as a direct function of the logarithm of the modulus of the restraining body and the density of the wood.

Swelling stresses are important to the performance of bonded joints and materials because a swelling stress is imposed on the adhesive at the same time that the moisture content of the adhesive is increasing, which softens and weakens the adhesive. Strength loss of the adhesive may be recovered upon drying, if the adhesive has not ruptured. This behavior is discussed in Section VI.

Shrinking. The shrinkage stresses that develop in wood when it dries under uniaxial and biaxial restraint are probably similar in magnitude to and controlled by the same factors that control the swelling stress of wood. In drying, however, the moisture gradient, which undoubtedly is present during water absorption, plays a significant role. This moisture gradient has several effects that are more important during desorption than during sorption. First, the wood at the surface is shrinking (under tension), while the wood in the interior remains in its original swollen state (under compression). Second, the modulus of the wood is increasing, so stress increases faster for each decrement of moisture content. Third,' the wood becomes more elastic and less plastic, and therefore less able to accommodate large tensile strains during shrinkage. The end result is that during drying, tensile stresses arise that can cause fracture. In contrast, during swelling, compressive stresses develop more slowly; although the compressive stresses may cause buckling or warp, they are less likely to fracture the wood or the joint.

Several authors have developed theoretical models for predicting drying stresses as a function of drying time and other conditions

(Youngs and Norris 1958; Kawai, Nakato, and Sadoh 1979a,b; Morgan, Thomas, and Lewis 1982). The models show that critical tensile stresses occur within minutes to several hours upon exposure to drying conditions, depending on the severity of those conditions. Because of the importance of drying stresses to delamination, some of these models are discussed in more detail in Section VI. Drying stresses are also important in the performance of bonded joints and materials because they can cause dimensional instability.

E. Thermal and Dielectric Properties

Thermal Properties

Normally, the low thermal conductivity of wood is touted as one of its stellar properties in terms of insulating value. Compare the values of wood with other materials in Table 1.7. However, our interest is the effect of wood thermal conductivity on curing of

Table 1.7 Thermal Conductivity of Wood and Other Materials

Species	Density (lb/ft^3)	Thermal conductivity (k)[a]	Source[b]
Air	0.08	0.07	1
Balsa	7.1	0.31	1
Ceiba	7.1	0.33	1
Sawdust	12.0	0.40	1
Planer shavings	8.8	0.42	1
Cypress	29	0.67	1
White pine	32	0.79	1
Mahogany	34	0.92	1
Virginia pine	34	0.96	1
Oak	38	1.00	1
Maple	44	1.12	1
Window glass	--	3.6–7.2	2
Brick, common	--	4.8	2
Concrete		11–16	2
Steel	--	315	2
Aluminum	--	1400	2

[a]k, Thermal conductivity in Btu in./h ft^2 °F.
[b]1, ASTM (19891); 2, Kellogg (1981).

adhesives at elevated temperatures. The rate of heating of the uncured adhesive is an important variable in manufacturing plywood and other panel products. The lower the thermal conductivity, the slower the penetration of heat to the bondline, and thus the slower the cure. Slower cure means lower output and higher costs. Thermal conductivity increases with wood density (Table 1.7), moisture content, extractive content, and temperature. Thermal conductivity is greater (often as much as 2.5 times) parallel to the grain than perpendicular to the grain. The major factors are density and moisture content. Thermal conductivity for most wood species can be estimated from the relationship

$$k = S(1.39 + 0.028M) + 0.165$$

where k is thermal conductivity in Btu in. /h ft^2 °F, S is specific gravity based on volume at ambient moisture content and oven-dry weight, and M is moisture content as a percentage of oven-dry weight.

The relationship is presented graphically in Figure 1.19. The figure shows that heat transfer in bonding can be facilitated by using high pressure to density the veneer or mat of particles, and by using veneer or particles at high moisture content. The pressure and moisture content must be moderated, however, by the limits of the crushing strength of the wood and the curing behavior of the adhesive. These relationships are discussed more fully in Section V (bonding).

Dielectric Properties

When wood or any nonconductor is placed in a high-frequency electric field, some electric energy is stored by the material and recoverable as electric energy, and some is lost as heat. The dielectric power factor is a measure of the portion of the energy lost to heat. The dielectric power factor varies inversely with the resistivity and dielectric conductivity of the wood, and the frequency of the electric field. It varies strongly and directly with the moisture content of the wood, and directly but weakly with wood density. The dielectric power factor varies from 0 (no energy loss as heat) to 1.0 (all energy lost as heat) (Forest Products Laboratory 1987, Kellogg 1981).

The dielectric power factor of wood is important in curing adhesives with high-frequency energy. A joint or panel containing the wet adhesive is placed in a high-frequency electric field. The idea is to heat the adhesive, which has a very high dielectric power factor, and not the wood. Energy used to heat the wood is essentially wasted. The wet adhesive should have a dielectric power factor of

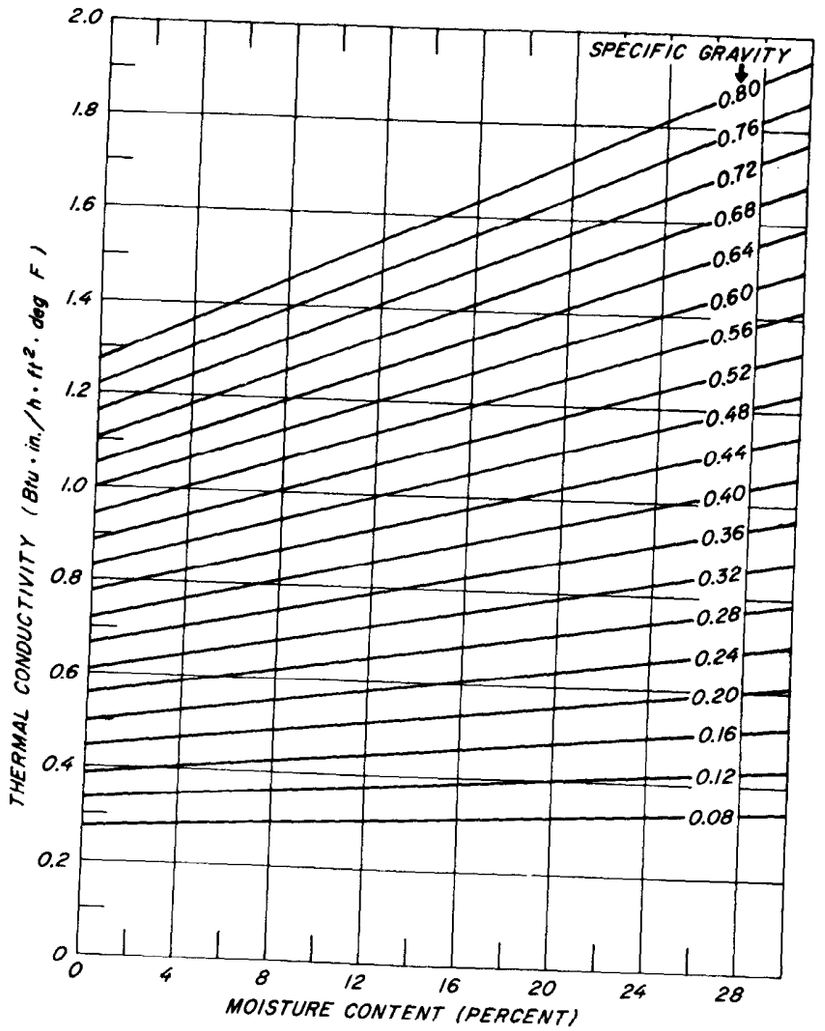


Figure 1.19 Computed thermal conductivity of wood perpendicular to the grain as determined by its moisture content and density.

1.0. The dielectric power factor of wood ranges from about 0.01 for dry low-density woods up to 0.95 for dense woods at high moisture content. Thus, radiofrequency curing of adhesives is most

efficient for dry, low-density woods. The highly variable dielectric properties of wood that determine the dielectric power factor interact in complex ways, causing it to rise and fall unpredictably at times. This may explain many of the difficulties some users experience in using radiofrequency heating for curing adhesives in wood joints and materials.

F. Wood Supply

The quality of the logs available for harvest directly affects the properties of the wood that is to be bonded. Among the more important factors are the maturity of the trees, the size of the logs, whether the logs are cut from live or dead trees, and whether the logs have been exposed to fire or subjected to insect, bacterial, or fungal attack.

The average age of the trees harvested and the average log size available for harvest have decreased over the last 25 years as old-growth timber is replaced with second growth and fast-growing plantation trees. The harvest of smaller, faster growing trees results in larger growth rings, coarser-textured wood, and higher percentages of juvenile wood (pith and core wood) in the lumber, veneer, flakes, or particles. In some species, faster growth means broader bands of difficult-to-bond latewood and possibly differences in the amount of extractive materials. In other species, faster growth means lower overall density. Juvenile wood is characteristically lower in density, latewood percentage, extractive content, and strength; however, it has higher porosity and longitudinal shrinkage than mature wood. These characteristics give juvenile wood distinctly different surface and bonding properties.

Another change, associated with the decreasing supply of logs in certain locations, is the increased use of logs from fire- and insect-killed trees. The wood from these trees is often partially dried or decayed. There is very little published information about the effects of these conditions upon the qualities of wood that are important to bonding. One particleboard manufacturer, who mixed particles from already-dry wood sources with those from green wood source?, found that the already partially-dry particles became overdried, and the overdried particles did not bond well. They tended to pull out of the surface during sanding, leaving small pits. These pits became a serious visual defect in panels overlaid with very thin films and intended for furniture manufacture.

Logs from salvage sales of timber stands damaged by fire, wind, or insects may contain decay. Heavily decayed wood seldom progresses beyond the primary or secondary breakdown of the log. In solid-wood products, the decay is usually detected visually and removed by trimming or edging. However, decay is more difficult to

detect in the early stages (incipient decay) and may end up in bonded solid-wood products. Should it escape detection, the decayed wood will be more porous, more permeable, and weaker than undecayed wood. Studies of Douglas fir veneer infected with white pocket rot revealed that such veneer could be adequately bonded with a wide variety of adhesives (Olson 1960). Plywood made from heavily infected veneers produced specimens with about half the strength of specimens from sound veneers. Block-shear specimens were made with either two sound adherends, one sound and one infected adherend, or two infected adherends. The specimens with one infected adherend were about 60% as strong as the control specimens, and the specimens with two infected adherends were about 44% as strong as the control specimens. Heavily decayed wood is more porous and permeable, properties that should lead to overpenetration by the adhesive-starved joints. In Olson's study (1960), higher spread rates and longer assembly times were found to control overpenetration and improve performance with soybean adhesive, but they were not effective with a hot-pressed phenol-formaldehyde adhesive.

In reconstituted products, the flaking process breaks heavily decayed wood into small fragments, which are removed during screen sizing of the flakes prior to bonding. However, wood containing incipient decay, decay that is not visible and that has not made the wood friable, may proceed into the manufacture of bonded products.

Logs stored in water for an extended time are thought to become infected with bacteria, Some living trees, such as the oaks, develop wet pockets in the heartwood that are caused by bacterial infection. This "wetwood" has different drying and processing characteristics than noninfected wood. Wetwood causes excessive drying defects, such as shake, checks, and collapse. Veneers with wetwood dry unevenly and have been identified as a source of bonding difficulty. One difficulty is reduced penetration by adhesives. The effects of the decay and bacterial organisms on adhesive wetting and the chemistry of cure are unknown; however, bacterial infections lower wood pH (Ward, USDA Forest Service, Forest Products Laboratoy, personal communication).

III. WOOD AND FIBER SURFACES

In this section we describe various methods for preparing wood surfaces, actions of cutting tools and their effects on surface quality, characteristics of prepared wood surfaces and how they interact with the adhesive during bonding, and influence of wood surface on the behavior of bonded joints and materials.

A. Surface Preparation

Three major reasons for preparing the wood surface before bonding are (1) to produce a close fit between the adherends, (2) to produce a freshly cut surface, and (3) to produce a mechanically sound surface. Usually, surface preparation involves some form of machining, either to create very flat surfaces or to create some specific mating shapes as for dowel or finger joints. In either case, tight control of the fit between the mating surfaces is necessary to ensure the thin, uniform-thickness bondline that characterizes high-quality joints. A freshly machined wood surface is important because it is most likely to be receptive to wetting by the adhesive. This promotes the development of strong adhesion forces, an important requirement for good bonding. We should note that in some processes, such as flaking and veneer cutting, it may be impossible or at least impractical to remachine the wood surface immediately before bonding. Finally, mechanical and thermal damage, which adversely affects bonding and joint performance, must be avoided in surface preparation. In the next section, we will describe common wood machining processes and how they affect the quality of the surface.

B. Machining Processes

Virtually all wood surfaces must be machined in preparation for bonding. The quality of the surface varies with the type of machining process as well as with how carefully the process is controlled. A microtomed surface is the smoothest possible surface given the inherent roughness (porosity) of the wood. Microtoming is a process normally used in cutting very thin sections of material for examination under a microscope. It is the preferred method for preparing a surface for adhesive bonding from the standpoint of smoothness and lack of damage. An extremely sharp knife and special knife holder are used for microtoming. The knife creates a very flat surface. It cleanly cleaves both earlywood and latewood cells without compression damage, and it exposes a maximum of fresh wood substance with the least damage to the surface and subsurface cells. Next in order of surface quality are hand-planed surfaces. Hand planing closely resembles knife planing but lacks the same degree of control of surface flatness, and the knives are not as sharp as microtome knives.

Following microtoming and hand planing, which are not industrially practical, other machining processes for preparing surfaces (in increasing order of their severity or damage to the wood) are machine joining, machine planing, jointer sawing, and conventional

rip sawing. The surface quality obtained with these processes is strongly affected by the number of cutter marks per inch and the direction of cut. Surfaces of near-microtome quality can be obtained with carefully sharpened knives, a shallow depth of cut, and a moderate feed rate. Unfortunately, under production conditions, many factors tend to interfere-the knives become dull before the end of the shift, the feed rolls may crush the surface, or the knives may be improperly or excessively jointed. Jointing is the practice of grinding a bevel on the underside of the knife edge to improve the wearing properties of the edge. Jointing is also used to renew the sharpness of the edge between major regrindings. Jointing and its effects on surface quality are discussed in the section on peripheral milling.

Sawing is the primary means both for reducing logs to lumber and in shaping lumber in secondary manufacturing, such as the manufacture of furniture. However, the surfaces left by large band and circular saws used in primary breakdown of the log are unsuitable for adhesive bonding. Lumber prepared by a special circular saw called a straight-line rip saw is used for preparing lumber for edge-bonded panels for furniture and millwork. This saw is designed with special feedworks and hold-down devices, and is equipped with a special blade to provide a smooth and sound surface that approaches the quality of a knife-planed surface.

Reineke (1943) listed several criteria that indicate the acceptability or unacceptability of a sawn surface for bonding.

The attributes of an acceptable sawn surface are as follows:

1. The wood must be of moderate density, such as spruce, western hemlock, Douglas fir, or yellow poplar,
2. Individual cells are distinct when observed under 10× magnification.
3. The surface has a transparency or sheen when observed with a magnifier at right angles to the fiber and from a low angle to the surface.
4. Saw toothmarks are clean, sharp, and uniform in depth.
5. Whiskers stand free from, rather than embedded in, the surface.

The attributes of an unacceptable sawn surface are as follows:

1. Individual cells are indistinct under magnification.
2. The surface appears dull or lackluster, or is glazed or discolored.
3. Saw toothmarks are rounded and lack sharp edges.
4. Whiskers are embedded in the surface or rolled up, crumpled, or wadded. Loose ends of cells are crushed or broomed.
5. The earlywood layers are convex.

6. The crushed earlywood raises and embedded fibers rise when a drop of water is applied to the surface.

The guides and feedworks of saws must not allow the board to move laterally as the cut is being made, and very close attention must be paid to the sharpness of the saw. Reineke (1943) states that sawn surfaces should not deviate from the average plane more than ±0.015 in. in either edge or face bonding. Reineke's guidelines for allowable surface deviations are based on his experience with woods of moderate density. Tighter restrictions are undoubtedly necessary for the surface variations of dense hardwoods. Surfaces suitable for all but the most demanding applications can be obtained by sawing wood with special equipment and by paying close attention to detail. Many of Reineke's guidelines apply to all forms of machined wood surfaces that are prepared for bonding.

Peeling is the primary means of reducing logs to veneer, especially softwood veneer for construction plywoods and hardwood veneer for some types of decorative plywood. In peeling, the length of a log is turned against a stationary knife. Peeling approximates simple orthogonal cutting, except for the addition of pressure ahead of the knife that compresses the veneer to minimize cracking.

Slicing is an orthogonal cutting process, and it is best suited for cutting thin veneers for decorative plywood. Slicing also employs a nosebar. Logs for slicing are first sawn lengthwise to expose a particular plane of the log. Each plane produces a characteristic wood-grain figure. More attention must be paid to the quality of the surface produced in cutting veneer and especially in slicing than in sawing because there is no opportunity for secondary surface preparation before bonding. The surface created by the knife in cutting the green wood is dried and bonded without further preparation.

Flaking is quite similar to peeling or slicing, except that at the same time the material is cut parallel to the grain, it is also cut or scored across the grain to form discrete flakes or strands of controlled length. The control of length is important in the manufacture of structural flakeboard. In flaking, as in peeling and slicing, there is no opportunity to improve the surface after primary manufacture.

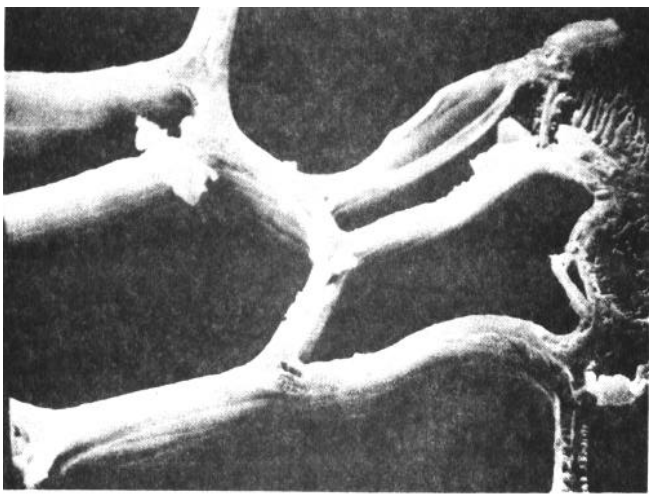
Particles used to manufacture particleboard are usually residues from sawing, planing, and sanding wood in other manufacturing processes. As such, the particles have physical characteristics representative of those processes. The residues are usually processed through a hammermill or refiner, machines that reduce particle size and improve uniformity. The residues are then screen sized to obtain small, uniformly sized particles.

Abrasive planing is a common method for surface preparation in the furniture industry because of its potential advantages over knife planing. One principal advantage in terms of bonding is the superior thickness control and, consequently, more uniform pressure over the surface during bonding. A negative effect of abrasive planing is that it mechanically damages wood cells near the surface. Surfaces prepared by abrasive planers vary in roughness with the grit size.

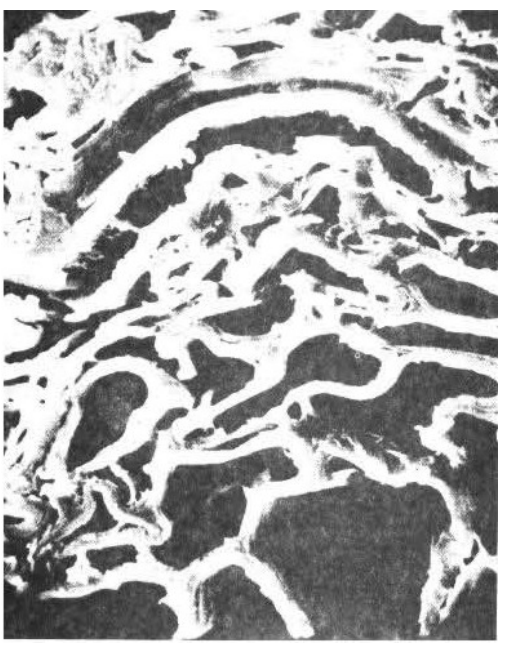
Ideally, for adhesive bonding as well as for finishing, the machining process will cut the wood cells at the surface and not crush or otherwise damage them. However, microscopic studies reveal that under production conditions, this situation may be the exception rather than the rule. Thin-walled cells that lie at the surface (such as earlywood tracheids in softwoods and vessels or parenchyma in hardwoods) are indeed more likely to be cleaved or sheared parallel to and through the lumen (longitudinal transwall fracture) by the actions of cutting tools. Thick-walled cells (such as latewood tracheids in softwoods and fibers in hardwoods) tend to cleave or shear parallel to but within the cell wall, usually in the middle lamella (intercellular) or between the S-1 and S-2 layers (intrawall). However, under adverse conditions, thin-walled cells at the surface may be crushed and matted, and thick-walled cells at the surface may be pushed downward, crushing the underlying thin-walled cells. Figure 1.20a shows an end view of a piece of wood near the surface that was cleanly cut without compression damage; Figure 1.20b shows the crushed cells and fractured cell walls near the surface of a piece of wood that was improperly surfaced.

The two basic forms of machining are orthogonal cutting and peripheral milling. In orthogonal cutting, the cutting edge is perpendicular to the direction of travel, and the surface created by the cutting edge is a plane parallel to the work surface. Hand planing and veneer slicing are good examples of orthogonal cutting. Industrial processes that represent orthogonal cutting are band sawing, veneer peeling, and flaking. In peripheral milling, the cutting edge is affixed to the periphery of a rotating tool so that the contact between the cutting edge and the wood surface is intermittent and follows a curved path through the wood. In contrast to orthogonal cutting, the surface left by peripheral milling is a series of troughs produced by the curved path of the cutting edge through the wood. Machine-knife planing and abrasive planing are peripheral milling processes.

When a cutting tool, whether a saw or knife or abrasive particle, is forced against a piece of wood, it creates some combination of shearing, cleaving, and compressing stresses within the wood. The mix of forces depends to a great extent upon the tool geometry.



(a)



(b)

Figure 1.20 End-grain view of earlywood cells just beneath the surface of wood that was surfaced with (a) a properly sharpened and jointed hand-fed knife planer and (b) an abrasive planer using 36 grit.

All cutting tools, whether formed of metal or of an abrasive material, have a rake angle, a clearance angle, and a sharpness angle (Figure 1.21a). The rake angle is formed by the cutting face (top surface) of the tool and a line constructed perpendicular to the wood surface. The clearance angle is formed by the underside of the tool and the wood surface. The sharpness angle is the angle between the two faces of the tool. The combination of forces arising from a given tool geometry controls the type of particles that are

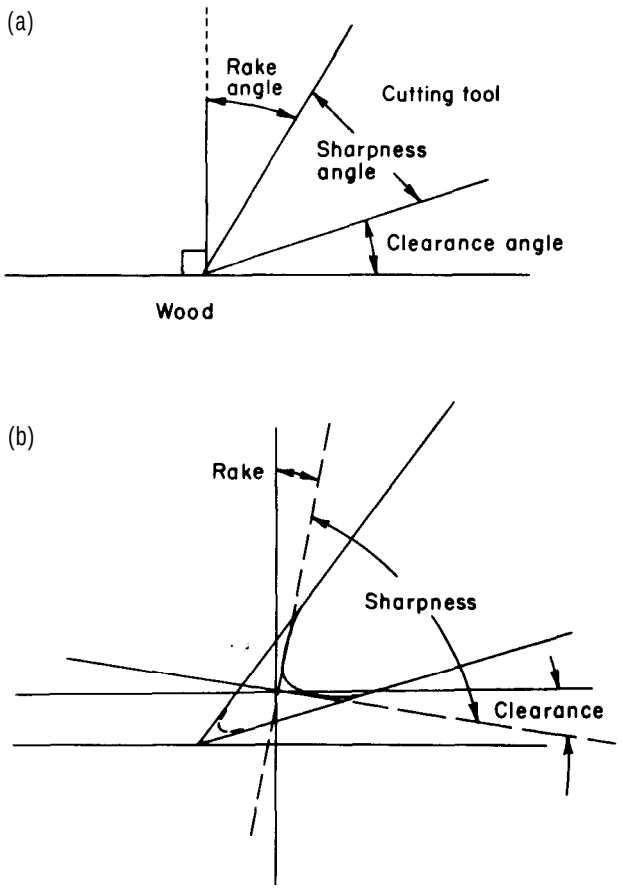


Figure 1.21 The angles of a cutting tool: (a) a sharp tool and (b) a dull tool.

formed and the quality of the machined surface. Other factors are involved, and these will be discussed in the next section. Of special note is the fact that as a tool dulls, all three cutting-tool angles change (Figure 1.21b), and these changes and their effects on surface quality strongly affect adhesive bonding and joint performance.

Orthogonal Cutting

The quality of a machined wood surface is affected by the direction of cut in relation to the wood structure as well as by the cutting tool geometry. The longitudinal surface planes, such as the longitudinal-radial (LR) and longitudinal-tangential (LT) and those planes in between are the most important for adhesive bonding. The orthogonal machining directions in the longitudinal planes are referred to as the 90-0 cut (parallel to the grain) and the 0-90 cut (perpendicular to the grain) (Figure 1.22). A cut in the transverse plane, referred to as a 90-90 cut, is less important because of the difficulty of bonding the end grain of wood.

The 90-0 Surfaces. Most 90-0 surfaces prepared for adhesive bonding are formed by a knife jointer, or by a knife- or abrasive-planer. The rake angle of these tools controls the type of chips that form in the 90-0 cutting mode, and thus the type of surface (Koch 1955). Three types of chips have been observed (Koch 1985). Type I chips form when the rake angle is large ($\geq 25°$). A large rake angle creates large tension or cleavage forces perpendicular to the surface ahead of the cutting edge (Figure 1.23a). Given the proper rake angle and straight grain, woods with low cleavage resistance, high strength and stiffness, and low moisture content are most conducive to the formation of Type I chips. Rake angles between 25° and 35° tend to form Type I chips because the force perpendicular to the grain is tension regardless of the depth of cut or the moisture content. Low wood moisture content promotes cleavage and splitting rather than shear failure. If the grain is exactly parallel to the surface (Figure 1.24a), the chips will form by cleavage parallel to the surface, and the surface quality will depend on the location of the wood failure and the sharpness of the edge. If the grain slopes up against the direction the cutting edge is traveling, a cleavage crack forms a splinter that tends to run down into the wood (Figure 1.24b), until the splinter, acting as a small cantilever beam, is broken off. The resultant surface is frequently termed chipped grain. If the grain slopes up in the direction the cutting edge is traveling, chipping is unlikely because splinters cannot form. Any crack that begins to form will follow the grain back up to the surface (Figure 1.24c).

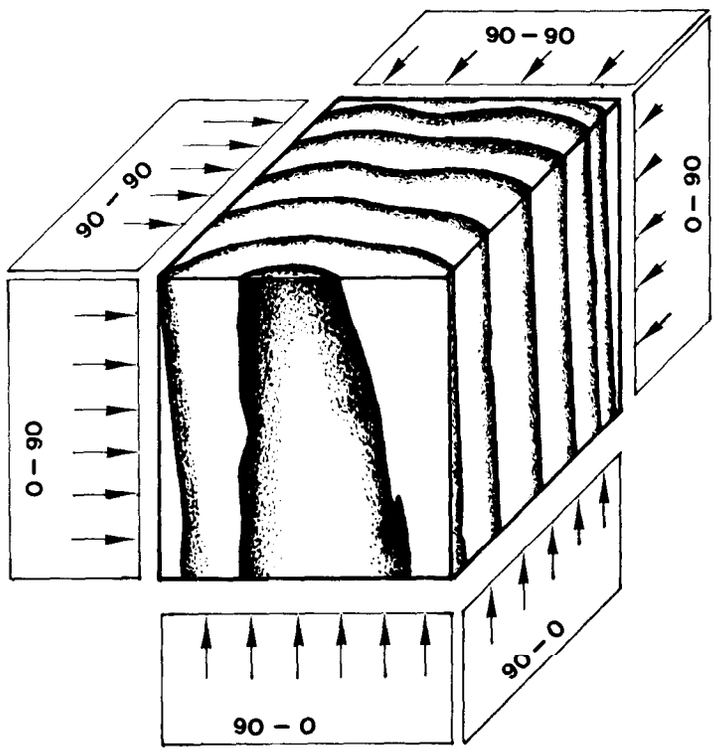


Figure 1.22 Codes for the direction of travel of a cutting edge with respect to the orthogonal directions of wood structure.

Type II chips form under limited conditions that induce compression-shear failure parallel to the surface ahead of the cutting edge (Figure 1.23b). Potentially damaging compression forces perpendicular to the surface may also arise, but at the proper rake angle, the compression and tensile forces perpendicular to the surface negate each other. A light cut (thin chips), an intermediate to high wood moisture content, and a 5-20° rake angle favor the formation of Type II chips in hardwoods. The rake angle that produces Type II chips varies between softwoods and hardwoods, and by species. Under the proper conditions, Type II chips characteristically form in a smooth spiral shape. Since little splitting or compression damage occurs, the resultant surface is excellent for bonding. Because the surface left by Type II chips is so desirable, Stewart (1977) developed a formula for calculating the rake angle that would promote

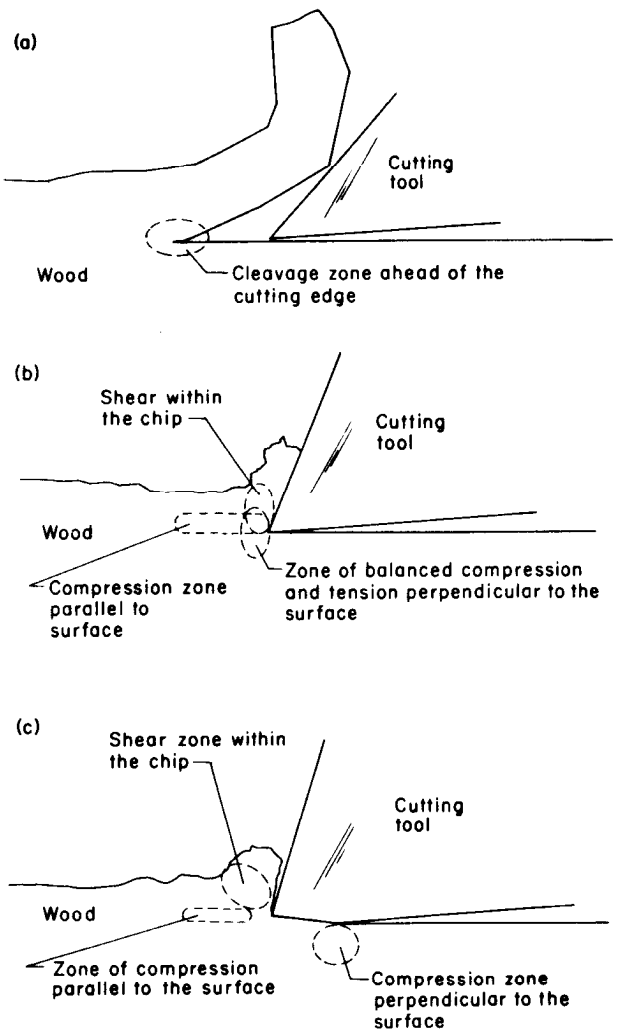


Figure 1.23 Actions of cutting tools in forming various types of chips in orthogonal cutting of wood: (a) Type I chips, (b) Type II chips, and (c) Type III chips (see discussion in Section III under the 90-0 surface; after Woodson 1979).

a Type II chip based on the parallel and perpendicular cutting forces of a given species:

$$\mu = \tan (\arctan F_n/F_p + \alpha)$$

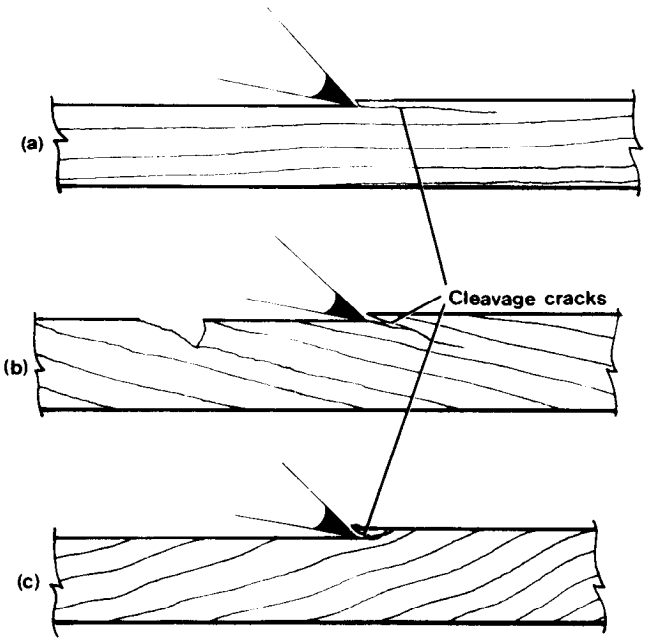


Figure 1.24 Effect of grain angle upon the surface quality resulting from Type I chip formation: (a) parallel grain, (b) grain sloping down in the direction the cutting edge is traveling, and (c) grain sloping up in the direction of cutting edge travel.

The cutting forces for a wide variety of southern hardwoods, at several directions of cut, moisture contents, and rake angles, have been meticulously measured and tabulated by Woodson (1979).

Type III chips also form under similar compression and shear forces as do Type II chips. However, Type III chips form at very small (5-10°) or even negative angles. Two conditions favor the formation of Type III chips: (1) the more severe compression forces, both parallel and perpendicular to the surface, and (2) the absence of a tension force to balance the compression force perpendicular to the surface (Figure 1.23c). Cells are crushed and particles may be incompletely severed, leaving fuzzy grain. When crushing occurs, the crushed wood may spring back, causing *raised grain*. The crushed cells are severely damaged, and they may constitute a weak layer in an adhesive joint. Type III chips are also a characteristic of dull tools that have small rake angles.

The clearance angle, the angle between the back of the tool and the wood surface, is usually 15°. However, dulling of the edge reduces the clearance angle and may in fact create a negative clearance angle (Figure 1.21b). A small or negative clearance angle increases the compression force perpendicular to the wood (Figure 1.23c) and causes raised grain or a weak boundary layer condition. Stewart (1989) developed a fixed-knife, pressure-bar method of planing that reportedly reduces or eliminates compression damage as well as the chipped grain that frequently results from peripheral knife-planing or the compression damage that characterizes abrasive planing.

The 0-90 Surfaces. The 0-90 surfaces for bonding are formed by a straight-line rip saw or by a veneer slicer, rotary veneer lathe, or one of several types of disk or ring flake-cutting machines. Under favorable conditions, chips emerge as a thin continuous veneer with relatively smooth surfaces and little subsurface damage, which Stewart (1979) likens to a Type III chip formed in the 90-0 cutting direction. Rake angle, moisture content, and depth of cut have strong effects on the wood surface quality. In general, 0-90 cutting requires much larger rake angles (50-70°) than 90-0 cutting. As either the rake angle decreases, the depth of cut increases, or the moisture content decreases, critical stress zones are likely to arise in the vicinity of the cutting edge. There is a tensile zone in the veneer as it bends away from the knife and another such zone in the wood surface at the tip of the knife (Figure 1.25). Excessive stress in the first zone is responsible for forming cracks on the underside of the chip. In cutting veneer, these cracks are called *lathe checks* (Figure 1.26). The stress in the second zone is responsible for tearing small chunks of wood from the surface of the workpiece, which is the backside of the veneer or flake. In veneer cutting, these destructive forces can be controlled to some degree by heating the log and by placing a pressure bar (nosebar) just ahead of the cutting edge (Figure 1.26). Heat plasticizes the wood, enabling the cutting of thicker veneer with fewer lathe checks. Heating is more beneficial in the cutting of dense species. Optimum cutting temperatures have been determined for many species of wood (International Union of Forestry Research Organizations 1973). The pressure creates a compressive force just ahead of the cutting edge that counteracts the tensile forces created by the veneer bending and cleaving.

The species of wood also affects the surface quality. Moderate-density, uniformly textured species usually produce better surfaces than low-density species or species with a great disparity between the earlywood and latewood densities. The angle of attack of the cutting edge to the growth rings is important in coarse-

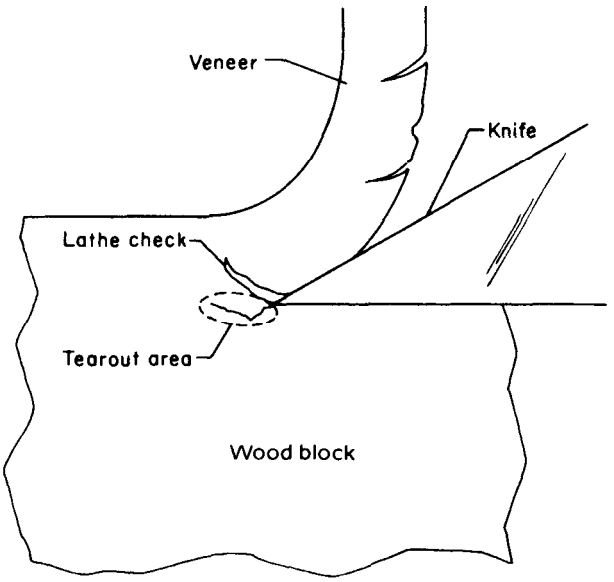


Figure 1.25 Tensile zones in veneer cutting that cause lathe checks and rough surfaces as a result of tearout.

textured softwoods and ring-porous hardwoods. As the knife bends the wood (chip, veneer, or flake) away from the surface, the stiff, unyielding latewood cracks, and the weak earlywood ahead of and below the cutting edge is often torn out of the surface (Figure 1.25). Stewart (1979) likens this to the formation of a Type I chip formed during 90-0 cutting.

The 90-90 Surfaces. The quality of 90-90 surfaces is dependent upon the rake angle, moisture content, density, and tool sharpness. Dry, low-density wood cut with a low rake angle allows the cutting edge to slide over the surface, cleaving the wood parallel to the grain and tearing pieces out perpendicular to the grain rather than severing the wood cleanly.

The quality of end-grain surfaces formed by 90-90 cutting is of little practical concern in adhesive bonding because of the weakness of bonded end-grain joints in relation to the strength of the wood. When a wood member must be joined at its end, joining is accomplished by dowels, mortise and tenon, scarf, or finger joints. Such end joints actually rely on shear between side-grain surfaces rather

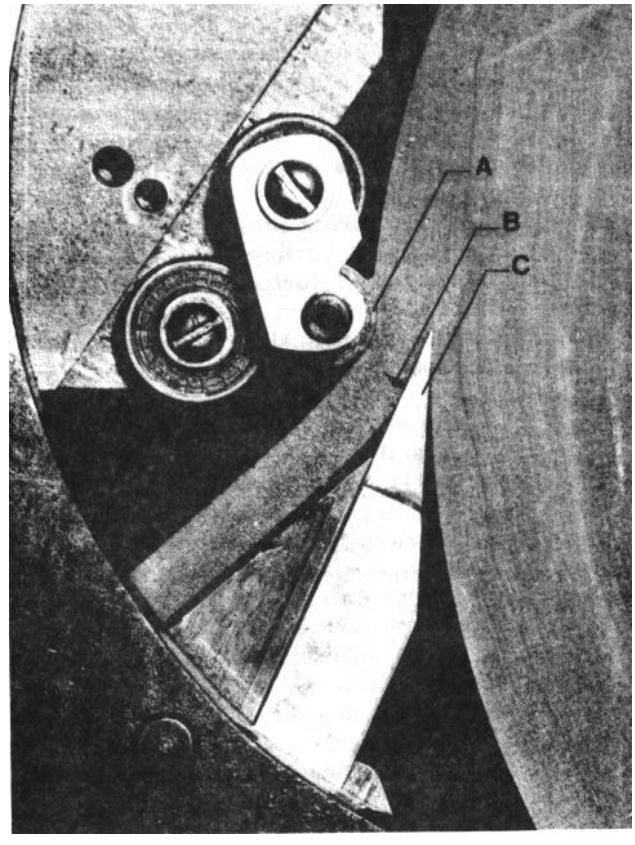


Figure 1.26 Flexure of veneer and formation of a lathe check as a result of tension zones in veneer cutting. A is pressure bar, B is lathe check, and C is the knife.

than tension between end-grain surfaces (see discussions on anisotropy and grain-angle effects in Section II and joint design in Section VI).

Peripheral Milling

Koch (1964) points out that orthogonal cutting might be considered a special case of peripheral milling in which the curved path is of infinite radius and the angular velocity of the edge is *zero.* Conversely,

peripheral milling could be considered a special case of orthogonal cutting when the tangent of the cutting edge is perpendicular to the direction of travel and the surface created is a plane parallel to the work surface. So for simplification, we will consider the actions of tools and their effects on surface quality in relation to bonding as orthogonal cutting processes.

The mechanisms of chip formation during peripheral milling are basically the same as those in orthogonal cutting. So are the factors affecting the quality of the machined surface-rake angle, depth of cut, sharpness, and moisture content. But peripheral milling presents several additional surface-quality factors important in adhesive bonding: knife marks per inch, knife mark height, and knife jointing.

As in orthogonal cutting, the best quality surface is obtained when a Type II chip is produced, and rake angle is the most important factor. A common rake angle for softwoods is 30°; however, this angle can vary over a wide range and still yield good results. A common compromise for hardwoods is a 20° rake angle, but better results are obtained when a specific optimum rake angle is determined for each species (Davis 1962). Specific gravity and the number of rings per inch seem to have little effect. The species differences are apparently due to differences in wood anatomy. Oak, for example, is quite insensitive to rake angle, whereas species such as hackberry, American elm, and red maple may yield twice as many defect-free pieces at an optimized rake angle than at the poorest angle (Davis 1962). The best chip formation has been found when wood is machined between 6 and 8% moisture content.

A greater number of knife marks per inch along the surface is more conducive to high-quality surfaces than fewer marks. The number can be increased and the height decreased by increasing the revolutions per minute of the cutter, decreasing the feed speed, or increasing the number of knives around the cutter head (compare Figure 1.27a and b). The height of the knife marks is also affected by the diameter of the cutter; smaller cutters produce deeper marks. A large-diameter cutter with many knives, coupled with a high number of revolutions per minute and lower feed, produces the best results. Conversely, a small-diameter cutter with proportionally fewer knives, coupled with a low number of revolutions per minute and a rapid feed rate, produces deeper knife marks and more defects, such as chipped grain. When two surfaces with deep knife marks are mated for bonding, the bondline will be thin at the points where two peaks of opposite surfaces touch and thick at the points where two valleys adjoin. Surface quality improves as the number of knife marks per inch increases from 4 to 14, but little improvement is made beyond 16 knife marks (Koch 1964).

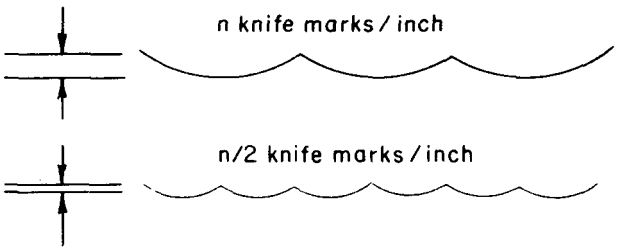


Figure 1.27 Influence of knife marks per inch on wood surface quality (smoothness).

Jointing a knife, as distinguished from the wood-machining process of knife jointing, is the process of trueing all the cutting edges in a cutterhead so that they travel in the same cutting circle. This is an important step toward obtaining a high-quality surface. After the knives have been ground to the proper rake and clearance angles (sharpened) and reinstalled in the cutterhead, the cutterhead is revolved at operating speed against an abrasive stone. This operation, called jointing, removes a small amount of metal from the backside (clearance angle side) of the knife. If the knives in a cutterhead are not jointed, one cutting edge will take a larger cut than all the others. The effect on the surface is as if the cutterhead had only one cutting edge, and the difference between the peaks and valleys of the cut will be large. The resultant surface will actually appear wavy.

Jointing the knife broadens the width of the land (Figure 1.28, line BD) behind the cutting edge and reduces the clearance angle. Eventually, when the land behind the edge becomes wide enough (Figure 1.28, line CE), the heel of the land (Figure 1.28, point E) becomes the first point of contact with the surface; the heel exerts damaging compression forces perpendicular to the surface as it is forced across the wood surface. Rubbing by the heel also creates enough frictional heat to burnish or even char the surface, which inactivates the surface toward adhesives. Knives should be reground or heel-sharpened when the land produced by jointing becomes about 1/32 in. wide (Koch 1985).

Koch (1964) states that virtually any wood can be machined without defects if the various cutting conditions are adjusted to an optimum for the species. He notes, however, that some species are more easily planed under a wider range of conditions than other species.

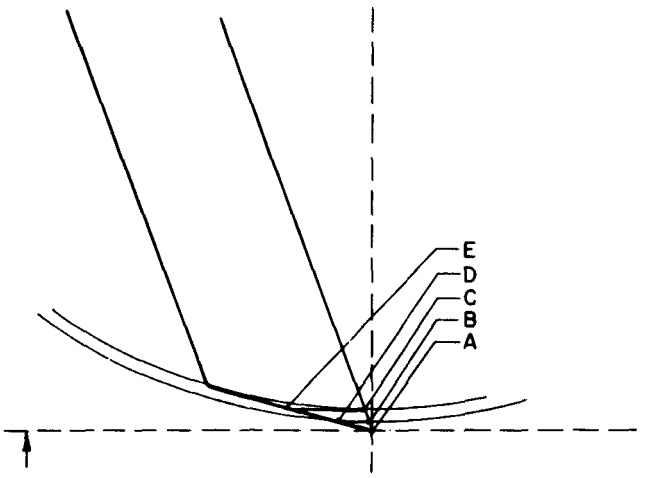


Figure 1.28 The effect of "jointing" the cutting edge upon the shape of the cutting edge and compression perpendicular to the wood surface. When first sharpened, the tool edge is at position A. When the tool is "jointed," the edge moves to position B and a "heel" is formed at position D. The heel at D is inside the radius of the cutting edge B. With continued jointing, the edge moves to position C and the heel to position E, and the heel is outside the radius of the cutting edge. When the heel has a greater radius than the cutting edge, the wood beneath the heel is compressed and smeared, not cleaved and sheared.

Other Machining Processes

Straight-Line Rip Saw. The straight-line rip saw is often used in the furniture industry for cutting pieces to width before edge bonding. Experience has shown that satisfactory surfaces can be obtained if the saw feedworks are properly maintained to make a straight cut, and if the blade is properly selected and maintained to minimize machining damage to the surface. A sawn surface is formed by the corner of the saw tooth or the side of the tooth depending on the style of the tooth. The machining process combines the orthogonal 90-0 and 0-90 cutting actions, with the ratio dependent upon how far the saw blade protrudes through the workpiece. The best surface quality in terms of smoothness is obtained by using

slower feed speeds and cutting with a minimum of blade protrusion (St. Laurent 1973). The appearance and feel of smoothness, however, is an unreliable criterion for the quality of the surface for bonding. For example, compression and burnishing of the surface by a dull saw tooth (or knife edge) leave a smooth surface that may be mechanically and chemically unsuitable for bonding. A surface that is formed by cleanly cleaving or shearing the cells, even though somewhat rougher, is a higher quality surface for bonding (Reineke 1943).

Abrasive Planing. The thickness tolerance of a properly operating abrasive planer may surpass that of a knife planer. Unfortunately, the abrasive-planed surface is often created at the expense of damaging the wood cells at or near the surface. An abrasive planer is built for heavy cut, and it uses a steel roller to back the abrasive and ensure a uniform depth of cut. A particle of abrasive with a large negative rake angle, backed by a hard roll, plows a furrow and creates large compression forces against the wood surface (Figure 1.29). The weaker earlywood cells may be sheared away, but the strong latewood cells are more likely to be mashed down into the soft underlying earlywood rather than be sheared and cleaved,

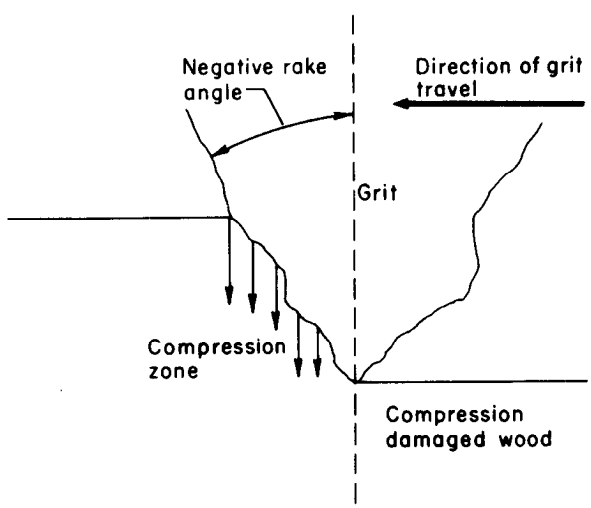


Figure 1.29 Downward force created by sandpaper grit that crushes the underlying wood as the grit travels parallel to the grain during abrasive planing.

producing the crushed and cracked cells (Murmanis, River, and Stewart 1983). Figures 1.20a,b and 1.42a,b show the difference between undamaged cells at or near an undamaged surface and crushed and matted cells at or near an abrasive-planed surface. The same effect can be created by a dull or improperly sharpened knife or saw. Such damaged cells are detrimental to the resistance of a bonded joint to cyclic swelling and shrinkage stresses (Jokerst and Stewart 1976). The damage occurs at all grit sizes, although it is worse with coarse grits (Caster, Kutscha, and Leick 1985; Murmanis, River, and Stewart 1986). The damage does not seem related to feed speed or depth of cut. The type and extent of damage may be influenced by species, density variations, ray tissue orientation, and possibly the moisture content (Murmanis, River, and Stewart 1986; Stewart and Crist 1982).

An abrasive planer may also raise the temperature of the surface more than a properly sharpened and operated knife planer. Coarse grit and higher belt speeds produce higher temperatures. The negative rake angle of the grit increases friction, which generates heat. The grit also dulls, as do metal cutting tools.

Boring. The surface quality obtained in boring is important in adhesive-bonded wood-dowel applications. There are many types of specialized drill bits. The type frequently used for doweling, a double-spur bit, has two lips (shaving action), two spurs at the periphery of the lips, and a center point. The spurs first cut the wood in a circle, then the lips shave off the chips in the direction the bit is moving into the workpiece. The cutting actions and chip formation in the boring operation are similar to that of orthogonal cutting. When boring into the side grain, the spurs alternately cut in the 90-0 mode and then in the 90-90 mode, while the lips cut alternately in the 90-0 mode and the 0-90 mode. When boring into the end grain, both the spurs are cutting continuously in the 0-90 mode and the lips in the 90-90 mode. The rake angle of the lips is typically 30-35° and the clearance angle is 10-15°. A twist drill without point or spurs is also used to drill dowel holes, especially in end grain (Koch 1985). When boring across the grain, Davis (1962) found that the diameter of the hole was consistently larger across the grain than parallel to the grain. The size of a hole bored with the same bit in various species of wood produced oversized holes in some species and undersized holes in others. The size of the hole also varies with moisture content. The diameter increases as moisture content increases; however, the increase is greater across the grain than parallel to it.

In southern pine, a coarse-textured wood, smoother holes can be bored across the grain than along it, and dry wood produces smoother holes than wet wood (McMillin and Woodson 1974). Bits

with spurs drill smoother holes than simple twist bits. Smoothness is little affected by spindle (bit-rotation) speed if a spur bit is used (Komatsu 1976). When boring along the grain, McMillin and Woodson (1974) found little difference in hole surface quality with various types of bits. However, Komatsu (1979) found that twist bits produced rounder and more uniformly sized holes. Hole smoothness improves as feed rate decreases and is little affected by spindle speed or specific gravity (McMillin and Woodson 1974).

In dowel-joint strength and durability, the proper spindle speed depends on the species and density of the wood. It should be as low as possible to produce a smooth but unburnished or charred surface. The feed and withdrawal rates should be as rapid as possible to prevent burning or burnishing of the surface (Sparkes 1966a, 1969). Hoyle (1956) found that a moderate spindle speed (2880 rpm) consistently produced higher strength joints than faster or slower speeds, but chip thickness between 0.008 and 0.062 in. had little effect.

Hole size is another important factor, and the recommendations for hole size in relation to dowel size vary depending on whether the dowel is plain or grooved. Most researchers have found that an exact fit or slightly oversized dowel provides the highest strength, providing the joint is not starved of adhesive. Nearn, Norton, and Murphey (1953) found that a hole oversized in diameter by 0.015-0.031 in. produced stronger joints with 0.375-in. plain and spiral grooved dowels than a hole of the exact diameter. Eckelman (1969), however, reported that maximum strength was obtained with plain dowels and holes of the same diameter or not more than 0.001 in. oversize. Sparkes (1966a) recommends hole diameters within 0.005 in. of the dowel diameter for single- or double-grooved dowels, but 0.020 in. undersized holes for multi-grooved dowels.

Mortising. Mortising is a process of creating a rectangular or oval hole to fit a tenon. Mortising is accomplished by boring and chiseling, by special routers, or by reciprocating chisels (Koch 1985). Many of the same factors that apply to boring and orthogonal cutting apply to the quality of the mortised surface for adhesive bonding. In the standard hollow-chisel bored mortise, the portion of the cut parallel to the grain (which is most important for the strength of a joint) produces a smooth, sound surface. Cuts across the grain are likely to crush and tear the wood, especially in lower density species or in the softer earlywood tissue in coarse-textured woods. However, the end-grain portion (narrow end) of a mortise is relatively unimportant to joint strength. The number of off-sized mortises and the degree of off-sizing increases as the species density decreases (Davis 1962).

Water Jet and Laser Cutting. Water jet and laser methods have found limited applications in cutting wood (Koch 1985, Szymani and Dickinson 1975). These types of machining offer the opportunity to make intricate cuts, with the added advantage of very little loss of material. Scanning electron micrographs (McMillin and Harry 1971) showed that laser-cut surfaces, although blackened, are much smoother than conventionally cut surfaces. There was no evidence of mechanical damage, but the surfaces appeared to be deformed thermoplastically.

Barnekov, McMillin, and Huber (1986) studied the process variables that influence the quality of a laser-cut surface. Later, these authors reported that composite panel materials, such as particleboard and plywood machined by laser, are rough, uneven, and charred, and burned to an uneven depth (Barnekov, Huber, and McMillin 1989). Such a surface is certainly not conducive to the attainment of high-quality adhesive bonds. Barnekov, Huber, and McMillin (1989) attempted to optimize conditions and found that the best surfaces (meaning the smoothest, flattest, and least charred) were obtained with a 400- to 500-W laser output, focusing the beam on the board surface, and cutting at 20 in. /min. They also recommended using a beam focal length of 7.5 in. and an air-jet assist. Under these conditions, the average divergence (from an ideally flat surface) of the actual surface was 0.004-0.006 in. This divergence should be tolerable by most bonding systems. However, char and burning to variable depths are still problems that require some mechanical machining of the wood before bonding.

Little information about the quality of adhesive bonds to laser-cut surfaces is found in the literature. McMillin and Huber (1985) indicate that the quality characteristics of the surface vary with the species and, in particular, with differences in the variation in density resulting from the growth pattern (earlywood compared to latewood) of the species. For example, the growth pattern causes little variation in density in diffuse porous sweetgum, but extreme variation between earlywood and latewood density in ring-porous red oak. As might be expected, the depth of char varies more in oak, with deeper char in the porous earlywood than in the dense latewood. McMillin and Huber (1985) compared the strength of bonded joints made from boards surfaced by either a straight-line rip saw, a laser, or a laser followed by light sanding. Oak and sweetgum joints with laser-cut surfaces were 75 and 43% as strong as the respective sawn joints of these species. Joints with lightly sanded, laser-cut oak and sweetgum were only 34 and 32% weaker, respectively, than the joints made with sawn surfaces. However, sanding increased the amount of kerf lost, thus negating at least one advantage of laser machining. Additional research on

bonding laser-cut wood is currently underway (Rabiej, Behm, and Khan in preparation).

Heat and Moisture Content Effects

The temperature and the moisture content of the wood so strongly affect the mechanical properties of the wood that they necessarily affect how the wood fails during machining and, consequently, the quality of the machined surface. Most primary sawing processes, such as the breakdown of the log into lumber, are performed on green (wet) wood, but many resawing operations are performed on already dried wood. Peripheral milling of surfaces for bonding will almost always be performed on air- or kiln-dried wood. Of course, water is present in green logs. But water and heat are often combined to soften wood before cutting veneer (Lutz 1978, Sellers 1985) to reduce lathe checking and surface tearout. Water and heat are also used in preparing wood fiber for bonding as in hardboard manufacture (Suchsland and Woodson 1986). Soaking and heating are carried out according to schedules that have been empirically evolved to yield the highest quality veneer, flakes, or pulp. Briefly, the heat and water plasticize the lignin and hemicellulose components of the cell wall substance, and this softening changes where and how the wood cells fracture during machining and, consequently, the chemistry of the surface. These relationships are discussed in the next paragraphs.

C. Chemistry of Wood and Fiber Surfaces

The chemistry of a wood surface varies with the type of drying process (ambient *air* or forced air), the machining process (knife *or* abrasive, sharp or dull), the plane of the cut (radial, tangential, or transverse), and the condition of the wood when surfaced (cool and dry or hot and wet). In some cases, the bulk wood or the surface might also receive a chemical treatment before bonding, such as preservative, fire-retardant, or dimensional-stabilizer treatments.

Wood Substance

The basic chemistry of wood was discussed in Section II. We will now discuss features particularly relevant to adhesive bonding. Wood, no matter how it is prepared for bonding, presents several different chemical surfaces to the adhesive (Figure 1.30). Data presented by Salehuddin (1970) show the percentage of wood substance comprised of each of the three major constituents, cellulose, lignin, and hemicellulose, their accessibility to the adhesive for bonding, and their contribution to the adhesive bond through

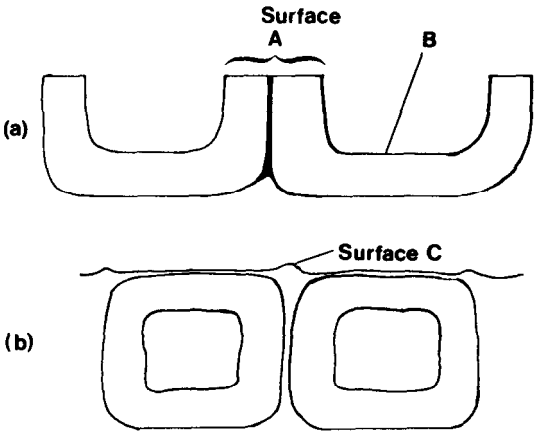


Figure 1.30 Characteristic machined wood surfaces for bonding (microscopic view): (a) Surface A-excised cell wall substance rich in cellulose and hemicellulose. Surface B-cell lumen wall rich in lignin but coated with aged protoplasmic residues. (b) Surface C-middle lamella/primary wall rich in lignin and pectic substances.

hydrogen bonding (Table 1.8). Hemicellulose, even though a less abundant constituent, is totally accessible for bonding and therefore contributes more than cellulose. Lignin contributes very little to hydrogen bonding. Three distinct types of surfaces are (1) the highly polar, cellulose- and hemicellulose-rich secondary wall (Figure 1.30a, surface A), (2) the residue-coated lumen wall (Figure 1.30a, surface B), and (3) the lignin-rich compound middle lamella (Figure 1.30b, surface C). Surfaces A and C are freshly exposed by transwall, and intercellular or intrawall fracture of the cell during machining the wood in preparation for bonding. Surface B is an old surface, although its character could be modified by mechanical forces or by the heat generated during machining.

In surface B, the lumen wall is dimensionally stable, and thus it will not exert much stress on an adhesive bond as the wood swells and shrinks. However, this surface is coated with a layer of protoplasmic materials, called the *warty layer*. This layer is composed of 47-60% carbon, 32-40% oxygen, 5.5-6% hydrogen, 3.6-7.1% methoxyl, and 0.6-2.1% nitrogen (Cronshaw, Davies, and Wardrop 1961). The warty layer is also extremely resistant to dissolution by strong chemical reagents, including boiling water, concentrated sulfuric

Table 1.8 Accessibility and Contribution of Cell Wall Constituents to Hydrogen Bonding

	Constitution of cell wall (%)	Accessibility for bonding (%)	Contribution to bonding (%)
Cellulose	50	35	17.5
Hemicellulose	24	100	24
Lignin	26	30	7.8

acid, boiling 17.5% sodium hydroxide solution, boiling pyridine, and boiling butanol plus hydrochloric acid (Wardrop, Liese, and Davies 1959). A surface with these characteristics would apparently not be receptive to adhesive bonding.

The excised or cut secondary wall (surface A), which has an abundance of available hydroxyl groups, provides the best opportunities for adhesion (Tarkow and Southerland 1964). However, Ward, Cote, and Day (1964) point out that this region, in contrast to the lumen wall, experiences roughly 1.5 times as much swelling as the bulk wood because the lumen does not swell. These authors further point out that cutting through the cell wall eliminates the swelling restraint exerted on the S-2 layer by the S-1 and S-3 layers. Thus, although the secondary wall should be very receptive to adhesion, the resulting bond will be subjected to greater stress as the wood swells and shrinks. The excised secondary wall is most likely to be exposed in thin-walled cells, in thick-walled cells when large rake angles are used, and when temperature and moisture content are relatively low.

Surface C is likely to be exposed by the fracture of thick-walled cells, especially when cut by dull or improperly sharpened tools or when the wood is wet and hot (Woodward 1980). Koran (1986) pulled apart spruce wood in tension perpendicular to the grain and found that the percentage of tracheids with transwall fractures decreased from about 45% when wood was Fractured at 0°C, to about 20% at 100°C, to 0% at 200°C. The percentage of tracheids with intrawall fractures increased as temperature increased. Furthermore, of those cells that fractured intrawall, the fracture tended to occur in the S-1 layer below 100°C; in the primary wall, the fracture tended to occur above 150°C. Mjoeberg (1981) also noted that pulp chips showed a preference for splitting in the middle lamella and that the amount of lignin on the surface of defibrated wood increased

with the temperature. Fibers from pulp made at 170°C had surfaces with higher lignin content than fibers from a conventional thermomechanical pulp (TMP) manufactured at 127°C. The high lignin content surface of the 170°C pulp was attributed to thermal plasticization of the lignin and hemicellulose in the outer layers of the cell wall and the compound middle lamella. Under these conditions, the lignin and hemicellulosic matrix materials, which constitute a higher percentage of the wood substance in the outer wall layers and the compound middle lamella, soften and allow fracture to occur intrawall. The different location of cell wall fracture and, consequently, the different chemistry of the surface could be important in bonding. The lignin-rich middle lamella/primary wall region (surface C) is more dimensionally stable than the secondary wall, but it is also less receptive to adhesion (Table 1.8).

The middle lamella/primary wall region presents a large area in interwall fracture and a proportionally small area in transwall fracture, especially in the latewood. The cell lumen (surface B) presents the largest area for bonding, especially in the earlywood zone. The lumen surface is dimensionally quite stable, but it is often coated with a warty layer and a variety of proteinacous protoplasmic residues left over from cell formation. These residues and the age of the surface probably minimize the number of reactive sites or free hydroxyls available for adhesive bonding. Adequate bonds may depend on the adhesive's ability to displace these materials during bonding.

The pH and buffering capacity of wood affect the setting of chemically curing adhesives. These effects depend upon the compatibility of the pH and buffering capacity of the wood with the pH of the adhesive. The gel time of an alkaline phenol-formaldehyde adhesive is sensitive to pH (Nguyen 1975). Johns and Niazi (1980) investigated the effects of pH and the acid- and base-buffering capacities of 10 hardwoods and 9 softwoods on the gel time of a urea-formaldehyde adhesive. All the woods were acidic and reduced the gel time of the acid-catalyzed urea-formaldehyde resin, but there was no difference between hardwoods and softwoods of the same pH. The gel time diminished from 3 to 77% under the conditions of the test. Both pH and acid-buffering capacity had high positive correlations (0.82-0.92) with gel time. There was no correlation with base-buffering capacity.

In an expanded study, Wospakrik (1984) uncovered strong interactions between additional chemical characteristics of wood and other types of adhesives. The major chemical characteristics studied were the acid- and base-buffering capacity; bound, soluble, and total acid content; pH; and extractive content. The species were oak, Douglas fir, Philippine mahogany, and red alder. The results were evaluated in terms of the strength and percentage of

wood failure obtained with epoxy, emulsion-polymer-isocyanate, and resorcinol-phenol-formaldehyde adhesives. The strength of epoxy and resorcinol-phenol-formaldehyde joints correlated highly with the pH and acid-buffering capacity of the four woods, if the effect of density was removed. The percentage of wood failure obtained with epoxy and resorcinol-phenol-formaldehyde adhesives correlated well with the acid content and acid-buffering capacities of the woods. The percentage of wood failure of joints bonded with polymer-emulsion-isocyanate correlated with the base-buffering capacity and bound acid content, but joint strength did not correlate with any of the chemical characteristics.

Subramanian, Somasckharan, and Johns (1983) distinguished between total acid, bound acid, and acids that were either soluble or insoluble in sodium acetate. They derived a formula for total acid as follows :

$$\text{Total acid} = \text{bound acid} + \text{sodium-acetate-insoluble acid} + \text{sodium-acetate-soluble acid}$$

The total acid content consists of bound acids as well as extractable acidic materials. Therefore, the insoluble acid content is based on bound acids and acidic extractives that are insoluble in aqueous sodium acetate. The authors determined the insoluble acid content as the difference between the total acid content and the content resulting from extraneous materials that could be extracted with aqueous sodium acetate. They found a strong correlation between the [sodium acetate-] insoluble-acid content of two hardwoods and three softwoods and the gel time of urea-formaldehyde resin.

Extractives

The wide variety of extraneous materials found in wood has already been described. These materials normally constitute 0-5% of the weight of wood, although in some species they may constitute up to 40% of the weight. The effects of extractives increase with concentration. In the first place, a heavy concentration of extractives at the surface creates a physical barrier, which blocks the adhesive from intimate molecular contact with the wood. Such a layer may also lower the surface energy, reducing wetting and penetration by the adhesive, and thus slowing removal of water from the adhesive during setting. When present in sufficient quantity, extractives that are soluble in the adhesive can dilute and weaken the physical structure of the adhesive layer. Other extractives may alter or interfere with the chemistry of the curing process.

The literature abounds with reports of interference by extractives with the wetting of the surface by adhesives or with adhesive setting.

The extractives are acidic, and when dissolved, they diffuse into the adhesive (Nguyen 1975). The concentration of soluble extractives in the adhesive may be as high as 10-20%. Nguyen (1975) believes this is enough to cause premature gelation of phenol-formaldehyde adhesive and to lower the ultimate degree of cure. Wospakrik (1984) found a high correlation (0.87) between extractive content and the adjusted shear strength of epoxy-resin-bonded joints, and fairly strong correlations (0.66 and 0.69) between extractive content and the wood failure obtained with isocyanate- and phenol-resorcinol-bonded joints. Although the extractives were not identified, they were extracted by an alcohol-benzene, alcohol, hot-water extraction sequence, which removes most types of wood extractives. Mizumachi (1973) and Mizumachi and Morita (1975) measured the effects of mixing wood flour with urea-formaldehyde and phenol-formaldehyde adhesives on the activation energies of the curing reactions. They studied the effects of 20 wood species. The urea-formaldehyde reaction, which alone had an activation energy of 29 kcal/mole, was strongly affected by the addition of wood powder. Ten percent by weight of wood powder induced a range of activation energies from 26 kcal/mole to ≥63 kcal/mole, with most energies above the 29-kcal/mole baseline. The phenol-formaldehyde reaction, with an activation energy of 18 kcal/mole, was less sensitive. The addition of 10% by weight of wood powder induced a range of activation energies from 14 to 26 kcal/mole, with most above the 18-kcal/mole baseline. In a sense the extractives in the wood flour raised the barrier against, or increased the energy required to cure the adhesive.

In the oaks, low-pH extractives were also found to interfere with bonding by alkaline phenol-formaldehyde adhesives (Roffael and Rauch 1974). Extraction or treatment of the wood surfaces with boiling water or alkaline solutions improved the bond quality. Kuo, Dicarlo, and Hse (1984) also studied the effects of oak extractives on the cure of an alkaline phenol-formaldehyde adhesive and concluded that the adverse effect was not due to neutralization of the curing process. Ether- and alcohol-soluble extractives in yellow meranti and kapur have also been shown to cause poor bonding with alkaline phenol-formaldehyde adhesive. Hse and Kuo (1988) have reviewed the literature pertaining to the effects of extractives on wood bonding and finishing.

Drying Effects

Wood in the living tree normally has a moisture content in the range of 50-200% of its oven-dry weight. After the tree dies or is cut down, the wood will dry naturally to 5-20% moisture content in ambient air. Wood should be dried to within this range if it is expected to reach equilibrium with its intended end-use environment

before fabricated into various finished products. This is especially important before any manufacturing process that involves bonding. Today, wood is dried in heated, humidity-controlled kilns or in various types of dryers. The very process of drying changes the chemical as well as the physical nature of the wood surface. In kiln drying, wood stays relatively cool during the active loss of moisiure, and the major effects of drying are the movement and concentration of extractives at the surface. After moisture loss, continued exposure of the wood to elevated temperatures induces thermal changes in the extractives and in the wood substance.

Distribution of Extractives. Air drying may change the distribution of extractives in a board, but kiln drying has greater potential to alter both the concentration and the chemical nature of extractives at and just below the wood surface. The higher temperatures used in kiln drying lower viscosity and increase the solubility of nonvolatile extractives, thus facilitating their migration to the wood surface. There they concentrate as the water and volatile organic extractives evaporate (Huffman 1955, Troughton and Chow 1971).

In a given piece of wood, the extractives concentration is usually relatively uniform prior to drying; with drying, the concentration diminishes in the core and increases in the outer shell, resulting in a concentration gradient. The higher the moisture content of the wood when drying begins, the higher the final concentration of extractives in the outer shell and the steeper the gradient from the outer shell to the core. For example, in two separate experiments involving redwood heartwood (*Sequoia sempervirons*) dried from the green to the dry condition, the content of water-soluble extractives at the surface increased by 40 and 96%, respectively; the content of water-soluble extractives in the outer shell of the dried boards from the green to the dry condition was respectively 2 and 5 times higher than that in the core (Anderson, Ellwood, Zavarin, and Erickson 1960). The water-soluble extractives were largely tannins and other polyphenolic materials, cyclitols, polysaccharides, and other simple sugars. The final extractives contents are of particular note. The outer 3/32-in. shell of the pieces in the first experiment contained 25% by weight of water-soluble extractives; in the second experiment, the outer shell contained 40% by weight of water-soluble extractives. Because of the gradient, the concentration of extractives was probably much higher on the surface itself. The same effect probably occurs with extractives that are insoluble in water but soluble in volatile materials.

Plomley, Hillis, and Hirst (1973) found that hydrolyzable tannins decreased the wet and, in some cases, the dry bond quality.

They suggest that these tannins must reach a threshold level of concentration at the wood surface (0.4-2.0 g dry extract/m^2) before they affect the cure of phenol or resorcinol adhesives. More specifically, they noted that the ellagic, but not the gallic, acid moiety in the hydrolyzable tannin had a strong adverse effect on wet bond quality. The authors believe that the tannins, if not displaced from the surface by the adhesive, provide a water-soluble and thus water-sensitive layer between the wood and the adhesive. In other cases, the adhesive may displace the extractives, which are then absorbed by the adhesive. The absorbed tannin may form a weak boundary layer by simply diluting the adhesive or by interfering with the polymerization and cross-linking of the resin. In tests with one species, the hydrolyzable tannins did not affect bond quality unless an additional conditioning treatment (steaming and redrying) was used after drying to remove collapse. The authors suspected that this treatment raised the concentration of hydrolyzable tannins above the threshold level for interference with the bondline.

In solid wood members, the surface concentration of extractives is removed when the wood is planed or sawn before bonding. However, because of the gradient, a fairly deep cut may be required to achieve a surface with a significantly lower concentration of extractives. With veneer, there is little or no opportunity to remove the heavily contaminated surface; however, the concentration of extractives should also be lower because veneer is thin.

Chemical Modification of Extractives. The drying process can also alter the chemical nature of the extractives. Extractives exposed to high temperature during drying in kilns or ovens may be converted from hydrophilic to hydrophobic substances. For example, easily displaced water-soluble extractives may be converted to less easily displaced hot-alcohol-soluble extractives. In the study by Anderson, Ellwood, Zavarin, and Erickson (1960), the amount of cold water extractives in the outer shell of pieces of lumber increased by about the same amount (114 and 133%, respectively) whether or not the wood was kiln dried at 84 or 25% relative humidity (RH). The amount of hot-alcohol-soluble extractives (polymerized tannins and phlobaphenes) did not increase as much; however, there was a large difference in the increase between drying at high or low humidity. When dried at high humidity (84% RH), the amount of hot-alcohol-soluble extractives in the outer shell increased 86%; when dried at low humidity (25% RH), the increase was only 19%. The authors concluded that the greater increase in hot-alcohol-soluble extractives in drying at high humidity was due to the conversion of water-soluble extractives to hot-alcohol-soluble extractives under the more moist drying conditions.

Physical Effects of Drying. Northcott, Colbeck, Hancock, and Shen (1959) conditioned two sets of Douglas fir veneer to the same moisture content. One set was dried from the green condition to several levels of moisture content. The other set was dried below the lowest test moisture content and then allowed to adsorb moisture to the desired moisture content. The authors noted, but could not' explain, a greater adverse effect on bond quality of high adsorbed moisture content than for the same moisture content reached by desorption. Drying below the level of a monomolecular layer of water may convert the wood substance at the surface from a hydrophilic to hydrophobic condition. As moisture is lost, the cell wall shrinks, becoming less permeable and penetrable. The available hydroxyl units of the cell wall substance come close enough to each other for mutual hydrogen bonding. These actions reduce the ability of the wood to absorb water from the adhesive as it is setting (Hancock 1963). They also reduce the availability and accessibility of hydroxyl units for wetting and adhesion. Wellons (1980) found that at room temperature, the contact angle of an aqueous sodium hydroxide solution increased from about 75° to about 112° as the wood moisture content decreased from 18% to oven-dry. In spite of the decreased wettability of very dry wood, Wellons concluded that poor wettability was not a factor in bonding with caustic phenol-formaldehyde adhesives at high temperatures because wettability is vastly improved at such temperatures. Wellons also concluded that the adhesive is more likely to bond poorly because the adhesive film dries out (loses water to the wood or air) before properly curing.

Overdrying. Overdrying refers to drying wood at high temperatures or for relatively long periods after the wood has lost all its bound water and is no longer protected by the cooling effect of the evaporating water. One major factor leading to overdrying is the large difference between the moisture content of the sapwood and heartwood. The sapwood normally contains water in its cell walls and within the lumens equivalent to 100-200% of the oven-dry weight of the wood substance. The heartwood normally contains only 50-60% moisture. In air drying, the difference between heartwood and sapwood does not impose any difficulty beyond the longer time required to dry the one or the other. Impermeable heartwood may take longer to reach EMC than sapwood. In either case, however, the material (heartwood or sapwood) that dries out first quickly rises to the temperature of the oven or kiln and subsequently is exposed to that temperature for the duration of the drying schedule. This high-temperature exposure can chemically degrade the wood surface for wetting and adhesion through a variety of mechanisms.

Christiansen (in press a, b) conducted an extensive review of the literature pertaining to the effects of overdrying wood, The review was particularly oriented toward discovering specific interactions between wood surfaces and phenol-formaldehyde-resin adhesives. Christiansen concluded that overdrying reduces adhesively bonded joint strength by one or more mechanisms, including degrading wood strength, oxidation and pyrolysis of reactive bonding sites, chemical interference with adhesion, and chemical interference with adhesive cure.

The loss of wood strength clearly affects the strength of a bonded joint. The effects of temperature and thermal aging on the mechanical properties of wood are discussed in Section II.

Oxidation and pyrolysis during drying are important factors in reducing bondability. Chow (1971) found decreased strength and markedly decreased wood failure in plywood made from veneers exposed to oxidative or pyrolytic conditions between 100 and 240°C. He suggested that carboxylation under these conditions reduces the number of hydroxyl and aldehyde groups available for bonding. Chow determined by infrared spectroscopy that heating in air first decreased the number of initial carboxyl and ester groups. These groups occur primarily in the hemicelluloses and are known to be heat labile. Then, as heating continued, the number of carboxyl groups increased as a result of oxidative carboxylation of hydroxyl and aldehyde groups on cellulose, hemicellulose, and lignin. The loss of these potential bonding sites was apparently responsible for the great loss in bond quality. Interference with bonding, or critical surface inactivation, occurred after what Chow called the "time to reach significant carboxylation."

The reaction in Chow's study (1971) seemed to be temperature dependent. Furthermore, the rate of the reaction seemed to depend upon whether or not the extractives had been removed from the wood. The presence of fatty acids among the extractives appeared to accelerate oxidative carboxylation, especially at temperatures below 200°C. By extrapolating the time-temperature curves for both extracted and unextracted wood, Chow found that at 350°C, carboxylation and thus inactivation were essentially instantaneous. Conversely, by extrapolating to lower temperatures, the higher extractives content was associated with shorter inactivation time.

Oxidation was the more important process for carboxylation below 180°C, but pyrolysis and oxidation were equally effective above 180°C. The difference between the rates of conversion in air or in nitrogen narrowed as the temperature increased. At 220°C, the difference was minimal. Chow (1971) stated this as evidence that the deactivation is controlled by pyrolysis rather than oxidation at higher temperatures.

Chow and Mukai (1972) found further support for the conclusion that oxidation affects the chemical surface characteristics of wood by studying the effects of ozone on plywood bonds. The strength and wood failure of plywood made from veneers pretreated with moisture and ozone at room temperature diminished with the duration of the treatment. Thermal degradation has also been related to decreased wettability and water absorption (Hernadi and Domotor 1981).

The temperature in some kilns or ovens may reach 400-1000°F. When wet hardwoods are exposed to high temperatures for a given period, acetyl groups in the wood are converted to acetic acid. The pH of water in the wood may drop as low as 3.5. Under these conditions, dilute hot-acid hydrolysis creates water-soluble polysaccharide and lignin fragments. Acid hydrolysis is a time-temperature-dependent reaction. Therefore, although drying times are relatively short, soluble polysaccharide and lignin reaction products could conceivably be created. Such soluble fragments could concentrate at the surface and interfere with bonding just as soluble extractives can.

D. Roughness

A wood surface is complex because of variations in the cell morphology, the mechanisms of cell fracture, and the type and quality of machining (Marian and Stumbo 1962a). Marian, Stumbo, and Maxey (1958) described three levels of roughness based on (1) the porosity, or the size and distribution of various types of cells characteristic of a given species, (2) the superimposed machining marks characteristic of a given process, such as knife planing or sawing, and (3) the incidental machining marks or surface variations caused by machine vibration, cutters that protrude beyond the normal cutting path, or variations in feed rate or direction. Suchsland (1957) considered three texture levels independent of machining: (1) submicroscopic (cell wall structure), (2) microscopic (cell diameter, cell wall thickness), and (3) technological (annual-ring structure).

If wood is surfaced with a sharp cutting tool, the anatomically determined roughness will be maximized by longitudinal transwall fracture of the type shown in Figures 1.13, 1.14, and 1.31a,b. The surface should consist of a series of troughs formed by cell lumens and cleaved cell walls. Earlywood surfaces formed of large deep troughs and thin edges of cleaved cell walls are the roughest (Figure 1.31a). Latewood surfaces formed of shallow troughs and broad edges of cleaved cell walls are the least porous (Figure 1.31b). The roughness of a surface that is cut perfectly with a microtome is largely a function of cell wall thickness and lumen diameter-in essence, of porosity. If the wood is surfaced with a dull or improperly

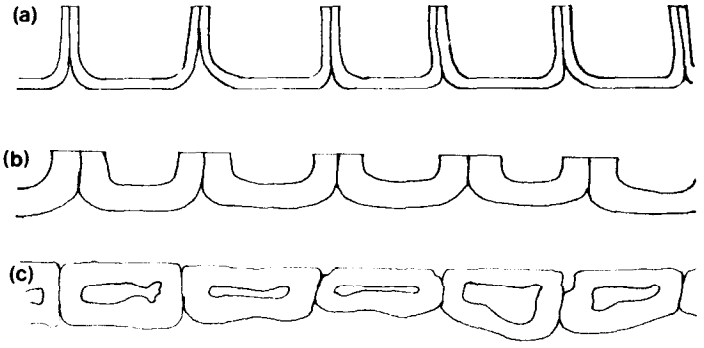


Figure 1.31 Roughness of wood surfaces: (a) roughest as a result of longitudinal transwall fracture of thin-walled large lumen cell structure, (b) smoother surface as a result of longitudinal transwall fracture of thick-walled, small lumen cell structure, and (c) smoothest surface as a result of longitudinal intrawall fracture and compression and smearing of cell walls.

sharpened cutting tool, intrawall failure of the type shown in Figures 1.13b,c and 1.30b will most likely occur. The cell walls are heated, compressed, and smeared, forming a smoother and even less porous surface than that formed with a sharp tool, whether on latewood or earlywood (Figures 1.31c and 1.32).

The strength of bonded joints increases with increasing porosity up to a point; beyond that point, strength decreases as porosity increases (Suchsland 1957). Suchsland attributed the increasing strength to the increasing area available for bonding and to improved mechanical interlocking with the increasing porosity and roughness of the surface. On the other hand, the wood strength decreases with increasing porosity as a result of decreasing density. Maximum joint strength occurs at the point where the increasing strength of the bond intersects the decreasing strength of the wood. This dependence of adhesive joint strength on porosity as described by Suchsland (1957) is shown schematically in Figure 1.33. The relationship between porosity-based roughness and bond strength is an important factor underlying the relationship between bond strength, density, and the percentage of wood failure that is discussed in Section VI. The same relationship between roughness and strength would be expected for roughness created by the cutting tool. In the next section, we will further discuss how roughness influences bonding through its interaction with the liquid adhesive.

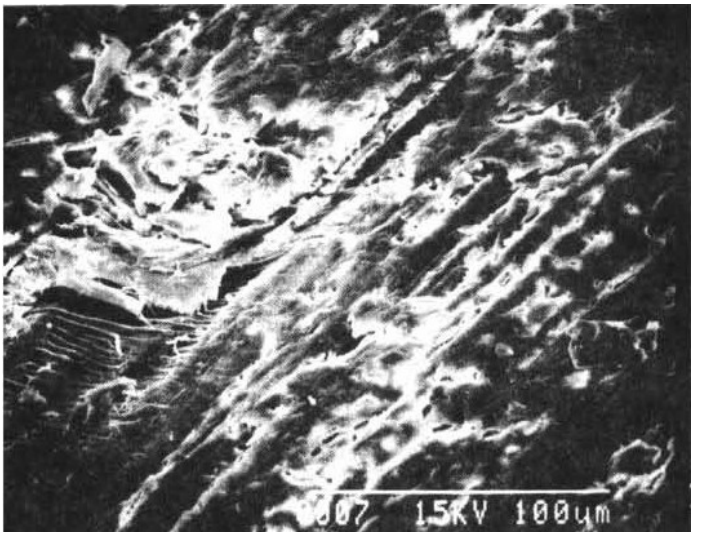


Figure 1.32 Compressed and smeared surface formed by planing with a dull knife or a knife that has been excessively jointed.

The forces of adhesion, that is, the physical forces between molecules, are ineffective at distances greater than about 3-4 nm. Yet even the most carefully machined wood consists of peaks, valleys, crevices, and pores that greatly exceed this distance. The roughness created by cutting through the cell lumina alone may range from as little as 30,000 nm up to 300,000 nm in depth. Even under pressure, the intimate contact required for bonding is achieved only over a relatively small proportion of the total surface area, and excessive pressure will cause irreparable mechanical damage to the wood. Finally, external pressure causes elastic deformation of the adherends and consequent stress on the bondline when that pressure is released (Figure 1.17).

E. Interactions Between Liquids and Wood Surfaces

Liquids, including liquid adhesives, are able to flow and penetrate the cracks and crevices of a rough surface. As the liquid penetrates the rough surface, it may be able to displace air, water, and other contaminants. When this happens, the 'liquid adheres to the surface and is said to wet the surface. Flow, penetration, and adsorption describe the process of wetting that is necessary for bonding

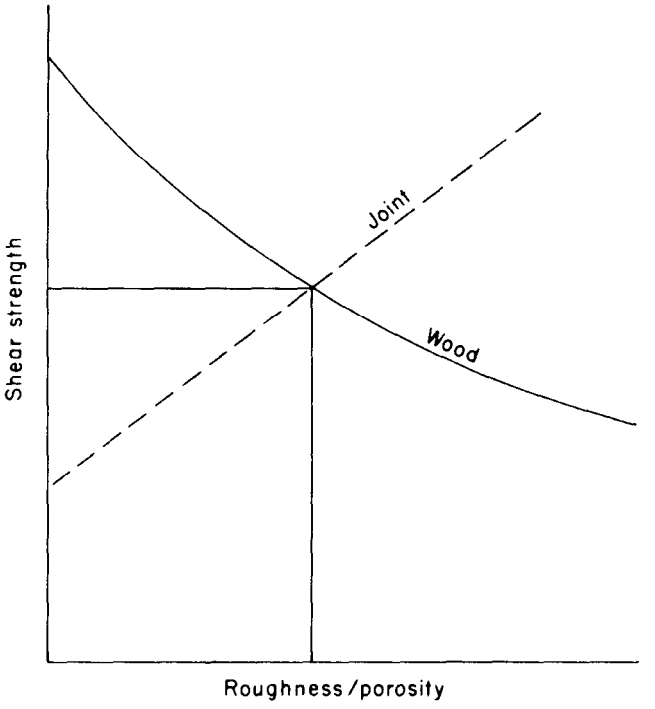


Figure 1.33 Relationship between the shear strength of bonded joints and the porosity or roughness of the wood.

of wood and other adherends with adhesives. We will discuss how wood and wood surface characteristics interact with liquid adhesives to affect wetting.

Contact Angle and Critical Surface Tension

A discussion of the thermodynamical basis for wetting is beyond the scope of this discussion; a full discussion may be found in many books and articles on adhesion (Eley 1961, Patrick 1967, Gutowski 1987). These relations have also been discussed with specific reference to wood surfaces by Marian and Stumbo (1962b), and Collett (1972). Simply stated, during wetting, a liquid displaces air from the solid surface and is itself adsorbed by that surface. The process of wetting is controlled by the relative surface energies of the respective solid, liquid, and gas phases at their juncture. Wetting can be quantified by the equilibrium contact angle formed by the

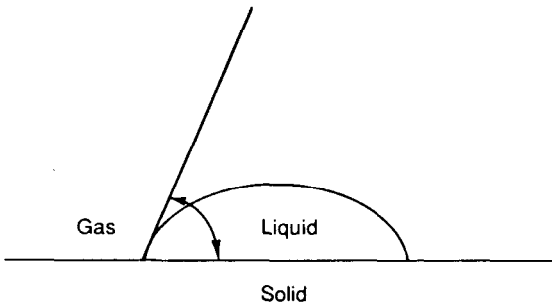


Figure 1.34 The contact angle of a liquid with a solid surface formed at the juncture of the solid, liquid, and gas phases during wetting.

intersection of the solid, liquid, and gas phases (Figure 1.34). As a general rule, an organic liquid will wet an organic surface when the surface energy of the liquid molecules is just equal to or lower than the surface energy of the solid. The energy of the gas phase is normally very low, and it is usually disregarded. When good wetting occurs, the contact angle becomes very small or disappears, and the liquid spreads or flows spontaneously across the surface. A further requirement for wetting, or at least rapid wetting, is that the liquid be of sufficiently low viscosity to flow and be able to penetrate surface roughness.

The surface energy of a liquid is easily determined, but the surface energy of a solid is difficult to measure. An easily determined approximation of the surface energy called the *critical surface tension* was developed by Zisman (1963). The critical surface tension is the surface energy of a liquid that will just spread spontaneously across a solid surface. It is the surface tension (extrapolated to the intercept with zero contact angle) of an empirical relationship between the surface tensions and the cosine of the corresponding contact angles for a series of homologous liquids placed on the surface. The critical surface tension *may* vary slightly from the true surface energy of the solid, depending upon the type of liquid chosen for the experiment. The critical surface tension has been used by Gray (1962) to approximate the surface energy of wood. In a study of 19 species, the critical surface tension ranged from lows of 11 dyn/cm for unsanded parana pine at 20% moisture content and 15 dyn/cm for English oak at 8% moisture content, to highs of 74 dyn/cm for sanded yellow birch and European beech and 81 dyn/cm for sanded parana pine at 8% moisture content. Most values for the critical surface tension of wood fall within the range of 40-70 dyn/cm.

Accurate measurements of contact angles on wood are confounded by the inherent roughness, porosity, and absorptive and swelling potentialities of wood surfaces. The changing surface slope across a rough wood surface means that a true angle cannot be measured. The measured angle is actually an average contact angle. If the contact angle formed by the liquid is less than 90°, the liquid should be able to penetrate the porous wood surface. This results in gradual absorption of the droplet. Since the contact angle decreases as the volume of the droplet decreases, the droplet may never reach equilibrium. To avoid these difficulties, some researchers have measured contact angles as the droplet advances and recedes upon an inclined surface, or the height of liquid imbibed by a piece of wood or a glass tube filled with ground wood when one end of the piece or column is placed in contact with the liquid (Freeman 1959, Bodig 1962). Casilla, Chow, and Steiner (1981) developed an immersion technique that measures not only the surface tension of the wood but also the amount of liquid absorbed by the wood.

Properties of the Liquid Adhesive

pH Stamm (1964b) noted that cellulosic materials such as wood adsorb acids poorly. Alkalis, on the other hand, are readily adsorbed and, in fact, swell wood well beyond the normal water-swollen state. Wellons (1980) pointed out that a caustic adhesive has greater solvent power for extractive materials at the wood surface. In spite of these facts and the fact that most wood adhesives are either acidic or basic, most researchers have used distilled water to measure wettability. Jordan and Wellons (1977), however, recognized the importance of pH and used an alkaline (sodium hydroxide) solution of pH 11, in the same range as phenol-formaldehyde adhesives. They did not compare the difference in wetting between the alkaline solution and distilled water. Casilla, Chow, and Steiner (1981) made such a comparison in a study of the difference in the wetting behavior of a hardwood and a softwood. The wetting behavior obtained with distilled water and sodium hydroxide solution was quite similar on the unaged softwood (white spruce) surface. However, the hardwood (padauk) surface wet much more readily with the caustic solution than with distilled water. The better wettability by the caustic solution was attributed to its lower surface tension, strong swelling power, and its resultant ability to open new bonding sites. Casilla, Chow, and Steiner (1981) also demonstrated reduced wettability as the pH of the wetting solution was reduced in six steps from 13.6 to 5.7. Later, Casilla, Chow, Steiner, and Warren (1984) found the same effect with four species of meranti.

Solvent Characteristics. The solvent power, polar nature, and hydrogen-bonding strength of the liquid in an adhesive all affect its ability to wet wood. The heat of wetting is a measure of a solvent's ability to wet the surface and swell the wood. Kajita, Mukudai, and Yata (1979) found that the highest total heats of wetting of wood were obtained with strong hydrogen-bonding, low-molecular-weight solvents such as water, ethanol, methanol, and ethylene glycol (wetting heats of 20, 12.5, 15, and 16 cal/g, respectively). Higher-molecular-weight glycols had much lower heats of wetting (about 1.5 cal/g), presumably because their large molecular volume prevented their penetration of even the most accessible amorphous regions of the cell wall. High heats of wetting were also noted for some other solvents, such as formamide, ethylenediamine, N, N-dimethyl formamide, and dimethyl sulfoxide (22, 60, 22, and 26 cal/g). These solvents are more polar than water and are thought to have the ability to swell the wood more than water, but their large molecular volume slows the rate of cell wall penetration and thus the rate of heat evolution. Nonpolar aprotic solvents such as benzene and toluene do not generate high heats of wetting, although their heats are higher than many high-molecular-weight protic solvents (5-10 cal/g).

When a solvent wets wood, it first penetrates the gross capillary structure such as the cell lumens and intercellular pits. Next, it penetrates the spaces between the microfibrils in the secondary wall. If the solvent has a swelling capacity for wood, then it expands the cell wall, creating transient cell-wall capillaries. Stamm (1964b) recorded the swelling capacities of numerous liquids and found among them that formamide, formic acid, and pyridine swelled wood 23, 20, and 18% more than water; methanol, ethanol, acetic acid, and acetone swelled wood 5, 17, 25, and 37% less than these compounds, respectively.

As an example of the effects that swelling has upon the opportunities for the adhesive to interact with the wood, Cowling and Stamm (1963) reported that the gross capillary structure of wood-lumens and pits-has a contact area of about 15 $ft^2/in.^3$ of wood. In contrast, the contact area formed by a swelling liquid, which opens the transient capillaries, can be as high as 0.5 $acre/in.^3$.

Dissolved molecules, such as an adhesive polymer, are carried into the transient capillaries of the cell wall if they are not too large. Tarkow, Feist, and Southerland (1966) determined that molecules of polyethylene glycol, with molecular weight up to 3000 in a water solution, penetrate the transient capillaries.

Surface Tension. Casilla, Chow, Steiner, and Warren (1984) determined that wettability of wood by caustic aqueous solutions increases as the surface tension of the wetting liquid decreases.

However, the lowest adhesive surface tension (low surface energy) is not always the best or even a necessary condition for bonding a low-surface-energy solid such as wood. In a series of experiments, Herczeg (1965) used a urea-formaldehyde resin, modified with various levels of a surfactant, to bond joints of Douglas fir. The strength of the joints increased as the surface tension of the resin decreased from 63 to 50 dyn/cm, which is about equal to the critical surface tension of wood. A further decrease in surface tension to 39 dyn/cm caused overpenetration by the adhesive and a reduction in joint strength. Earlier, Gray (1962) had reached the same conclusion : that low liquid surface tension leads to easy wetting but poor adhesion. Stronger adhesion results from using a liquid adhesive with relatively high surface tension as long as wetting is obtained. Furthermore, an adhesive that wets wood poorly as a free droplet under ambient room conditions may wet very well under the influence of spreading, pressing, and heating during an actual bonding operation (Wellons 1980).

A low contact angle is very important to capillary flow into the complex porous structure of wood. Inside wood, the entrapped gases, foreign matter, and water must be displaced or absorbed into the adhesive for the adhesive itself to make intimate contact with sound wood structure. Liquids of low surface energy are necessary for especially difficult-to-wet woods, such as greenheart, teak, unsanded oak, and ekki. Once wetting is attained, adhesion should be adequate (Gray 1962).

Wood Factors that Affect Wetting, Flow, and Penetration

Although a low contact angle and low surface energy may indicate good wetting and therefore good adhesion by an adhesive, the wood itself has numerous strong influences on the end result. The three processes involved in wetting-adhesion, flow, and penetration-are influenced by the density or porosity of the wood, species of wood with its particular extractives, age of the wood surface, acidic characteristics of the wood, and wood moisture content.

Density. Density must be considered a key factor controlling wetting and wettability because it affects all three aspects of wetting. Sakuno and Goto (1967, 1970a) studied the relationship between wettability and specific gravity of 18 tropical and temperate woods, and found a strong negative correlation. However, several species, such as teak, apitong, and kapur, did not fit the correlation. Freeman (1959) also reported a correlation between wettability and specific gravity. However, examination of his studies revealed that only the maximum wettability at a given specific gravity correlated with specific gravity (Figure 1.35). The maximum wettability decreases as the specific gravity increases. None of the

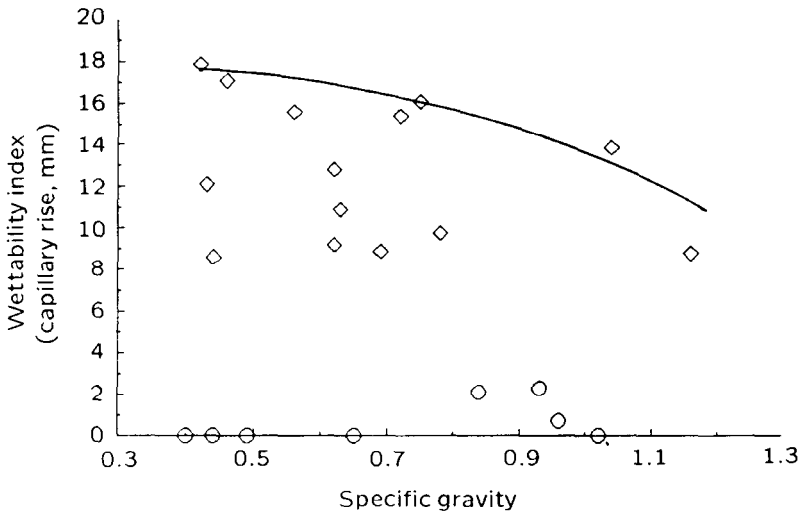


Figure 1.35 The relationship between wood wettability and specific gravity (based on data from Freeman 1959).

studies showed any relationship between the minimum wettability and specific gravity over a wide range of specific gravities (Figure 1.35). Each study included a group of species over an extended range of specific gravities that were essentially nonwettable. The explanation may be high extractives content that could obscure the basic underlying relationship of wettability with the specific gravity of these woods. Although the authors did not measure extractives content, these difficult-to-wet species are reported in another source (Chudnoff 1984) as species highly resistant to attack by microorganisms. Extractives are the major factor that protect wood from attack by microorganisms, and the degree of resistance is related to their concentration ; therefore, these difficult-to-wet species probably possess significant levels of extractives.

Species. A wood species, by its peculiar chemical constitution (especially extractives content), indirectly influences wetting and wettability. Chen (1975) determined the advancing and receding contact angles of water droplets on the planed surfaces of 13 tropical woods. He found that the contact angles were reasonably correlated with the calculated water of hydration of these species. The water of hydration is the average molecular weight of wood substance required to adsorb 1 molecular weight of water between the oven-dry

condition and the fiber saturation point. The wettability decreases (the receding contact angle increased from about 0° to 52°) as the availability of hydroxyls decreases (the amount of wood substance required to absorb 1 molecular weight of water of hydration increases from about 265 to about 325 molecular weight). A high requirement of wood substance implies that a particular wood has a low availability of hydroxyls in the wood or on the surface. The availability of hydroxyls is controlled by the wood structure and extractives of each species.

Sakuno and Goto (1967, 1969, 1970b) evaluated the dependence of wettability upon extractives content of 36 tropical and 15 temperate woods. The wettability of species below 0.80 average specific gravity decreased sharply as the extractive content increased from 0 to almost 2% of the dry weight of the wood. The wettability of species above 0.80 average specific gravity did not correlate with the percentage of extractives. The strength and percentage of wood failure of joints bonded with urea-formaldehyde and phenol-formaldehyde adhesives were moderately dependent upon specific gravity, wettability, and the percentage of ether extractives for those species below 0.8 average specific gravity. Joint strength became increasingly sensitive to the species extractives content and wettability as the average specific gravity for the species decreased.

Aging. Chemical and physical changes begin to occur in a wood surface immediately after it is machined. Contaminants also may fall upon the surface or be sorbed from the air. Numerous researchers have reported decreases in the wettability of wood with increasing surface age. Gray (1962) exposed the surfaces of 15 species of wood to laboratory air for up to 180 h and noted significant increases in the initial contact angle of droplets of calcium chloride solution placed on the aged surfaces. In general, the wettability of surfaces of species easily wetted at the outset declined more than that of poorly wetted species. Herczeg (1965) found a highly significant decrease in wettability when Douglas fir earlywood and latewood surfaces were aged in ambient air for periods up to 45 h. Sakuno, Goto, and Katsube (1971, 1972, 1973) reported mixed results from studies of the effects of aging upon the wettability of eight temperate woods. In the first group of three species, wettability decreased with atmospheric aging over a 6-month period, during which the surfaces were protected from airborne contaminants and light. The strength of joints made with either urea-formaldehyde, resorcinol-formaldehyde, poly(vinyl acetate), or casein adhesives decreased as the surface aged. In a second group of three species, wettability did not decrease under similar aging conditions, and the strength of joints made with the aged surfaces actually seemed to benefit from the surface aging before

bonding. In the last group of two species, wettability and joint strength decreased moderately with most adhesives as the surfaces aged.

The percentage of delamination was also measured as a function of surface aging before bonding. Higher percentages of bondline failure (delamination) in a given soak-dry treatment should be expected of poly(vinyl acetate) and casein compared to urea-formaldehyde and resorcinol-formaldehyde simply because the former adhesives are capable of redissolving in water. However, the surprising result was that with most species, the percentages of delamination of poly(vinyl acetate) joints increased markedly as the period of aging before bonding increased. Increases in delamination with aging in joints bonded with other adhesives either were slight or only occurred at the longer aging times. This suggests that good wettability is more critical to poly(vinyl acetate) and casein adhesives than to the formaldehyde-based adhesives. Stumbo (1964) found a 30-50% decrease in the tensile strength of bonded joints made with wood surfaces aged for up to 5 months before bonding. Heat aging at 160°C changed the wettability indices of a low-density softwood and a high-density hardwood by distilled water from positive to negative in less than 20 min (Casilla, Chow, and Steiner 1981).

Moisture Content. The importance to wetting of the moisture in the wood (with its strong attraction to the polar hydroxyl groups of wood substance as well as its affinity for water and polar polymers in certain waterborne adhesives) is clearly indicated by measurements of the critical surface tension of wood. The critical surface tension of wood decreases from about 70 dyn/cm at 30% wood moisture content to 20-40 dyn/cm at 0-38 moisture content (oven-dry weight basis) (Wellons 1980, 1983). Also, when very low moisture contents are attained, there may be a permanent loss of the available polar hydroxyl groups that promote wetting by polar liquids. Removing the last bound water from the cell wall substance brings the hydroxyl groups of the cellulose chains close enough together to form a strong, mutually satisfying intramolecular bond (Salehuddin 1970). This can be seen in the hysteresis effect on moisture sorption and desorption from the atmosphere. In a desorption-sorption cycle, wood equilibrates at a higher moisture content during desorption than during subsequent sorption at the same temperature and relative humidity. Strong swelling agents, such as the sodium hydroxide solution in phenol-formaldehyde adhesives, should be able to break the hydroxyl bonds and restore their accessibility to the adhesive. However, Wellons (1980) demonstrated that even caustic solutions have more difficulty wetting wood as the moisture content decreases from 18 to 0%.

The surface energy of moist wood is actually higher than that of dry wood (Wellons 1983) and thus more easily wetted. Gray (1962) demonstrated that the critical surface tension determined from receding contact angles was much higher than that determined from advancing contact angles. After an advancing droplet has wet the wood, the local moisture content of the wood increases. As the wood absorbs moisture, it swells, and it thus opens additional sites for adsorption. The additional adsorption sites raise the wood surface energy and thus the critical surface tension.

Marian and Stumbo (1962b) pointed out that both the heat of sorption and the shear strength are functions of the wood moisture content. More significantly, both the heat of sorption and the shear strength (moisture content at bonding) reach their maximum levels at about the same moisture content (10-12%). This is significant because 10-12% moisture content is roughly equivalent to a uniform monomolecular layer of water adsorbed on all the accessible porous and microporous surfaces of the wood and wood substance. Based on this observation, Marian and Stumbo suggest that water is necessary for adhesive bonding. Salehuddin (1970) reached a similar conclusion that a definite amount of water in wood is necessary for optimal adhesion; that wood-adhesive bonds are in fact formed through an intermediary layer of adsorbed water.

Roughness. Collett (1972) extensively reviewed the relationships between wood surface properties, including roughness and adhesion. He concluded that a roughened surface (such as that created by light sanding) contributes to bond strength not by increasing mechanical adhesion but rather by promoting "a more spontaneous spreading," which in turn leads to improved wetting. Wenzel (1936, 1949) demonstrated that the cosine of the contact angle varies directly with roughness; that is, wetting improves with roughness. However, Zisman (1977) cautioned that roughening the surface to improve wetting is justified only to the extent that improvements in strength from improved wetting outweigh losses in strength from surface voids that are not filled by adhesive as a result of dust or entrapped gases.

Sandoval-Botello (1971) studied the effect of roughness on the wetting behavior of Douglas fir. The surfaces were prepared by sawing, sanding, planing, and microtoming. The advancing and receding contact angles were then determined on both earlywood and latewood tissues for a series of homologous silicone and polyethylene-glycol liquids of varying molecular weights. From the contact angle results, Sandoval-Botello determined the work values of adhesion, spreading, and penetration. All three measures showed peak values as functions of the liquid surface tension. Both wetting and penetration work values tended to peak in the range of 30-40

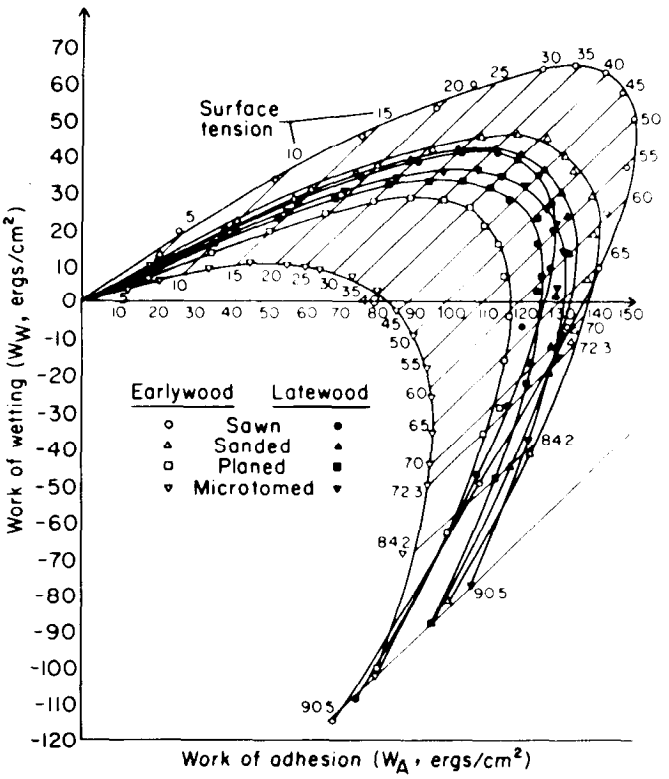


Figure 1.36 Model for the work of wetting (W_W) and the work of adhesion (WA) as functions of the surface roughness of Douglas fir lumber and the surface tension of the liquid (Sandoval-Botello 1971).

dyn/cm, whereas the adhesion work value tended to peak between 50 and 60 dyn/cm. Sandoval also developed a model for the maximum work of wetting and adhesion as functions of the type of tissue (earlywood compared to latewood), surface roughness, and surface tension of the liquid (Figure 1.36). The critical surface tensions for these surfaces ranged from 41 dyn/cm for microtomed earlywood to 70 dyn/cm for microtomed latewood. The model confirms Gray's (1962) observation that maximum adhesion is not necessarily obtained with the adhesive that most easily wets the surface. For example, the model in Figure 1.36 shows that the best wettability (maximum work of wetting, W_W) of microtomed Douglas

fir earlywood will be obtained with a liquid having a surface tension of about 20 dyn/cm, whereas the best adhesion (maximum work of adhesion, WA) will be obtained with a liquid having a surface tension of about 65 dyn/cm. The fact that W_W is negative implies that additional energy is required in the form of mechanical spreading or pressure to obtain wetting. But once wetting is established, the model predicts that WA will be superior with an adhesive having a surface tension of about 65 dyn/cm.

Thompson and Choong (1968) observed a possible interaction between roughness, extractives content, and wettability. They found only a 2% difference in the strength of joints of planed or sawn surfaces of cottonwood and willow sapwood; however, planed and sawn heartwood joints were 9 and 14%, respectively, weaker than the sapwood joints. The authors suggested that these reductions in heartwood bond strength may have been caused by poorer wettability caused by the presence of extractives and thus incomplete filling of voids in the rough-sawn heartwood surface. This also seems to confirm Zisman's (1963) statement that although roughness may enhance wetting, roughness is only useful to the extent that the adhesive is able to penetrate all the voids and displace air pockets.

F. Revitalization and Modification of Wood and Fiber Surfaces

Planing

Planing has been the most effective and traditional method for revitalizing wood surfaces for bonding. Dougal, Krahmer, Wellons, and Kanarek (1980) compared planing and solvent extraction for their effectiveness in promoting bonds that would resist delamination in plywood. The plywood was made with three tropical woods that are frequently difficult to bond: keruing, kapur, and balau. Some keruing veneer bonds well, in spite of the fact that it is poorly wetted by water; kapur has good wettability, but bonds poorly. Planed veneers produced plywood that consistently passed the minimum 85% wood failure standard for exterior plywood and, in fact, consistently produced wood failures equal to or higher than that of unplaned veneer. Planing also improved both the level and uniformity of wood failure in keruing plywood, which are otherwise quite variable.

Using scanning electron microscopy, Dougal and associates (1980) also noted open ray cells, open longitudinal cell lumens, and much debris on the surface of the original veneer. Planing closed the open cavities by folding the cell walls or by pushing debris into them. As a result, the surface was smoother and cleaner than that produced by the veneer lathe. The authors theorized that planing decreases the exposure of the lumen wall with its more difficult-to-

wet surface and increases the exposure of cell wall substance as a result of intrawall fracture.

Sanding

Gray (1962) demonstrated that sanding raises the critical surface tension of wood (improves wettability). However, sanding is generally not recommended for preparing wood surfaces for bonding. As explained previously, abrasive planing (hard backup roll) causes significant surface and subsurface damage to the cells that can lead to poor performance of the bonded joint in service. Heavy sanding (soft backup roll) can destroy the flatness of a surface by preferentially removing the softer earlywood tissue and leaving the harder latewood tissue, with the result that pressure during bonding will be uneven and bond quality will be variable.

Light hand or machine sanding with a fine grit may be acceptable as long as not enough wood is removed to affect the flatness of the surface. Very light sanding will often significantly improve wettability of a surface that has been inactivated because of overdrying or the accumulation of extractives (Figure 1.37). However. if the problem is related to extractives, once the sandpaper becomes coated with the extractives, sanding may worsen the problem by transferring these materials to unaffected surfaces.

Solvent Washing

Removal of extractives by washing or dipping is a less effective means for revitalizing wood surfaces than is planing. In some species studied by Dougal, Krahmer, Wellons, and Kanarek (1980), the extraction process actually lowered the amount of wood failure. The average wood failure values for the untreated, extracted, and planed veneers were 80, 79, and 94%, respectively.

Teak can be a difficult wood to bond. The blame is usually placed upon its oily extractives. These are frequently so heavy that the wood has an oily sensation. However, all teak is not difficult to bond, nor does extraction always improve bondability. Gamble Brothers (1945) washed teak surfaces with acetone and improved the strength of resorcinol-formaldehyde-bonded joints from 1025 to 1262 lb/in.^{2} and wood failure from 63 to 83%. Troop and Wangaard (1950), however, had no difficulty obtaining 2040 lb/in.^{2} and 92% wood failure with no treatment using the same type of adhesive. Sparkes (1966b) showed that acetone extracts of teak had little effect on the strength of beech joints coated with the extract, but that ether extracts lowered joint strength by 36, 42, and 25% in joints bonded with urea-formaldehyde, poly(vinyl acetate), and resorcinol-formaldehyde adhesives, respectively.

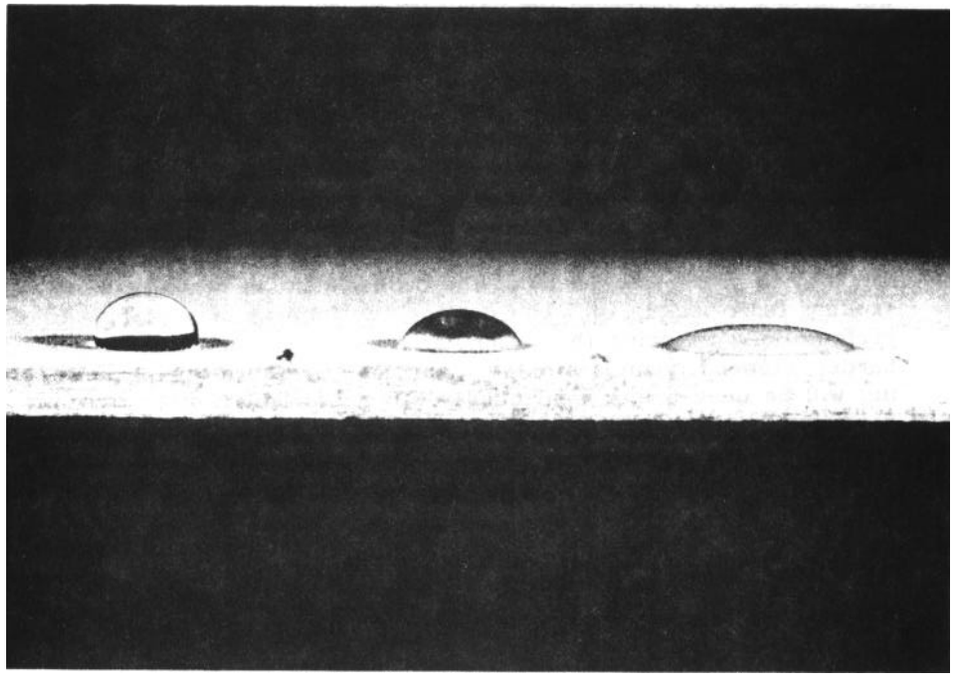


Figure 1.37 Improvement in the wettability, by light abrasion, of an aged yellow birch veneer surface as shown by a water drop test. The shapes of the three drops applied at the same time and photographed 30 s later illustrate the poor wettability of the aged surface (left), a surface renewed by two light passes with 320-grit sandpaper (center), and a surface renewed by four light passes with 320 grit (right).

Washing with various organic solvents, including carbon tetrachloride, benzene, acetone, and alcohol, did not significantly improve the bond quality of lignum vitae (Rapp 1948). However, washing, or sanding followed by washing with a 10% solution of sodium hydroxide, was very effective. These treatments increased strength from 1185 lb/in.^{2} to 1770 and 2000 lb/in.^{2}, respectively, and wood failure was increased from 22% to 30 and 37%, respectively. This solution has a long history for improving the bondability of certain difficult-to-bond woods (Truax and Harrison 1925, Forest Products Laboratory 1961). The same treatment has recently been

used to improve the bondability of southern pines treated with the preservative chromated copper arsenate (Vick 1981).

Chemical Modification

In the 1970s and 1980s, considerable efforts were mounted to activate wood surfaces through chemical treatments with the goal of developing chemically bonded joints without polymeric adhesives. These efforts have been well summarized by Zavarin (1984) and Johns (1989). None of the methods has been entirely successful in creating water-durable joints without the addition of a filler or bridging material, thus reemphasizing the need for continuous intimate contact over a large percentage of the surface rather than points of contact that cover a small percentage of the surface. Nevertheless, several methods have been proven to successfully activate wood surfaces for improved bonding. The most successful of these combine an acidic, alkaline, or oxidative treatment with heat. Chemicals used for this type of treatment have included ferric salts, sulfuric acid, hydrochloric acid, nitric acid, hydrogen peroxide, and sodium hydroxide.

Unfortunately, acidic bondlines do not have a good record for durability in service as a result of the weakening effect of the acid on the wood. Alkaline treatments, however, have proven more durable. Not coincidentally, most exterior-grade plywood is made with highly alkaline phenol-formaldehyde resin adhesives. In phenol-formaldehyde adhesives, plasticization of the wood adjacent to the bondline by the caustic presumably contributes to the high durability of plywood made with these adhesives. Plasticization of the adjoining wood helps to relieve the inherent stress concentration at the interface between the wood surface and the adhesive layer. In addition, a simple wash with a sodium hydroxide solution improves the wettability of difficult-to-bond woods.

Building on these ideas, Young, Fujita, and River (1985) developed waterproof bonds by pretreating the wood surface with a strong 3 N sodium hydroxide solution and bonding with methylated lignin adhesive. They speculate that the treatment has both chemical and physical effects. The alkaline solution reduces surface tension and removes extractives from the surface. It also hydrolyzes cell wall constituents and increases the size of submicroscopic pores in the wood. If these changes actually occur, they would improve the mechanical interlocking between the wood and the adhesive and increase the availability and accessibility for hydrogen bonding of hydroxyl units, which are thought to be the major contributor to adhesive bond strength.

IV. WOOD ELEMENTS AND BONDED WOOD PRODUCTS

A. Unique Processibility of Wood

Wood is a unique material in many respects. Its most obvious qualities are the warmth it can provide and its beauty. Moreover, wood combines beauty with structural efficiency. Few realize that pound for pound, wood is as strong and stiff along the grain as many of the strongest materials (Table 1.9). We use more wood than all other major building materials combined, with the exception of sand and gravel, and yet wood is the only renewable structural material. Perhaps the most unique features of wood are its anisotropy and the ease with which wood can be cut, shaped, and reassembled.

Whole trees can easily and cheaply be reduced to smaller pieces or *elements* and reassembled in new shapes to reduce weight, conserve materials, modify properties, or create new shapes. Consider that primitive humans crudely fashioned shelter, canoes, furniture, and containers from whole logs using only fire and stone tools.

Table 1.9 Specific Strength and Stiffness of Wood and Other Common Materials

Material	Tensile strength (km)	Stiffness[a] (Mm)
Douglas fir, latewood fiber	257	8.8
Boron wire	136	16
E-Glass fiber	136	2.9
Steel wire	54	2.7
Aluminum wire	24	2.8
Douglas fir, clear lumber	28	2.2
Douglas fir, construction lumber	14	1.8

[a]Specific strength or stiffness = property (kgf/m^2)/density (kg/m^3) = km or Mm.

These items were necessarily bulky and heavy. Obviously, primitive humans did not take their furniture with them! Major breakthroughs for wood utilization were the discovery of metals and the development of metal tools. These developments allowed people to break wood down into smaller elements more easily, to rearrange those elements, and to shape them into useful products. The smaller elements were easily fastened together with pegs or leather thongs, and the resulting whole could be made lighter and more efficient than the primitive equivalent fashioned from whole logs or branches. The ease of shaping and combining wood elements led to a freedom of design that we still admire. Consider the beautiful Egyptian furniture from the days of the pharaohs, the powerful Phoenician sailing ships (much larger than even the largest tree trunk), and the graceful Polynesian outrigger canoe. Today, reassembled wood elements are present in such familiar items as houses, furniture, and paper bags.

We take wooden articles of everyday living for granted, not realizing that we can afford these products because wood is easy and economical to machine and bond, and consequently its processing costs are low in comparison to those of other construction materials (Table 1.10). None of the nonwood structural materials (with the exception of gravel) is as cheaply processed as lumber, and only concrete and brick are cheaper than the most energy-intensive wood products.

B. Usefulness of Wood Anisotropy

Many common reassembled wood articles would not exist were it not for the anisotropic nature of wood. Virtually all reconstituted wood materials rely on the directional differences, or anisotropy, in strength, stiffness, and dimensional stability of wood elements, and upon our ability to arrange these anisotropic elements to advantage. The most striking of reassembled wood materials are plywood, flakeboard, hardboard, and paper. All of these owe their usefulness to our ability to create high stiffness and dimensional stability in a two-dimensional plane as opposed to a single axis (fiber) or a three-dimensional (isotropic) solid. Most other raw construction materials are isotropic, and they must be stiffened or made artificially anisotropic by forming ribs, webs, or corrugations.

C. Table of Wood Elements

Marra (1972) traces the discovery or development of 14 wood elements in his description of a nonperiodic table of wood elements. We previously mentioned that wood in round form (logs and branches) has been used as is or has been crudely shaped by stone or

Table 1.10 Comparative Processing Costs of Construction Materials[a]

Materials	Total cost ($\times 10^6$ Btu/ton)
Wood-based	
Lumber	(3.47)[b]
Oak flooring	(5.70)
Laminated veneer lumber	3.05
Plywood	3.17
Flakeboard	(1.11)
Medium density fiberboard	6.56
Insulation board	9.87
Particleboard	6.57
Wet-process hardboard	18.86
Nonwood	
Gravel	0.06
Gypsum	2.87
Asphalt shingles	5.73
Concrete	8.12
Brick	8.30
Steel slab	24.00
Carpet or pad	35.29
Steel studs and joints	48.65
Aluminum siding	198.80

[a]Jahn and Preston (1976).
[b]Numbers in parentheses indicate an energy surplus from the use of processing residues as fuel.

bone implements for millions of years. Moreover, the development of the first true wood elements, lumber and veneer, awaited the development of metallic cutting tools, which occurred within the last several thousand years. Hundreds of years then passed before the next wood elements were discovered. Finally, in the nineteenth century, an emerging chemical technology permitted the discovery of fiber and cellulose. After 1900, the addition of wood elements quickened with the discovery of 10 new elements. Although all the recent elements owe their existence to human imagination and to the availability of cheap energy and high-speed

steel cutting tools, they owe their usefulness to their relative ease of bonding and the availability of cheap, durable, synthetic-resin adhesives. Without these advantages, most smaller wood elements would serve for no better purpose than garden mulch. We will describe these elements and how they are used in various reconstituted and composite wood products.

A useful way to relate wood elements to various reconstituted and composite wood products is to arrange them in a table of diminishing dimensions as compiled by G. G. Marra (1972, 1981) (Table 1.11). Some smaller wood elements are shown in Figure 1.38. The right-hand column of Table 1.11 lists the present technological application of each element. Although we may not recognize these elements, know how their properties differ, or be familiar with their advantages, most of these elements are used in familiar products. Sawn beams and lumber maintain the maximum anisotropy of

Table 1.11 Common Wood Elements in a Series of Diminishing Dimensions[a]

Element	Length (mm)	Width (mm)	Thickness (mm)	Bonded product
Lumber	1000-6000	100-300	10-300	Beams, arches
Veneer	1000-2500	100-1200	0.5-10	Plywood, laminated veneer lumber
Wafers	25-75	25-75	0.5-1.0	Waferboard
Flakes	10-75	10-75	0.25-0.5	Flakeboard
Strands	10-75	5-75	0.25-0.5	Oriented strand board
Splinters	10-75	0.15-0.6	0.15-0.6	Splinterboard
Particles	1-10	0.15-1	0.15-1	Particleboard
Fiber-bundles	1-10	0.03-0.3	0.03-0.3	Fiberboard
Fibers/fibrils	0.5-10	0.0003-0.03	0.0003-0.3	Paper
Cellulose/ lignin	- - - - molecular dimensions - - - -			Plastics, films, filaments

[a]G. Marra (1972).

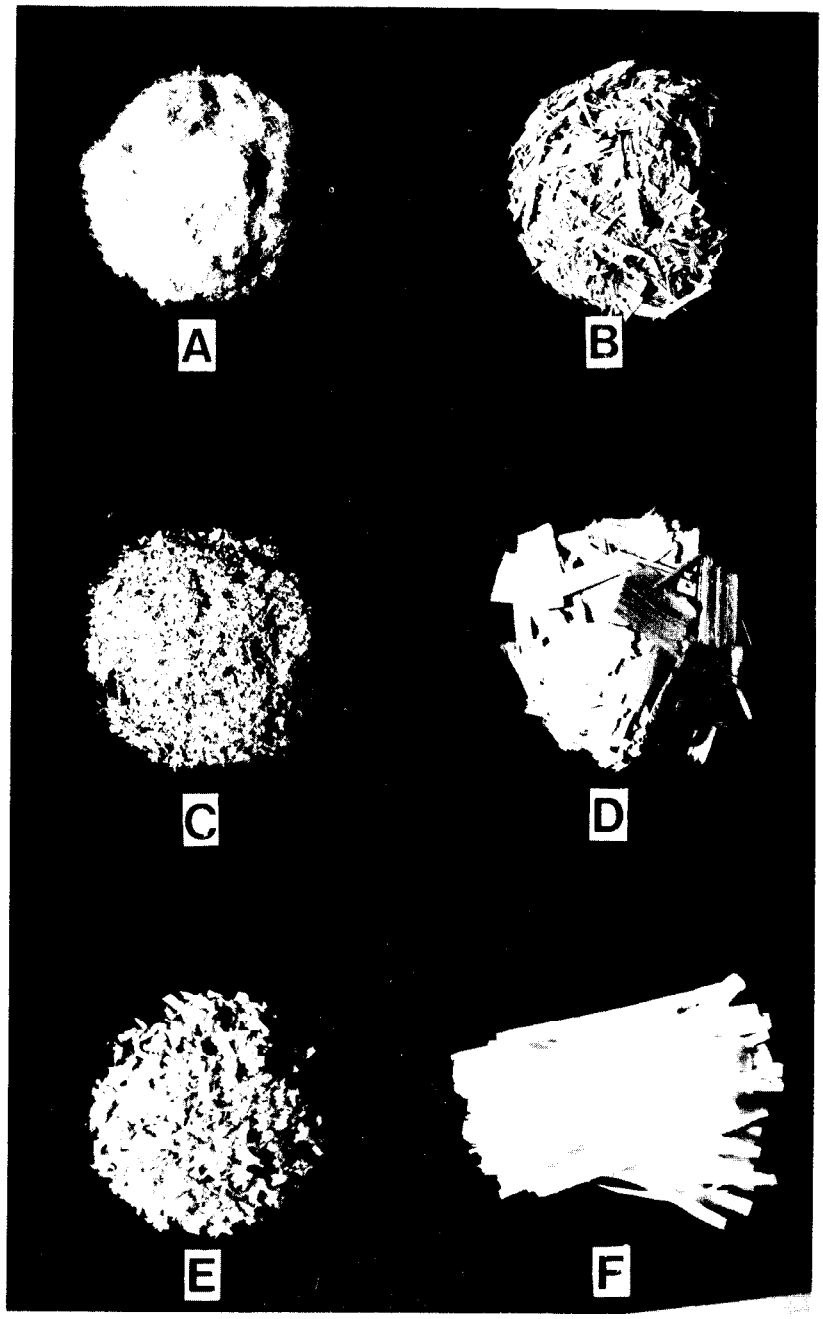


Figure 1.38 Several types of wood elements used in the manufacture of reconstituted panel materials: (A) fiber bundles, (B) strands, (C) sawdust, (D) wafers, (E) planer shavings, and (F) long flakes.

the tree trunk for maximum efficiency as stiff vertical and horizontal support members. Generally, further breakdown reduces the anisotropy; from another viewpoint, breakdown allows the technologist to create materials with properties different than those of whole wood. Many people do not understand the need for different types of panels. The answer lies in materials technology, which applies knowledge of the properties and behavior of specific materials to the design of materials or products that are most efficient for specific functions. Some materials are designed for beauty and others for efficient enclosure of space, structural stiffness, or a flat, smooth finished surface (Table 1.12). For example, the panel materials of plywood, waferboard, flakeboard, and oriented strandboard are most efficient at providing structural rigidity and enclosing space.

D. Combinations of Wood Elements and Other Materials in Products

Primary Processes and Products

The materials in Table 1.12 represent some possibilities for bonding single wood elements. The initial bonding of single elements is a primary bonding process, and the result is usually a fairly low value-added product (often a commodity product).

Even with a single wood element, many variations in properties of a given type of material are possible. The quality, thickness, and number of boards can be varied to control the strength and stiffness of a beam. The size and location of particles can be varied to control the surface smoothness and internal bond strength of particleboard. The thickness and degree of orientation of flakes can be varied to control the directional modulus of elasticity and thickness swelling of flakeboard. Of course, the species of wood and the type and quantity of resin used can also be varied to control properties. The products listed in Table 1.12 are by no means all-inclusive. They are intended to show:

1. The diversity of primary products that are produced by bonding wood.
2. The necessity for these products to meet a variety of performance requirements.
3. The involvement of different bonding processes.

A more detailed discussion of primary bonding processes and products can be found in several publications (A. Marra 1981, G. Marra 1972, Moslemi 1974, Sellers 1985, Forest Products Laboratory 1978, Koch 1972, 1985, Kelly 1977, Suchsland and Woodson 1986).

Lumber has been the traditional starting material for manufacturing many primary products made by bonding pieces edge to edge,

Table 1.12 Single-Element Products and Their Primary Properties

Product	Primary property	Secondary property	Typical end use
Laminated lumber beams	Strength	Shape	Buildings, bridges, ships
Parallel laminated veneer lumber	Strength	Predictability	Engineered beams, purlins and trusses
Softwood plywood	Stiffness	Space enclosure	Building sheathing/subflooring
Hardwood plywood	Beauty	Dimensional stability	Furniture/decorative paneling
Waferboard	Stiffness	Lower cost than softwood plywood	Building sheathing/subflooring
Flakeboard	Stiffness	Lower cost than plywood, some opportunity to orient elements	Building sheathing/subflooring
Oriented strandboard	Stiffness	Increased ability to orient elements	Building sheathing/subflooring
Particleboard	Smooth surface	Lowest cost	Furniture/flooring underlay
High- and medium-density fiberboard	Smooth surface	Stiffness	Furniture/paneling building siding
Low-density fiberboard	Insulation	Sound absorption	Building insulation ceiling panels

face to face, and end to end. These products include laminated lumber for beams, arches, roof decking, truck flooring, bowling pins, butcher blocks, knife holders, and drawing boards; lumber cores for furniture panels, flush doors, and other panels; and finger-jointed stock for decorative trim and window and door frames. Many products are produced by bonding small pieces of lumber into larger pieces simply to utilize harvested timber most efficiently.

Another primary bonding process, which involves rotary-sliced veneer, actually produces new types of lumber, called laminated veneer lumber (LVL) and Parallam*. These products are produced by laminating veneer sheets or strands, with their grain directions parallel, into panels, which are then ripped into lumber widths. The LVL products are of increasing importance as high-quality solid-sawn structural lumber in long lengths becomes scarcer and more expensive. Hardwood LVL has been used for many years as curved furniture parts. More recently, softwood LVL has become very important as truss components, I-beams, bench seats, truck decking, door and window headers, scaffold planking, ladder stock, bridge stringers, and other interior and exterior applications. An unusual application where LVL has demonstrated superior performance over aluminum and fiber-reinforced composite materials is in the construction of large blades for wind generators. The LVL products can be manufactured at a 15-30% greater yield than is obtainable by sawing. Species that are difficult to treat with preservatives are effectively treated in LVL form because of the multitude of longitudinal cracks (lathe checks) created by the veneer cutting process. Mechanical properties of LVL products are more uniform than those in solid-sawn lumber, and strength is comparable to that of the highest structural grades of lumber; lamination reduces the size of and disperses strength-reducing characteristics such as knots and short grain, which are found in most lower grades of construction lumber. This homogenization of defects practically eliminates warping in LVL products.

An older veneer product is manufactured by the cross-grain restructuring of the wood into a sheet-like material that has distinct advantages over solid wood. This material, *plywood*, has equalized strength and split-resistance in all directions (with the exception of perpendicular to the panel) as well as greatly improved dimensional stability when subjected to moisture changes. Decorative panels are produced primarily from hardwoods and structural panels from softwoods, although this distinction is becoming somewhat blurred. Some

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*The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

low- to moderate-density hardwoods are being used in structural panels, often in conjunction with softwood veneers. Specialty plywoods are produced for use in boats, highway signs, railroad cars, and concrete forms,

Wood elements as large as and smaller than wafers (Table 1.11, Figure 1.38) are bonded together to make a number of panel products-waferboard, flakeboard, oriented strandboard, particleboard, and fiberboard. These materials can be produced with a wide variety of properties. In a single panel, it is possible to vary species, thickness or form of the wood element, moisture content, type of resin binder, resin content, thickness of layers, and various degrees of element orientation. The distinction between primary and secondary bonding becomes a little fuzzy here because some composites can be formed all in one operation-for example, a resin-impregnated paper overlay on a reconstituted panel. The largest volumes of panel products are manufactured as commodities for structural sheating, floor underlayment, and casegood construction.

Secondary Processes and Products

Secondary processes combine two or more different types of wood elements or nonwood materials. These elements and materials are combined to add value or to produce special properties. The possibilities are obviously limitless; Table 1.13 shows how special properties are achieved in a few secondary products. For example, lumber is combined with steel or fiberglass and other materials to produce snow and water skis, skateboards, hockey sticks, tennis rackets, and archery bows.

Overlay materials are often bonded to reconstituted panels to provide some desired appearance or to improve surface properties. Common overlay materials include vinyl films, kraft paper, resin-impregnated paper, metal foils, veneers, high-density decorative laminates, textile fabrics, fiberglass, and other thin materials. These materials are often applied to only one surface of a panel, such as a vinyl film on particleboard for a furniture application. In other cases, it is desirable to overlay both faces of a panel. For example, resin-impregnated papers are bonded to plywood to enhance the paintability of highway signs, and impregnated papers are bonded to thick plywood to reduce surface checking and increase the service life of concrete forms. Another common example is the application of high-density decorative laminate on both faces of a particleboard core for kitchen countertops. By this construction, the swelling or shrinking of one surface, which is the result of normal moisture content variation, is balanced by equal swelling or shrinking of the opposite surface. Without this balance, the countertop will most assuredly warp.

Table 1.13 Products Based on Two or More Elements

Product	Elements	Special properties
Overlaid plywood	Veneer, phenolic treated paper	Smooth surface with exterior durability
COM-PLY	Veneer, particles	Knot free, warp free southern pine lumber
Furniture panel	Particles, fibers	Dimensionally stable, printable surface
Siding	Flakes, treated paper	Paintable, simulated wood grain boards
Automotive panels	Wood flour/ fiber bundles	Heat formable
Container panels	Veneer, aluminum sheet	Toughness, stiffness, wear resistance
Building panels	Flakes, expanded foam	Insulation, large size, stiffness, light weight

Bonding processes are used with plywood or flakeboard and various core materials to produce a wide variety of composite panels. *Stressed-skin panels* are manufactured by bonding a thin, stiff sheet, such as plywood, to a lumber frame. These panels are used as load-bearing panels in structures. *Sandwich panels* consist of thin, stiff, high-strength materials bonded to the faces of a low-density, light-weight core such as balsa wood, paper honeycomb, or polymeric foams. Stressed-skin and sandwich panels exhibit strength, stiffness, and light weight that are unobtainable in any other way. *Flush doors* utilize thin plywood faces, called doorskins, in a manner similar to that used to make sandwich and stressed-skin composites. In *solid-core doors,* the plywood is bonded to a lumber frame, and the space between the rails and styles is completely filled with lumber pieces bonded edge to edge and end to end. In *hollow-core doors,* this space is filled with a variety of different materials bonded to the door skins. Some examples of core materials are expanded foams, mineral composition board (for fire doors), particleboard, thin pieces of lumber in a lattice or ladder form, paper honeycomb, and cross sections of cardboard tubes. These filler materials help to stiffen the doorskin and to maintain a flat, smooth surface on the door. Furniture

panels are produced by bonding a reconstituted panel to thin decorative materials to add depth and thickness and better fastening capability during furniture assembly. The edges of this type of furniture panel are often covered (edge banded) with veneers, decorative laminates, or thin lumber.

Tertiary Processes and Products

Tertiary bonding processes are assembly bonding processes that generate a three-dimensional form or enclose space. Typical examples are furniture (cabinets, chairs, and tables), boxes, houses, boats, and airplanes. In tertiary bonding, a large number of joint configurations are used : face, edge, lap, finger, scarf, dowel, spline, mortise and tenon, dovetail, miter, dado, and tongue and groove. The designs of these configurations vary. Adhesives are used in structures in many different ways and under a wide variety of conditions. The joints may be either structural (load bearing), semistructural (stiffening), or nonstructural. They may be used in either exterior (including marine), protected-exterior, high-humidity interior, or low-humidity interior environments. The bonding process may take place under controlled conditions in factories or under adverse conditions characteristic of on-site construction. Typical building applications include the bonding of subfloor sheathing to joists, wall sheathing to framing in shear walls, decorative floor coverings and tile to sheathing, lumber to plywood in box beams, and plywood gussets to lumber in roof trusses. Demonstration houses have been assembled using primarily adhesives and a minimum of mechanical fasteners. An increasing number of units are being manufactured in factories, and the use of adhesives in their assembly is expected to grow. Adhesives are used in the construction of small pleasure and racing boats as well as large all-wood naval minesweepers. Many small homebuilt and experimental wooden aircraft are also assembled with adhesives.

V. FUNDAMENTALS OF WOOD BONDING

A. Mechanisms of Adhesion

The American Society for Testing and Materials (ASTM) defines an *adhesive* as a substance capable of holding materials together by surface attachment, and *adhesion* as the state in which two surfaces are held together by interfacial forces, which may consist of valence forces, interlocking action, or both of these (ASTM 1989d). The mechanisms by which a liquid adhesive makes intimate contact with a solid surface and then undergoes physical and chemical

changes to hold these surfaces together under long-term loading and severe service conditions are complex. In this section we discuss some fundamental principles of wood bonding, and we will concentrate on the practical aspects of the adhesive bond in wood materials.

In 1929, Browne and Brouse proposed that adhesion to wood was both mechanical and chemical. These concepts are still basically valid. *Mechanical adhesion,* or interlocking action as defined by the ASTM, means surfaces are held together by an adhesive that has penetrated a porous structure while liquid and anchored itself through solidification, Bonding to porous surfaces such as wood, paper, and textiles has been thought of as primarily mechanical, although strong evidence supports the presence of secondary, even primary, valence forces or *specific adhesion.*

The forces of attraction (hydrogen bonds, van der Waals forces, dispersion forces, and covalent bonds) that exist between atoms, ions, and molecules are responsible for the specific adhesion between the adhesive and the wood surface. Except in the case of certain coupling agents that chemically link reactive sites of adhesive and adherend, covalent bonding probably plays a minor role in most wood-adhesive bonds. Physical or intermolecular attractive forces play the more important role in adhesion to wood.

De Bruyne (1939) categorized the physical forces between molecules into two types-polar and nonpolar. Thus, liquids can be either polar or nonpolar although the degree of polarity may vary. Water, alcohol, and glycerine are polar; benzene and paraffin are nonpolar. Polar liquids mix as do nonpolar liquids, but polar and nonpolar liquids do not mix. The basic rule of adhesion is that strong joints cannot be made with a polar adhesive on a nonpolar surface nor with a nonpolar adhesive on a polar surface. This rule has been invalidated in a way by the development of coupling agents.

Wood surfaces are highly polar, and adhesives that develop bonds of the highest integrity to wood are also highly polar. Adhesives made from nonpolar and lower polarity materials, such as thermoplastic synthetic rubbers, acrylics, polyvinyls, and polyethylenes, can be formulated to develop strong bonds to wood. However, these bonds lack the water resistance that is obtained when highly polar adhesives, such as the phenolics, resorcinolics, melamines, isocyanates, and ureas, are used. Special chemicals called *coupling agents* with both polar and nonpolar functional groups can be applied to polar wood and bonded by nonpolar adhesives to improve the wet strength of the adhesive. For example, a polar surface like wood can be treated with a coupling agent and then bonded with a nonpolar adhesive such as polypropylene (Kolosick and Koutsky in preparation, Myers, Kolosick, Chahyadi, Coberly,

Koutsky, and Ermer in preparation). However, the actual bonds between the wood and the coupling agent and between the coupling agent and the adhesive still fit the polar-polar or nonpolar-nonpolar rule.

Three types of intermolecular attractive forces are important in adhesive-bond formation : dipole-dipole forces, hydrogen bonding, and London forces. Dipole-dipole forces occur between polar molecules. Polarized covalent bonds in molecules give rise to positive and negative poles, which attract one another such that molecules line up in positive-negative-positive-negative sequences. A special type of dipole-dipole force is the hydrogen bond, which exerts strong intermolecular attractions between certain positively charged, hydrogen-containing compounds and the unshared electrons on electronegative atoms of other molecules. Such forces of attraction are important in interfacial attraction of adhesives such as phenolic, amino, and epoxy resins, which carry amide, carboxyl, and hydroxyl groups that strongly attach to the polar hydroxyl groups on cellulosic and hemicellulosic structures of wood. London forces attract nonpolar molecules to each other. These molecules do not have permanent dipoles as do the polar molecules but instantaneous dipoles that induce matching dipoles in neighboring molecules. These instantaneous, ever-changing, and synchronized dipoles are not very strong, and they are the only attractive forces that exist between nonpolar molecules such as polyethylene, natural rubber, and most synthetic rubbers. The intermolecular attractive forces have been variously named, but they are generally called van der Waals forces, after the scientist who postulated their existence.

B. Setting of Adhesives

Once an adhesive has wet the adherend surface, the process of adhesion is completed by the transition of the adhesive from a liquid to a solid. The transition can be a physical change, as in cooling of thermoplastic adhesives, or a chemical change, such as polymerization and cross-linking of thermosetting adhesives. The three mechanisms by which an adhesive changes from the liquid to solid state are (1) solvent loss from the adhesive film, as in a poly(vinyl acetate) emulsion adhesive, (2) cooling of the hot film, as in a hot-melt adhesive, and (3) chemical reaction of the film, as in an epoxy adhesive. A fourth possibility is a combination of two of these mechanisms. For example, resorcinolic adhesives develop strength through solvent loss and chemical reaction.

In an adhesive that polymerizes and cross-links through a condensation reaction to develop a three-dimensional network, the water and alcohol solvent system is an essential reaction and dispersing

medium. The solvent must diffuse and evaporate from the adhesive film simultaneously with the chemical reaction. If solvent is lost before the chemical reaction is completed, then the film-forming medium is lost and the cross-linked network cannot be completed. On the other hand, if solvent loss is delayed, the solvent can physically block completion of the cross-link network. By whatever process, the adhesive is considered to have set when the viscosity of the adhesive has increased to the point where the adhesive film effectively resists the forces tending to separate the surfaces.

C. Bonding Process

Whether adhesive bonds are used for plywood, furniture, laminated beams, or a home fix-it project, certain fundamentals of the adhesive-bonding process must be understood to effect durable joints. A large number of complex factors enter into the manufacture of a strong joint. If any of these is not taken into account, the joint can ultimately weaken and fail.

The first step in bonding is to select an adhesive that is appropriate for the bonding conditions in the plant and the intended service conditions of the bonded joint or product. When the adhesive is delivered, the user must ensure that the adhesive is supplied in the form and condition claimed by the manufacturer, and that it is stored properly until used. Once this has been assured, the basic bonding process consists of the conditioning and surfacing of adherends, preparation and application of the adhesive, an assembly period, and a pressure period with controlled temperature. Some processes also require a conditioning or postcure period after the pressure period to complete the cure of the adhesive.

Adhesive Selection

The first step in the bonding process is selection of the proper adhesive for the expected service conditions. The factors to be considered in selecting an adhesive are thoroughly discussed in Section VI.C. It is also important to pay close attention to the adhesive manufacturers' guidelines for appropriate service applications of the adhesive.

Moisture Content Control

All phases of the bonding process are important, but proper drying and control of wood moisture content have extraordinary significance. Improper drying and lack of moisture content control after drying undoubtedly lead to more defective adhesive joints than any other factor. The bonding process seems simple enough, but it is most difficult to implement because wood varies greatly in

permeability and is highly hygroscopic. Proper moisture conditioning and control require continuous monitoring.

Drying to Equilibrium Moisture Content. Drying is the controlled process of lowering the wood moisture content from the levels found in the living tree, usually called the green condition, to some level near the equilibrium moisture content (EMC) expected in service. These EMC conditions vary over the United States (Figure 1.39). The average EMC for building interiors in most of the United States is 8%. Along southeastern coastal regions, the average is 11%, and in the arid southwest, it drops to 6%. The EMC range is 4-13%. However, during winter, EMC can drop to ≤4-5% in heated buildings in the northern tier states. This creates damaging shrinkage stresses in materials manufactured at higher moisture contents. For example, furniture made in the 11% EMC southeastern region and shipped to Minnesota for servce in heated buildings that have an EMC of about 4% will develop large shrinkage stresses and possibly

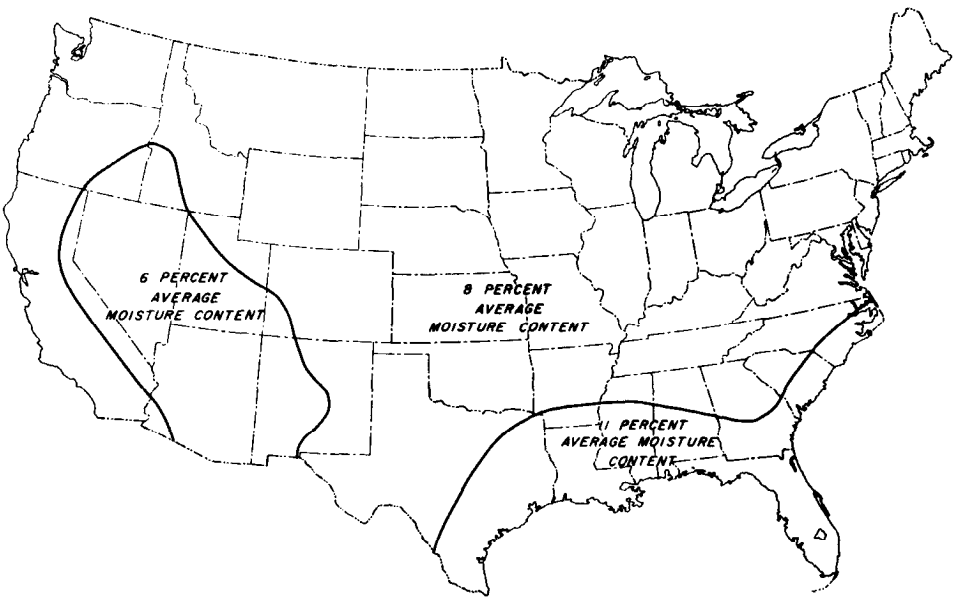

Figure 1.39 Average wood moisture content for interior use in various areas of the United States.

splits, delaminations, or appearance defects. Exterior moisture contents are higher, averaging near 12% and ranging from 7 to 14% throughout most of the United States (Forest Products Laboratory 1987). Manufacturers must be aware of these regional and seasonal variations and adjust their drying operations accordingly.

An exception to the rule of drying wood to the expected EMC in service is when the wood must be dried to a specific level required by the adhesive and bonding process. For example, conventional hot-press phenol-formaldehyde bonding requires the moisture content of the wood veneer to be as low as 4% before bonding to prevent the joint from blowing apart under steam pressure upon removal of the material from the hot press. New phenol-formaldehyde adhesives are less sensitive to wood moisture content. Another exception to the drying rule is that of isocyanate adhesives, which require a minimum amount of moisture in the wood at the surface to complete their chemical curing reaction.

Control of Moisture Content Variation. Drying wood to the average EMC for the bonding and service environment is only part of the story. The variation in moisture content within and between pieces of wood is also very important. Table 1.14 provides specific guidelines for the average EMC and for the allowable variation among individual pieces of wood for a given area (Peck 1950). Although the table allows ±2-3% moisture content above the average EMC for the products shown, the requirement for dense hardwoods is more stringent-the EMC should not vary more than ±1% about the recommended average EMC.

Drying may be done in ambient air, but today most wood for bonding is force dried in kilns or heated dryers. The opportunity for control is greater in kilns and dryers, but the hazards of damaging the surface are also greater. Drying wood in thick sections, such as lumber, may require secondary processes once the wood reaches the desired moisture content for service. These secondary processes, which are called *equalization* and *conditioning,* are almost mandatory if the wood is to be resawn before use. Conditioning is designed to reduce moisture content variability among pieces of lumber in a kiln and to alleviate drying stresses. Drying stresses arise from the moisture gradient, which is an unwanted but unavoidable aspect of forced hot-air drying. Failure to relieve drying stresses may cause serious warp, especially when the lumber is resawn before bonding. Equalization reduces the variability of moisture content within and among pieces. This facet of drying is extremely important in preparing wood, especially dense hardwoods for furniture manufacture. Equalization is usually accomplished by a simple extension of the drying schedule at the desired average EMC when the driest pieces reach a moisture content

Table 1.14 Recommended Moisture Content Values for Various Wood Applications at Time of Installation

	Moisture content (%)					
	Most U.S. areas		Dry south-western areas		Damp, warm coastal areas	
	Average	Individual pieces	Average	Individual pieces	Average	Individual pieces
Interior woodwork, flooring, furniture, laminated timbers, cold-press plywood	8	6-10	6	4-9	11	8-13
Exterior framing, sheathing, laminated timbers, siding, trim	12	9-14	9	7-12	12	9-14

2% below the desired EMC. Equalization and conditioning are sometimes accomplished simultaneously. The technique of drying, conditioning, and equalization are described in several books and manuals (Lutz 1978, Reitz and Page 1971, Rasmussen 1961, McMillen and Wengert 1978). A good discussion of conditioning and moisture content control may be found in the Wood Handbook (Forest Products Laboratory 1987).

As discussed in Section II, wood swells and shrinks as it gains and loses moisture in response to changes in the environment. Changes in the dimensions of individual pieces or of the bonded assembly can produce stresses great enough to rupture the bond or the wood itself. These problems can be minimized by following the prescribed guidelines and by applying good design principles.

Appearance defects in the finished surfaces of furniture are also traceable to moisture content variation during and immediately after the bonding operation. Among the more common problems in furniture manufacture are sunken joints, sunken boards, and splits. Sunken joints are caused not by improper drying or conditioning but by planing the bonded assembly on the side where the edges of the bondline are exposed before the water that has been absorbed

by the wood from the wet adhesive has dissipated. The absorbed water swells the wood adjacent to the bondline. If this surface is planed flat while the wood is still swollen, the wood will shrink when the water dissipates and leave a narrow trough at the bondline. These troughs are especially visible under glossy finishes.

A related defect, sunken boards, is caused by board-to-board variation in moisture content at the time of bonding. In this case, boards that are above (or below) the EMC will shrink (or swell) to a different dimension than adjacent boards if the bonded assembly is planed before all the pieces in the assembly reach EMC. This situation also leads to severe delamination or split ends.

Delamination or split ends of edge-bonded joints in furniture and cabinet panels, especially oak panels, is a common problem. In most cases, joints separate at the ends of the panel, but occasionally splits will run the full length of the panel. Microscopic examination indicates the joints are usually "starved" of adhesive or overly thick. Many factors may contribute to such joints. For the most part, defective joints result from pressure variation during setting, which has its origin in variation in moisture condition of the wood before, during, and after bonding.

The following provides an example of the bad results that are frequently obtained in bonding wood without close attention to the moisture content of the wood.

Wood that comes into a furniture plant at a moisture content above or below the EMC condition in the plant will shrink or swell at the ends. This variation in width of the pieces will cause pressure variation along the bondline. Boards cut to width before bonding at a moisture content higher or lower than the plant EMC will immediately begin to lose or gain moisture. Moisture diffuses from the ends of boards 10-15 times faster than it does from the side grain. The more rapid change in moisture content at the ends causes the width of the ends to change faster than the width at the center of the board. A difference of only a few thousandths of an inch in swelling or shrinking at the board ends can cause a significant difference in pressure distribution along the bondline. A moisture content change as little as 1 or 2% in a dense wood like oak or maple can cause enough dimensional change to cause substantial pressure variation (Table 1.15). The denser the wood, the smaller the difference needed to cause a problem. If the boards pick up moisture in the plant after they are sawn to width, the ends will swell. The result is that during bonding, the pressure will be much higher at the board ends than in the center of the bondline. If the boards lose moisture, the pressure at the ends will be lower than average, and the bondlines will be thick and weak. Clamp operators may try to compensate for shrinkage at the board ends by placing the clamps at the very ends of the panels instead

Table 1.15 Typical Size Changes in a 3-in.-Wide Piece of Wood

Moisture content change (percent)	Size change (in.)		
	Red oak	Hard maple	White pine
1	0.005 to 0.011	0.003 to 0.008	0.002 to 0.006
2	0.009 to 0.022	0.006 to 0.015	0.004 to 0.012
3	0.014 to 0.033	0.009 to 0.022	0.006 to 0.019
4	0.019 to 0.044	0.012 to 0.030	0.008 to 0.025

of spacing them and by increasing the clamping force. This applies a high force at the ends and may close the gap. However, when the clamping pressure is released, the adhesive at the end of the joint (which is still green) is immediately subjected to a high tensile stress as the surfaces try to spring open. This may lead to a type of starved joint with a very fine, thin-walled, and foamy appearance.

Loss of moisture from the faces and edges of boards is usually slower than that from the ends. However, enough moisture may be lost, especially from boards on the top of a stack, to cause the boards to crook or twist. As a result, the edges to be bonded no longer mate properly. Contact, hence bonding pressure, is no longer uniform along the bondline, and a few thousandths of an inch may be enough to cause problems. Clamping pressure helps flatten such irregularities; however, the wider the boards to be bonded, the less likely that a uniform pressure can be achieved and the more likely that part of the joint will be starved or thick.

Storage and Monitoring of Moisture Content. Wood that has been properly dried to 6-8% moisture content often gains moisture because the storage conditions are uncontrolled and at a higher EMC. This situation often occurs in the eastern half of the United States and along the Gulf Coast. Unfortunately, wood that has been dried to the proper moisture content will not remain at the final drying moisture content unless stored where the EMC is controlled at the end of the drying schedule. Failure to maintain the moisture content at a constant level after drying and before manufacture will result in various types of warp (Figure 1.40). Should the wood

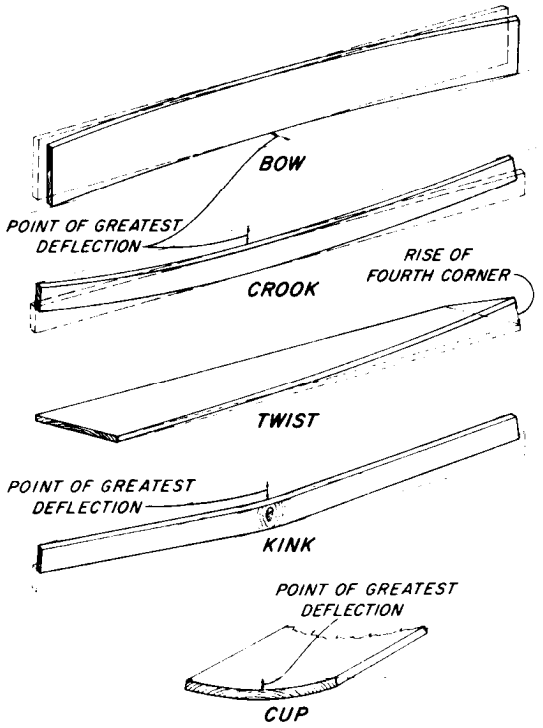

Figure 1.40 Various types of warp. Cup, twist, and crook are the most troublesome types of warp in manufacturing bonded wood products.

warp after preparation for bonding or after bonding, serious defects will occur.

The humidity control that is required to maintain wood moisture content at the desired level and within the prescribed limits of variation is shown in Figure 1.41. A simple and economical way to maintain the moisture content at the proper level is to store the wood in a closed, heated shed. The temperature in the shed need only be elevated enough above the outside temperature to maintain an EMC equal to the moisture content of the lumber (Table 1.16). Information on the variation of wood moisture content during storage and about various methods for maintaining moisture content at the desired level is available (Reitz 1978).

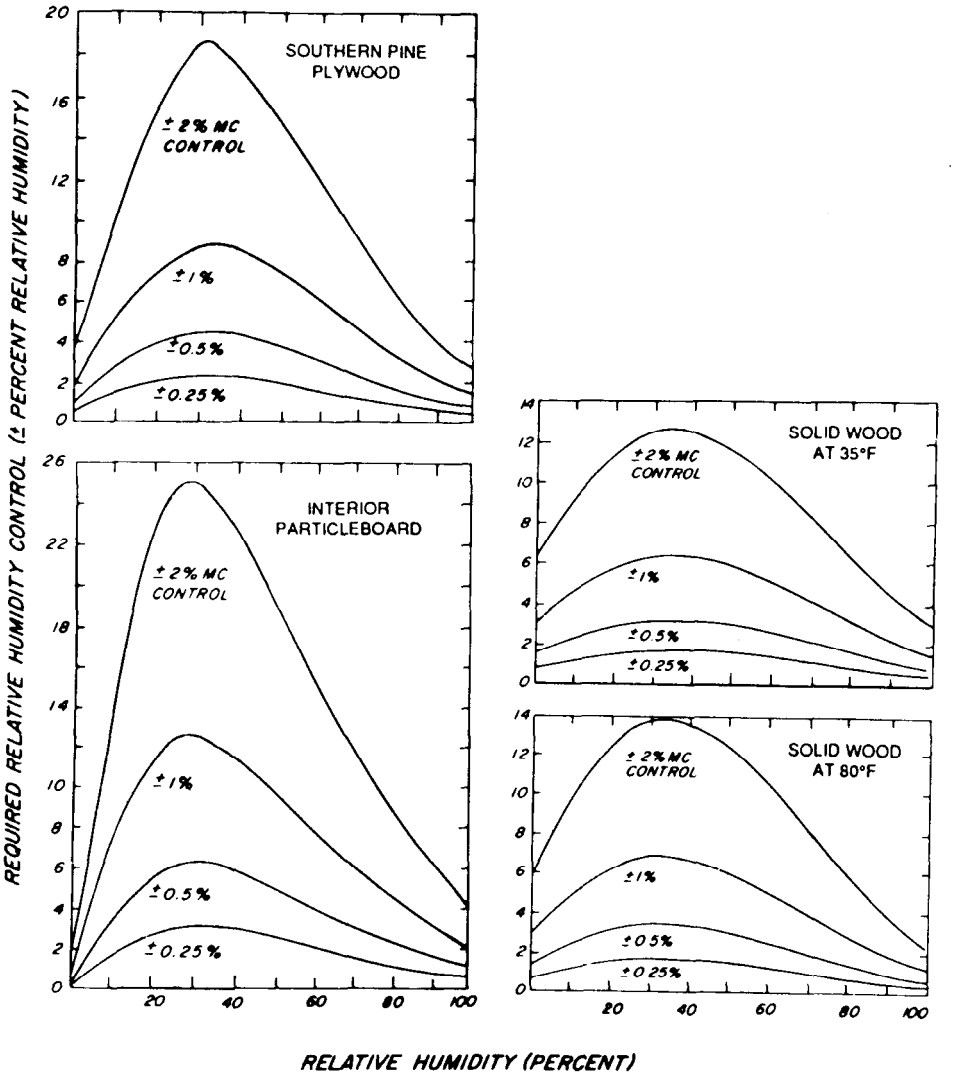

Figure 1.41 Relative humidity control required to maintain equilibrium moisture content of solid wood and some manufactured products within required limits at normal temperatures.

The moisture content of wood to be bonded should be determined when the wood comes into the plant and before the wood is stored. The wood should also be checked for drying stresses. Spot checks

Table 1.16 Temperature Elevation of a Storage Area to Maintain Equilibrium Moisture Content (EMC)

Outside relative humidity (%)	Desired EMC (%)						
	6	7	8	9	10	11	12
90	33[a]	29	23	18	15	11	9
80	30	25	19	14	11	8	6
70	25	20	15	10	7	4	3
60	20	15	9	6	3	–	–
50	15	10	5	1	–	–	–

[a]Degrees of elevation (°F).

should be made at several locations within the board, in several locations within a bundle of lumber, and in several bundles of lumber. The moisture content should also be monitored on the assembly line, probably before the rip-saw operation. This should preferably be a continuous moisture monitoring system with provision for removing those boards with moisture content outside the prescribed bounds.

After the wood has been prepared for bonding, it must be protected from moisture content change. In furniture plants, forced-air heaters or even sunshine through a window can cause rapid changes in moisture content of boards or bonded assemblies on the top and sides of stacks.

Surface Preparation

The ideal wood bonding surface is a clean, recently knife-cut surface free of torn fibers, machining marks, and burnishes. This kind of surface can be produced by a sharp planer, jointer, or machine with knife cutterheads. Modern carbide-tip saws kept at high cutting efficiency can provide good bonding surfaces, although these surfaces are not as smooth and free of torn fibers as surfaces cut with knife cutters. Abrasively planed and sanded surfaces, once thought to be good bonding surfaces, are now generally recognized as poorer than good-quality knife-cut surfaces because the irregular sanded surfaces have more crushed fibers

and greater opportunities for air entrapment. All the factors are discussed in Section III.

Adhesive Preparation

The adhesive should be stored in a cool, dry environment; neither maximum nor minimum temperatures prescribed by the manufacturer should be reached during storage. Before the adhesive is prepared for use, it should be checked to ensure that the recommended shelf-life has not been exceeded. Liquid thermosetting adhesives such as phenolics, resorcinols, and ureas will increase in molecular weight with time and temperature, which leads to higher viscosity and lowered reactivity. The poly(vinyl acetate) adhesives, which are emulsions, may settle out from suspension with excessive aging and become unusable. Isocyanate adhesives begin to react on the slightest exposure to moist air. Most wood adhesives contain water or organic solvents, so loss of solvent by evaporation will lead to premature viscosity buildup,

Most commercial adhesives require mixing one or more components before use. These components may include water, catalyst, fillers, and extenders. Adhesive suppliers and users generally prefer ready-to-use adhesives because the sources of potential errors that occur in proportioning and mixing operations can be eliminated. For example, an incorrect proportioning of adhesive resin with catalyst can lead to major production losses because of the large number of products that may be fabricated from a single batch of improperly measured or mixed adhesive. If adhesive components are weighed accurately and mixed according to the supplier's instructions, such problems will not occur.

After liquid and powdered adhesive components are mixed, the mixture should stand undisturbed for 10-15 min before use. This time allows components to wet out thoroughly, to swell (in some cases), and to build viscosity; entrained air bubbles also dissipate.

Mixed adhesives have definite working lives-that is, the length of time an adhesive remains spreadable and usable after mixing. The working lives of reactive adhesives, such as epoxy, urethane, resorcinolic, phenolic, melamine, and urea-formaldehyde resin adhesives, vary from seconds to several hours, depending on ambient temperature and reactivity with catalysts. Some of these adhesives build up significant heat as the exothermic reaction begins, so they must be cooled and stirred to prevent setting prior to use. Non-catalyzed adhesives generally have many hours of working life; their working life is primarily shortened by solvent evaporation. The adhesive supplier estimates the allowable working life for an adhesive, as affected by ambient temperature and moisture. These instructions should be followed for best performance.

Adhesive Application

Wetting, the critical step in bonding, takes place when the adhesive is applied to the surface. An adhesive must spread completely and uniformly over both bonding surfaces in controlled and adequate amounts to ensure the development of an effective bond under the given conditions of assembly and setting. In most bonding operations, the adhesive is spread on one surface only. This provides satisfactory wetting to the second surface as long as the adhesive film is able to adequately wet and penetrate (transfer) the opposite unspread surface when the joint is assembled. When both bonding surfaces are spread, a process called double-spreading, one-half the adhesive is spread on each surface. This practice is common when long assembly times are required to fabricate large assemblies such as glulam beams. The single-surface spreading operation is more critical than double-spreading because adequate wetting of the opposite surface depends upon how rapidly the viscosity of the adhesive changes on the spread surface. Surfaces are always double-spread with contact-bond adhesives because this bond is formed immediately on contact between two prespread surfaces.

The amount of the adhesive spread depends on several variables, all of which must be factored into the estimated spread rate before the adhesive is applied. These variables include adhesive solids (polymer) content, wood species, surface roughness, moisture content and temperature, open and closed assembly times, ambient temperature, relative humidity, and the relative balance between bond quality and cost of adhesive. Adhesive spread rates on single surfaces vary between 35 and 60 $lb/10^3\ ft^2$; double-spreading rates fall between 60 and 80 $lb/10^3\ ft^2$. Spreads are as high as 80-100 $lb/10^3\ ft^2$ when the wood is especially absorptive, such as southern pine veneer, or when assembly conditions are long and severe, as in the bonding of large glued-laminated timbers. The average thickness of most bonds to wood (not of the gap-filling type) after complete setting falls between 0.003 and 0.006 in.

Adhesives may be effectively spread in many ways. The method is usually dictated by the size of materials and the speed at which they must be spread for a given production process. A stiff-bristle paint brush is a simple and quite effective spreading tool, but it is hardly adequate for applying adhesive to 4- by 8-ft sheets of veneer. Roller, curtain, spray, and extruder coaters are used in production to apply very uniform spreads to large sheet materials. Roller spreaders or extruders are commonly used in lumber laminating. Extruders apply closely spaced, parallel beads of adhesive that flow into a continuous film of uniform thickness when the two bonding surfaces are brought together under pressure. Gap-filling adhesives for construction joints are applied in

an extruded bead from pressurized guns or nozzles, or from simple caulking guns that use disposable cartridges. The bead diameter is easily controlled. When the bead is put under pressure in the joint, it conforms and bridges the varying gaps between adherends.

Assembly and Setting Times

The assembly time is the interval between applying adhesive to the adherends and applying pressure to the assembly. It is one of the most critical steps in the bonding process. Except for the control of wood moisture content before bonding, more problems with weak or failed joints can be traced to this step than to any other. As described previously, an adhesive sets by one process or a combination of three processes-solvent loss, chemical reaction, or cooling. Because most wood adhesives are waterborne systems, any factor that affects the rate of liquid carrier loss (water or organic solvent loss) from the adhesive film during the assembly time will have a direct and proportional effect on the mobility of the adhesive and, thus, on the ability of the adhesive to flow, wet, and penetrate the bonding surfaces. Those adhesives that build viscosity and set by chemical reaction usually set by loss of moisture or solvent as well. Thus, if solvent and moisture losses during the assembly time are either too great or too small, the chemical reaction can be inhibited to the point where complete reaction never occurs. The *allowable assembly time* is usually a window of time during which the adhesive has the capability to wet the surface, flow freely, and yet remain in the bondline, and to penetrate but not overpenetrate the capillary structure of the wood. The allowable assembly and setting times for adhesives differ considerably depending on how they are formulated. For example, a high-solids poly(vinyl acetate) emulsion adhesive requires a shorter assembly and setting time than do emulsions of lower solids content. Other adhesives are formulated to release water from the emulsion system and coalesce faster, thus speeding wet tack and clampng time.

Assembly time is quite critical with hot-melt adhesives because the setting process is usually a matter of cooling the molten material; the heat loss occurs quickly in the presence of cooler air and materials. An assembly time that is too short is generally not a problem with hot-melt adhesives because the best flow, wetting, and penetration occur while the adhesive is hot and most mobile. But if the assembly time is too long, cooling will raise the viscosity and wetting problems will occur.

Wettability Effects. Freeman and Wangaard (1960) found that the strength obtained with woods of low wettability was little affected when the assembly time was extended far beyond the optimum.

However, the strength obtained with high-wettability woods was strongly and adversely affected. Adhesive viscosity and solids content increased more rapidly in highly wettable woods. The opposite is most likely true when the assembly time is much shorter than the optimum. Woods of low wettability inhibit water removal and the increase of viscosity and solids content. Consequently, the adhesive is likely to be excessively fluid when pressure is applied. The result of excessive fluidity under pressure is excessive flow, which results in starved joints and bleed-through in thin decorative veneers. These problems are increased by the reduction of adhesive viscosity during hot pressing.

Studies have shown that poor wettability, and consequently inadequate removal of water from the bondline, inhibits chemical cure of phenol-formaldehyde (Northcott, Colbeck, Hancock, and Shen 1959) and possibly other condensation-type adhesives. Bond quality decreased as the moisture content of the veneers increased from 3 to 12%. A combination of adverse factors, such as overdried veneer, short assembly time, and short press time, exacerbated this effect. Wellons (1980) proposed three possible conditions for poor bonding on Douglas fir veneer. First, veneer with high moisture content, when coupled with short assembly time, draws little moisture from the wet adhesive film. The resin viscosity remains low and the resin tends to overpenetrate during hot pressing. The bondline is starved and appears washed out, or it is filtered and appears grainy. Excessive moisture retention may also interfere with the adhesive cure. Second, veneer with low moisture content, although easily wet, may lose excessive moisture before pressing, especially if the assembly time is prolonged. The bondline will be dried out and may not transfer to the unspread adherend during hot pressing. Third, veneer with low moisture content that is not readily wet by the adhesive may retain excessive moisture. The adhesive will behave much like that in veneer with high moisture content, especially if the assembly time is short to moderate.

Types of Assembly Time. Assembly is the interval between the application of the adhesive to the surface or surfaces to be bonded and the application of bonding pressure. There are two types of assembly time. *Open assembly time* is the time during which the spread surfaces are left open, exposed to the air. *Closed assembly time* is the time during which the spread surfaces are closed together in the position they will be bonded before pressure is applied. A bonding process will often include a combination of open and closed assembly times.

Open assembly time allows for rapid escape of the solvent or liquid carrier from the adhesive and thus rapid buildup of adhesive

viscosity before pressing. Air temperature, relative humidity, and air flow have strong effects on the allowable open assembly time, as do the temperature and moisture content of the adherends. Hot, or very dry and absorbent, adherends shorten the allowable assembly time. Open assembly time is often used to reduce problems caused by overpenetration of the adhesive, such as starved joints or bleed-through. However, if open assembly time is too long, the adhesive becomes too viscous and immobile before the assembly is closed, and the adhesive will not transfer to or wet the second adherend-a condition referred to as dry-out in the plywood industry.

Closed assembly time promotes good wetting and penetration of both surfaces. Air temperature, humidity, and air flow have little effect during closed assembly. If open assembly time is minimized and the adhesive is still low in viscosity when the assembly is closed, then penetration will be maximized. For a given adhesive on given adherends under given assembly conditions, there are definite limits of open and closed assembly times during which the adhesive viscosity is neither too high nor too low to form sound bonds. Adhesive suppliers have developed guidelines for use of their products under varying moisture and temperature conditions. These instructions should be followed for optimum results.

Factors Affecting Assembly Time.

1. Wood effects. Many wood effects were discussed in Section III, E. However, a few subjects should be emphasized with regard to assembly time. The first is density. The higher the density of wood, the more slowly it will absorb water from the adhesive during the assembly and pressure periods, and the more spring-back stress the wood will place on the set but not fully hardened adhesive when the clamping pressure is released. The density and characteristic porosity of a wood species have great and highly variable effects on assembly and setting times of poly(vinyl acetate) adhesives. Generally, the higher-density ring-porous woods such as oak, ash, and hard maple require long assembly and setting times, primarily because water diffuses into high-density latewood bands more slowly than into lower-density earlywood bands. Therefore, viscosity will remain low in the latewood zones and the adhesive will be susceptible to squeezing out of the joint and into the large pores of the low-density earlywood zones. Long assembly times are required to minimize this tendency. Diffuse-porous hardwoods, such as yellow poplar, or a smooth, uniformly textured softwood, such as ponderosa pine, tolerate shorter assembly times than a ring-porous wood of similar density because water diffuses into the wood

more uniformly. Using an adhesive that sets by water loss, McNamara and Waters (1970) found that red oak (a ring-porous hardwood) required about twice as much time (~7.5 min) to develop 50% of its 8-h strength as did hard maple (~4 min) (a diffuse-porous hardwood) of about the same density. The authors attributed the slower removal of water from the adhesive by the oak to the large earlywood-latewood density gradient of the oak. Similar interactions have been demonstrated with chemically curing adhesives (Olson, Bruce, and Soper 1956).

Adhesives applied to dense, impermeable, high-pressure laminates and particleboards also require longer assembly and setting times because water diffuses into the laminates slowly and because the rates of wetting and penetration are slowed by resins, waxes, and highly densified flakes or fibers.

2. Moisture effects. The effects of various assembly conditions and wood characteristics upon assembly time must be understood in terms of the mechanism by which a given adhesive sets. For example, a poly(vinyl acetate) emulsion sets by loss of water from the adhesive film. During open assembly, water is lost primarily by evaporation into ambient air, and this process is largely governed by the laws of evaporation. During closed assembly and setting, water is lost primarily by diffusion into the wood; this process is largely controlled by the moisture content and permeability of the wood. Assuming that the adhesive adequately wets the wood, the cells closest to the adhesive have a limited capacity to absorb moisture from the film. Once the cells near the bondline approach saturation, less moisture can be accepted, so the adhesive increases in viscosity and sets more slowly.

   Expanding on this notion, the assembly time and, in the case of emulsion adhesives, the speed of setting are directly related to the amount of moisture present in the wood at the time of bonding. The higher the moisture content, the slower the rate of diffusion into the wood-hence, the longer the required assembly and setting times. High humidity can increase the moisture level of an unspread bonding surface and slow the rate of water or solvent absorption from the liquid adhesive film. This is noticeable when joints are machined several days before bonding. A heavy spread of adhesive will also lengthen assembly and setting times.

   Unlike the poly(vinyl acetate) emulsion adhesive, which does not penetrate wood deeply, the phenolic resin must penetrate not only into cell cavities but also into cell walls of sound wood structure to develop the highly durable, weatherproof bonds required for exterior plywood. Since phenolic resins are waterborne and highly polar, their mobility and penetration are

directly and critically affected by the amount of water present in both wood and adhesive during assembly and setting. During the assembly time, the adhesive viscosity normally increases if the wood moisture content is low enough to absorb some water and resin solids as the adhesive begins to penetrate. If the moisture content of the wood is too low, water will quickly diffuse into the wood, leaving a dry adhesive film without sufficient mobility to transfer, wet, and penetrate the unspread wood surface. If the moisture content of the wood is too high, the rate at which water and resin solids diffuse into the wood will again be diminished, the viscosity will not increase appreciably, and the adhesive will remain too mobile during hot pressing. Of course, an adhesive that contains too much water or one that is spread too heavily must be compensated for by extending the assembly time to allow excess moisture to dissipate.

Different wood species have different critical levels of wood moisture content for hot pressing of resin adhesives. Moisture tolerances for southern pine plywood, for example, are quite narrow-between 2-1/2 and 4-1/2% moisture content for conventional phenolic resins. If moisture content is above 5%, the moisture in the bondline may get so high that the joint weakens or ruptures. As the temperature increases from the platen surface toward the inner bondline, water in the wood vaporizes and moves toward the bondline, where it condenses in the adhesive to increase mobility of the adhesive. Recently, phenolic-adhesive systems have been developed that are less sensitive to moisture and will tolerate up to 20% wood moisture content.

3. Temperature effects. The temperature of the wood, adhesive, and ambient air are very important for determining assembly and setting times. The setting process may take place at a slower rate at room temperature or it may be accelerated at elevated temperatures. Conventional thermosetting resin adhesives such as urea-formaldehyde and resorcinol-formaldehyde will not set properly at temperatures below about 21°C (70°F). A poly(vinyl acetate) adhesive will set at lower temperatures, although the rate of strength development is much slower. The rates of evaporation and diffusion of water from the adhesive film are so much slower at low temperatures that cold-press clamp times almost double. Forced circulation of heated air helps to remove water from the adhesive film and to improve speed of setting at cool room temperatures. When a poly(vinyl acetate) adhesive is used at temperatures below its "chalk temperature," the dried bondline will be whiter than the usual colorless bondlines. Chalking occurs when the temperature is so low that evaporation and diffusion are slowed to the point

that the emulsion dries without coalescing, leaving a film of discrete particles. Chalking can be avoided by raising the temperature of either air, wood, or adhesive, or a combination of these factors.

The problem of controlling assembly factors of an aqueous phenol-formaldehyde-resin adhesive, which sets by chemical reaction as well *as* by water loss, is already complex, but it is exacerbated because setting is completed at high temperatures. Many factors affect this problem, all of which are governed in part by the laws of evaporation and diffusion. However, several material and assembly conditions that are somewhat specific to phenolic hot-press adhesives in commercial plywood manufacture are worthy of further description.

Not only do the moisture and temperature effects contribute to a highly mobile adhesive that overpenetrates the wood, but the steam generated from excess and entrapped moisture may actually blow the panel apart upon release of platen pressure. Even if a blow does not occur, the bondline will be very weak from "wash-out" where resin has overpenetrated and only the filler remains.

Assembly time of phenol-formaldehyde adhesives may also need adjustment to compensate for wood temperature effects; hot veneer tends to dry the adhesive too quickly, thereby inhibiting adhesive penetration. The result is a weak bond without enough adhesive penetration for the adhesive to become anchored in the wood.

With rising temperature, adhesive mobility is increased temporarily by the increasing kinetic energy. At nearly the same time, the resin begins to polymerize in a condensation reaction, but the reaction may be inhibited by the evaporative cooling effect of excessive moisture.

All of the above effects-wood, moisture, and temperature-must be understood and properly manipulated by the resin formulator to achieve a useful adhesive system. From a production standpoint, these effects mean that at cooler temperatures, moister, denser, and less wettable wood requires longer assembly and setting times at the risk of unsatisfactory performance in bonding and in subsequent service.

Pressing

When viewed microscopically, the surface of wood is highly irregular, even after it is planed with sharp knives. To effectively bridge two wood adherends, an adhesive must make intimate contact with surface

and subsurface cell structure. High pressure helps the adhesive penetrate into the microstructure and displace entrapped air bubbles. Intimate contact of the adhesive and surface would not occur thoroughly without pressure.

Most wood adhesives, even those setting by chemical reaction, are waterborne systems that must continually lose water from the bondline until the setting process is completed. Pressure must be applied continuously to ensure that the space formerly occupied by the solvent is closed; intimate contact must be maintained between adhesive film particles and between adhesive and adherend. If little or no pressure is maintained, voids are created and set in the bondlines by the solvent loss. When such joints are under load, the voids are points where cracks initiate, and these cracks lead to unexpected joint failure.

The amount of pressure required to bring adhesive and adherend into intimate contact generally depends on the flatness and hardness of the material being bonded. Dense, hard species, such as oak, hard maple, southern pine, and Douglas-fir, require 150-200 lb/in.^{2} to establish intimate contact between adhesive and adherend as well as a uniformly thick bondline. Lower-density species, such as basswood, white pine, redwood, and ponderosa pine, require pressures between 100 and 150 lb/in.^{2} Pressures at room temperature conditions generally need to be higher than pressures at hot-press conditions. At elevated temperatures, wood is plasticized and thus more able to deform and achieve a uniformly thick bondline. Crushing of the wood usually becomes the upper limiting factor on pressure during hot pressing. For softwood species, this upper limit is approximately 175-200 lb/in.^{2}

Adhesive bonds that must withstand high levels of stress, whether in wood furniture or in a structural laminated beam, generally provide highest stress resistance in thin bondlines: that is, 0.003-0.006 in. thick. As bondline thickness increases, joint strength decreases. Thick bondlines of brittle adhesives fracture more easily than thinner ones under stresses from loading and dimensional change. These bondlines also shrink more than thinner bondlines on setting and are more likely to include voids from lost solvent than are thinner bondlines. Furthermore, because thick bondlines are formed without sufficient pressure to force intimate contact between adhesive and adherend, the bondlines may contain voids at the interface. For certain construction applications, adhesives have been designed with gap-filling capability to bridge the uneven and rough surfaces between lumber and plywood. These adhesives are elastomer-based mastic-type adhesives that can bridge gaps up to 1/8 in. wide and provide shear strengths between 200 and 600 lb/in.^{2} While elastomeric adhesives do not provide structural-level resistance to creep, shear, and moisture,

they do provide adequate strength between poorly fitting construction materials that must be bridged to bond effectively.

Thick bonds are the result of inadequate pressure, assuming that the adhesive does not preset before pressure is applied, but also the result of poorly mating or rough surfaces. When thick bonds are opened, they may have a characteristic honeycombed appearante. If both bonding surfaces made initial contact but were subsequently separated slightly, the thin walls of the honeycomb might appear on both surfaces. However, if the adhesive-spread surface barely touched or did not touch the opposite unspread surface, very little adhesive will have been transferred from the unspread surface and the spread surface will appear smooth and shiny.

As previously discussed, nonuniform moisture content can cause edges of lumber to warp or otherwise depart from a straight line. When these edges are joined, pressure will not be uniform along the bondline; the bondline will have areas of extremely high pressure where squeeze-out will likely occur and areas of very low pressure where the bondline will be very thick. Both starved and thick bonds are weak and likely to lead to failure.

Inadequate pressure and thick bonds may also be caused by other means. One simple cause of low pressure is the application of an insufficient amount of force. For example, edge-bonded oak panels may require 200 lb/in.^{2} of pressure, yet force equivalent to only 50-100 lb/in.^{2} might actually be applied. On the other hand, adequate force may be applied, but the pressure can be nonuniform because clamps are not properly spaced or caul plates are too thin; in edge-bonding, the edge pieces in the panel may be too narrow to uniformly transfer force between the clamps. Poor machining of the edge of a piece of lumber may cause pressure to be distributed unevenly at some points along the bondline. Nonuniform pressure also results when a saw runs off a straight line, a cut edge is not at a 90° angle to the flat surface, or the end of a piece is cut narrower than the middle.

The final source of pressure variation involves calibration of the force applied by the clamping device(s). Many plants use screw clamps, which are tightened with a pneumatic wrench. The force is adjusted by using a compressometer to measure the force and adjusting the air pressure to the wrench. The air pressure should be calibrated and adjusted for each joint length and thickness. If either dimension or clamp spacing is changed during production, the air pressure should also be reset for that panel. Slight variations in joint dimensions or clamp spacing can be accommodated without changing the air pressure. If the change in bondline area causes more than about a 50-lb/in.^{2} change in bondline pressure, the clamping force should definitely be reset. Too often, the change is not made for the sake of saving time.

VI. PERFORMANCE OF BONDED JOINTS AND MATERIALS

A. Performance Criteria

In the previous section, we discussed interactions between the wood and the adhesive during the bonding process. In this section, we will assume that joints or products have been prepared with due consideration of those factors, and that the resultant joints or products are of good quality. The performance of these joints or products in service then depends on how the wood and the environment affect the strength, stability, and appearance of the bonded joint or product.

Strength and several related criteria are the primary measures of performance. The strength of a bonded joint or product is controlled by the type of adhesive, the bonding process, and the wood properties, but it is also strongly influenced by the design of the joint or product. High performance is manifest as strength exceeding that of solid wood, as a high percentage of wood failure on the surface of joints loaded to failure, or as a low percentage of delamination of bondlines in service.

Stability has two aspects: (1) the physical and chemical stability of the adhesive joint, which affects strength at a given time in a given environment, and (2) the dimensional stability or resistance of the bonded product or structure to warp and distortion in service. In this section, we discuss interactions between the adhesive, the wood, and the environment that affect performance and how performance is evaluated in light of these interactions.

Appearance also has two aspects. Obviously, the color of the adhesive itself has a direct bearing upon the acceptability of many decorative wood products. Less obviously, the adhesive or components of the adhesive may unacceptably alter the appearance of the wood, the wood finish, or a covering material.

B. Strength and Related Criteria

Strength

Adhesives and practical adhesive bonds are not as strong as wood in tension along the grain. However, many adhesives are stronger than wood in shear parallel to the grain (at least up to wood specific gravity of about 0.7-0.8) or tension perpendicular to the grain.*

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*In most cases, the measured strength of an adhesive bond is not the true strength of the adhesive but a strength peculiar to a combination of many factors, which include the strength and stiffness of the wood and the adhesive, bonding conditions, joint configuration, and environment.

The relationship between strength, wood failure, and density is discussed later.

If the adhesive strength exceeds the strength of the solid wood, then traditionally the adhesive has been ignored in the design of bonded wood joints or products. Adhesives less strong than wood have generally been relegated to semistructural *or* nonstructural roles because techniques for measuring their mechanical performance and design of joints based on adhesive capability have been lacking until recent years.

The strength and other mechanical properties of adhesively bonded joints vary with the environment and with age. In service, the strength of some adhesives, even though initially greater than that of wood, decreases faster than wood strength; in this case, the adhesive strength determines performance.

The elastic or viscoelastic properties of adhesives, such as shear modulus or creep modulus, are occasionally used to evaluate the performance of certain types of adhesives and for evaluating bonded products such as particle- and waferboards.

Of all the factors affecting the strength of bonded systems, the density of the wood, grain orientation, and joint design strongly affect the performance of those joints made with strong adhesives.

Wood Failure

Wood failure is the rupture of wood fibers in strength tests on bonded specimens. It is usually expressed as a percentage of wood failure averaged over the total bond area (ASTM 1989d). When an adhesively bonded joint is broken, the percentage of wood failure is used as an indicator of the bond quality, sometimes in lieu of a strength test. The percentage of wood failure can be estimated quickly and easily, but it is subjective and requires considerable practice to achieve accuracy and consistency. The amount and the depth of wood failure vary for several reasons, some related to the quality of the wood and some to the bonding procedure. If wood failure is deep, joint strength is high, and the adhesive is of a durable, permanent type, then the joint will probably be permanent. If wood failure is shallow, then regardless of the other factors, the permanence of the joint should be suspect.

Depth of Wood Failure. Shallow wood failure is fracture that remains relatively flat, smooth, and near the plane of the bondline. Such fracture may not follow the wood grain. A shallow wood failure sometimes appears fuzzy because individual cells or portions of cell wall are attached to the surface at one end and raise up on the other. At other times, a surface with shallow wood failure may be fairly smooth and dull. In contrast, the more desirable deep wood

failure usually follows the grain angle or the growth rings, is often rough, and deviates from the bondline. A surface with deep wood failure will often have a sheen because of the light-reflecting properties of cleanly cleaved cells.

Surface and Subsurface Damage. Shallow wood failure may be a sign of damaged surface and subsurface cells. Damage may be mechanical, resulting from peeling veneer, roller pressure in veneer dryers, abrasive planing, rip sawing, or excessive bonding pressure. The damage might also be chemical, resulting from acidic catalysts used with some adhesives or from fire-retardant treatments. Thermal degradation of surface cells can occur during high temperature drying (Christiansen in press, b).

Compression of the surface and subsurface cells apparently cracks the cell walls (Figure 1.20b) and creates a matted layer of flattened cells. The adhesive cannot penetrate the cell lumens to establish mechanical adhesion, nor can it penetrate the weakened matted layer to sound wood. Figure 1.42 shows the penetration of surface cells by the adhesive of an undamaged knife-planed surface and the lack of penetration of crushed and matted cells of a damaged abrasive-planed surface. Dry bond strength of mechanically damaged adherends is similar to the strength of joints formed with sound adherends. However, exposure of joints with damaged adherends to soaking and drying usually causes a dramatic loss in strength. Swelling and shrinking stress apparently aggravates the damage to the cells and weakens bonds formed without adequate adhesive penetration. As a result, shear strengths of redried specimens may fall to less than 30% of the strength of undamaged joints (River, Murmanis, and Stewart 1980; Caster, Kutscha, and Leick 1985). The wood failure, although high, is characteristically shallow. The depth of wood failure decreases as the grit size used in abrasive planing increases. Species (coarse-textured compared to even-textured), type of tissue (earlywood or latewood), and moisture content may have some bearing on the depth and extent of damage (Caster, Kutscha, and Leick 1985; Murmanis, River, and Stewart 1986).

Penetration of Adhesive. Poor penetration also has been linked with shallow wood failure of sound surfaces. First, if not enough adhesive is applied, voids will remain at the interface and the bond will be discontinuous. A growing crack will naturally follow the stress concentrations arising from these voids. Second, low penetration limits the ability of the adhesive to reinforce the area of the bondline and to diffuse the stress concentration that naturally occurs at the interface of two materials with different mechanical properties. The crack easily follows the stress concentration along

the discontinuous interface. At the microscopic level, shallow wood failure should take the form of longitudinal transwall failure if (1) the cells are mechanically damaged or the cellulose microfibrils are chemically or thermally degraded and (2) the adhesive does not penetrate through the damaged cells to sound wood. If the surface and subsurface are sound and shallow wood failure is caused by low adhesive application and poor penetration, then spotty intrawall fracture should be expected.

In the 1920s, an argument began over whether wood-adhesive bonds depend on mechanical or "specific" adhesion. This argument still has not been completely resolved. Even in metal bonding, mechanical interlocking may contribute significantly to strength and durability (Venables, McNamara, Chen, Sun, and Hopping 1979). Most likely, both mechanical and specific adhesion make significant contributions to joint strength. Studies have been conducted of joints between wood adherends cut with their grain angles at various orientations to the plane of the bondline and the direction of shear force (Furuno et al. 1983). Specimens were cut with the grain at an angle to the surface so the lumens were open to penetration by the adhesive. Some specimens were prepared so that the shearing action tended to force the plugs of adhesive deeper into the cell lumens. Others were prepared so that the shearing action tended to pull the adhesive plugs out of the lumens, and still others were made with the grain parallel to the bondline. Joints made to pull the plugs out of the lumens were stronger than joints with parallel grain; joint strength was 2488 and 1984 lb/in.^{2}, respectively, and wood failure 68 and 87%) respectively. These joints were also stronger than joints in which the shearing force tended to push the plugs into the lumens (strength 1706 lb/in.^{2} and wood failure 86%). The obvious conclusion is that the plugs-out configuration not only increases the mechanical interlocking and bonding area, but also reduces the stress concentration at the interface. The plugs-in configuration also increases adhesive penetration and the bond area compared to the parallel configuration, but it enhances crack growth in the wood (Furuno, Saiki, Goto, and Harada 1983).*

Where the adhesive actually contacts the lumen, the crack may pass through the S-2 to S-3 region if good adhesion exists (Furuno and Saiki 1988, Saiki 1984). If adhesion is poor or nonexistent, the crack will pass through the interface.

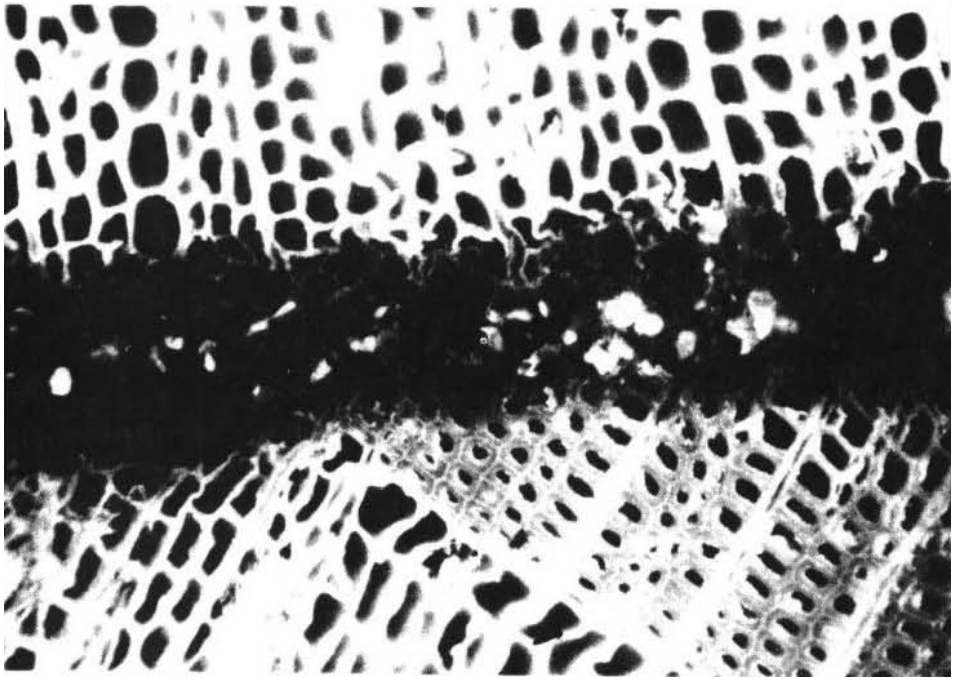
Adhesive penetration of the cell wall affects the nature of failure at the ultrastructural level. Penetration of the cell wall by phenol-formaldehyde and freshly mixed epoxy resins was revealed by fluorescence of the penetrated portions of the cell wall viewed under the microscope (Saiki 1984). When the adhesive was peeled from the wood, the cells fractured in the S-2 layer near the S-3 layer. Epoxy applied 6 h after mixing did not penetrate the cell

*Page 137 revised June 2004, and see insert on errata page 137a.

Errata
June 2004

Paragraph 1 (ending with reference to Furuno, Saiki, Goto, and Harada 1983) should end with the following sentences:

The opposite relationship was observed by Swietliczny (1980). Specimens with the grain angle oriented so that the adhesive plugs tended to be pushed in during testing produced higher shear strength than parallel grain orientation and also the orientation that caused the plugs to be pulled out. The difference between the test results can be explained by the different methods of loading, that is, tensile lap shear with no rotation restraint of the specimen used by Furuno et al. and the compressive block shear specimen with rotational restraint used by Swietliczny.

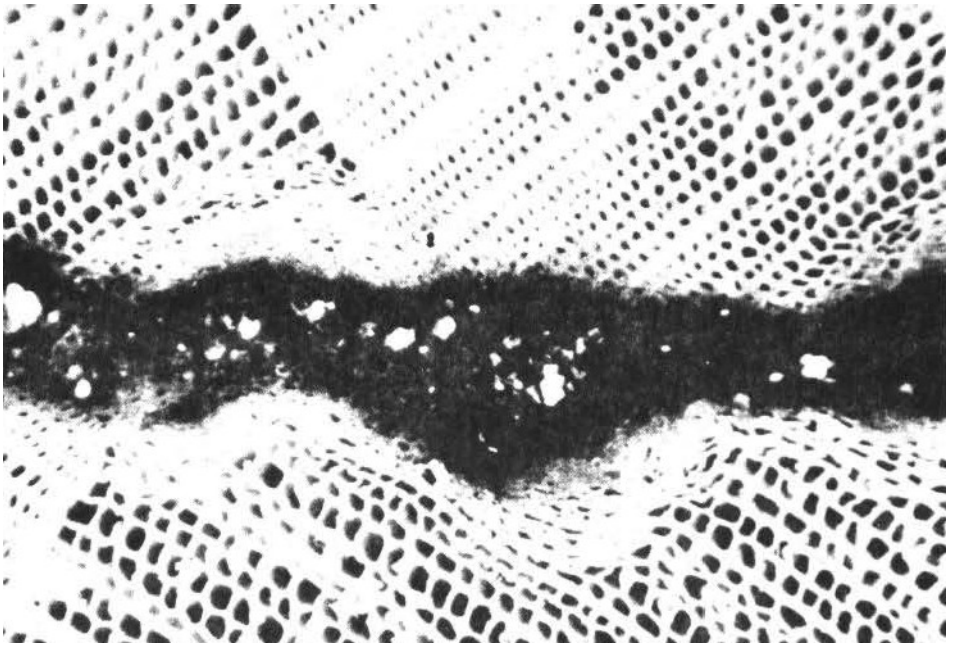


(a)

Figure 1.42 Bondlines between (a) sound wood surfaces and (b) crushed and matted wood surfaces. The adhesive penetrates the first layers of cells on the sound surface but does not penetrate the cells on the matted surface.

wall. In these joints, fracture occurred within the S-3 layer. Adhesive penetration of the cell wall apparently reinforces the weak interface between the cell wall layers.

Different adhesives have different adhesion to the important S-3 layer exposed on the cell lumen. Phenol-formaldehyde, which may penetrate the cell wall (Saiki 1984), apparently adheres to the S-3 layer with enough strength so that fracture always occurs in the S-3 or S-2 layers of the wood. In contrast, urea-formaldehyde adhesive may penetrate the cell lumen but it apparently does not penetrate the S-3 layer and it does not adhere to this layer as well as phenol-formaldehyde. Urea-formaldehyde also shrinks



(b)

Figure 1.42 (Continued)

extensively during cure, which places stress on the already weak bond. Under external stress, the joint fails at the interface between the adhesive and the S-3 layer, in contrast to the phenol-formaldehyde bond, which always fails in the wood (Furuno and Saiki 1988). This difference in adhesion to the S-3 layer may contribute to the lower resistance of urea-formaldehyde-bonded joints to cyclic swelling and shrinkage stresses.

The percentage of wood failure is not a useful measure of bond quality if the wood is decayed or unsound in any way. If the wood is unsound, high wood failure gives a false indication of high quality and environmental resistance. The correct interpretation will be made more readily if strength is measured concurrently. Density has a strong effect on the percentage of wood failure just as it does upon strength, especially above specific gravity of 0.8.

Density, Strength, and Wood Failure

Among the wood characteristics that control bond strength and performance, wood density is the single most important factor. We previously described how the strength of wood increases as an exponential function of specific gravity. The performance required of an adhesive also increases as a function of density. Unfortunately, the strength of the adhesive or the bond is sometimes a limiting factor.

There is a density above which the wood strength exceeds that of the adhesive. The joint strength may remain level or increase marginally; however, the percentage of wood failure and the indicated resistance of the bond to the environment decrease above this density. Truax (1929), working with natural resin adhesives and 40 wood species varying in density up to 0.84 g/cm^2, showed the possibility of such a transition at a density of about 0.70 g/cm^2. Strength increases as wood density increases, but the percentage of wood failure on the broken surface decreases. Freeman (1959), working with synthetic resin adhesives and 22 species varying in density up to 1.16 g/cm^2, found a transition with urea-formaldehyde at a density of 0.8 g/cm^2. However, Freeman did not observe a transition with phenol-resorcinol formaldehyde. Other researchers have also noted a transition in the range of 0.7-0.8 g/cm^2 density (Troop and Wangaard 1950, Chugg 1965, Sakuno and Goto 1970b, Freeman 1959, Chow and Chunsi 1979). Below this region, joint strength increases directly with density. Wood failure remains constant at a high level or decreases slightly as density increases. Wood density obviously controls joint strength with conventional rigid woodworking adhesives. Above 0.8 g/cm^2, joint strength remains level or declines, while the percentage of wood failure decreases precipitously. Obviously, the adhesive or adhesion strength controls strength above the density range of 0.7-0.8 g/cm^2. Freeman and Wangaard (1960) showed that wettability is an important controlling factor above this region.

The relationships of strength and percentage of wood failure to density are summarized in Figure 1.43. Variability, indicated by the width of the envelopes in Figure 1.43, increases with density. These increases are due to differences in the strengths of the various types of adhesives used by different investigators, and to the increasing variety, content, and effects of extractives upon adhesive and bond strength in higher density woods.

Several researchers developed mathematical relationships for the strength of bonded joints relative to the strength of solid wood as a function of the percentage of wood failure (Freeman 1959, Chow and Chunsi 1979, Rudnicki 1976, Kitazawa 1946). Chow and Chunsi

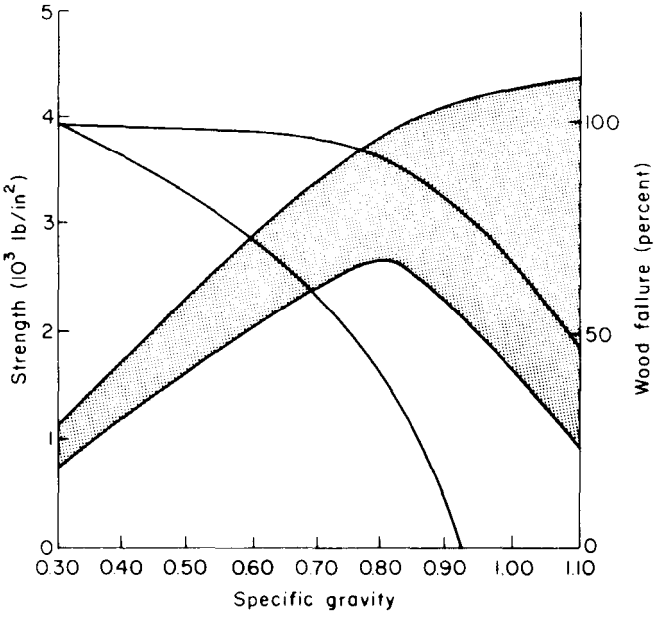


Figure 1.43 Schematic plot of strength and the percentage of wood failure as functions of wood specific gravity. Strength shown by the shaded envelope.

(1979) use the following formula to determine the relative strength of bonded joints*:

$$\text{Relative strength} = \frac{\left(\begin{array}{c}\text{strength of}\\ \text{bonded joint}\end{array}\right) \bullet \left(\begin{array}{c}\text{strength of}\\ \text{solid wood}\end{array}\right)}{\text{strength of solid wood}} \times 100$$

This formula shows a continuous relationship of strength to the percentage of wood failure over a range of density from 0.33 to 1.01 g/cm^2 and of wood failure from 0 to 100%. Relative strength

*This equation differs from the equation in Chow and Chunsi's paper but agrees with the data presented in their paper.

values greater than 1 mean that the strength of the bonded joint is greater than the strength of the solid wood of the same species.

Figure 1.44 is a plot of data for about 80 species that were extracted from studies by Truax (1929) and Chow and Chunsi (1979) and presented in the format of Chow and Chunsi. The center line is a second-order regression fit to the combined data. The scatter of the individual species about the regression line undoubtedly arises from the wood chemical and anatomical interactions with the adhesives as well as from experimental variation. In spite of variability, the relationship is clear: high wood failure equals high performance relative to the strength of the wood.

A joint that produces 60% wood failure will be within about ±20% of the strength of the solid wood. If the joint is as strong as the solid wood, then internal swelling and shrinking stresses or stress from external loads will be just as likely to cause failure of the wood as to cause failure of the joint. At 80% wood failure, the joint strength will be at least 90% but more likely from 100 to 140% of the strength of the solid wood. The fact that joint strength should be greater than the strength of the solid wood **seems** odd at first, but it is probably due to the reinforcing effect of the adhesive in the vicinity of the shear plane and differences in the method of

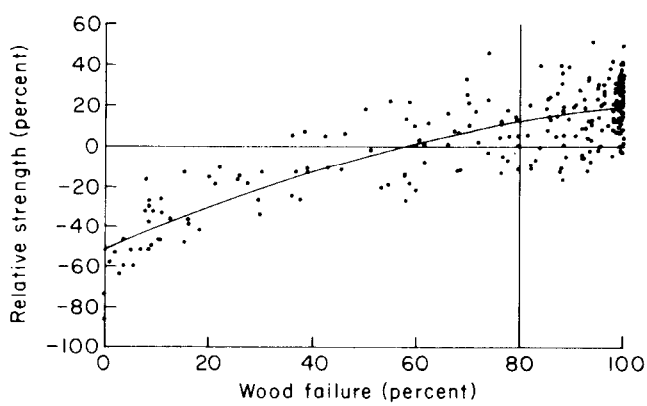


Figure 1.44 Relative strength of adhesively bonded shear test specimens as a function of the percentage of wood failure (see definition in text). A positive relative strength means that the bonded joint is stronger than the solid wood. Conversely, a negative relative strength means that the bonded joint is weaker than the solid wood.

testing solid and bonded wood joints (White and Green 1980, Okkonen and River 1989). This relationship could be useful in quality control and in assessing joing durability and permanence because it removes the effect of density. However, the technique requires coincidental testing of solid wood specimens of the same species.

If bonded joints or products are subjected to an accelerated aging treatment before they fail, then the percentage of wood failure can indicate the probable physical and chemical stability of the joint in relation to the wood. High wood failure (high joint strength) in wet and hot environments indicates an adhesive that may be more stable than wood. Most service environments also include externally applied loads and the forces arising from shrinking and swelling of the wood. High wood failure indicates that the joint will probably withstand these cyclical forces. One exception is that if the adhesive is not stronger than the wood but flexible and thick enough to deform, thus relieving critical stresses, the adhesive may still perform very well. An example of this type of an adhesive is a highly deformable but elastic material like a polyurethane or silicone elastomer-based material.

Wood failure is primarily a measure of the quality of solid wood joints, and it is seldom used for reconstituted panel products. Although microscopic evidence suggests that the same failure processes occur in reconstituted products as do in solid wood joints (Wilson and Krahmer 1976), determining the percentage of wood failure is difficult. We may presume, however, that the same factors that affect the percentage of wood failure in solid wood joints also affect the percentage of wood failure in reconstituted products.

Shear strength of wood varies according to the Hankinson formula. The strength decreases continuously as the grain angle changes from parallel to the direction of the stress to perpendicular to the direction of stress. Chugg and Parekh (1966) demonstrated that this relationship also holds in bonded side-grain to side-grain joints. The shear strength of joints decreases continuously as the angle between the grain directions of the two adherends increases from 0 to 90°. Wardle (1967) demonstrated that a different but similar relationship holds for bonded end-grain to side-grain joints (scarf joints). The strength of scarf joints increases at a decreasing rate as the slope of the scarf decreases from 1:2 (nearly perpendicular to the grain) to 1:20 (nearly parallel to the grain)-in other words, as the ratio of end grain to side grain decreases. Ninety-five percent of the strength of the solid wood can be achieved at the 1:20 slope. However, slopes in the range of 1:8 to 1:12 are most practical and economical, and are widely used. They provide strengths equal to 85-90% of the strength of the solid wood.

Grain angle has the opposite effect on fracture toughness. As would be expected, the load required to fracture a joint with zero grain to the bondline is the highest, and it decreases monotonically as the grain angle increases (until it is 90° to the bondline). When energy is considered, that is, when modulus and deformation are considered in the equation for fracture toughness (strain energy release rate), the energy required to cause crack growth actually increases as the grain angle increases from 0 to 90° (White 1977; Ruedy and Johnson 1979; Ebewele, River, and Koutsky (1979). An adequate explanation for this unexpected and anomalous behavior has not been found. However, this phenomenon may be due to increasing resin penetration and increasing effectiveness of the weak--interface, crack-stopping mechanism (Cook and Gordon 1964) as the grain angle increases.

Delamination

Delamination is the slow, usually progressive, rupture of a bondline arising from the cyclical stresses created by the swelling and shrinkage of solid wood adherends in service. Delamination generally indicates that the adhesive, or the joint formed by the adhesive, is not as strong or resistant to crack growth as the wood and thus is less able to resist the stresses imposed on it by the movement of the wood and by external loads. Because a bonded product can perform its function only if the bondline remains intact, the percentage of delamination of a bondline after exposure to a cyclical environment is a good measure of joint performance. This measure is commonly used in the plywood and laminated-timber industries. In a sense, irreversible thickness swelling (springback) of reconstituted panel products is also a measure of delamination.

The stress causing delamination may be tension or shear, or more likely a combination of the two. Murthy and Chamis (1989) used a three-dimensional finite element analysis for the effects of various types of external mechanical and environmental stresses on the edge delamination of fiber-reinforced composites. These authors found that delamination stresses created by thermal and moisture content changes were significantly greater than delamination stresses created by mechanical loading. They also found that edge delamination is dominated by interlaminar shear stress, although it may be triggered by interlaminar tension stress. In wood members, moisture-induced differential shrinkage occurs because of the lag of drying in the center of a wood member and the consequent lag of shrinkage there. This places the outer shell of the member in tension. When the tensile stresses become critical, the lumber cracks (checks), or if the member is laminated and the joint is weaker than the wood, the bondline delaminates.

In wood laminates, moisture-induced stresses, especially drying stresses, are in most cases much more severe than temperature-induced stresses (the exception might be extreme temperature change). Several studies have focused on calculating the magnitude of moisture-induced stresses. Dietz, Grinsfelder, and Reissner (1946) developed models based on the elastic behavior of wood for two cases:

Case 1 Shear stress = $0.7e_oE_xG_{xy}$

Case 2 Cleavage stress = $0.45e_oE_x2E_yG_{xy}$

where e_o is $a(M_1\text{-}M_2)$, a is the hygroscopic coefficient of shrinkage, M_1 is the initial moisture content, M_2 is the final moisture content, E_x is the tensile modulus perpendicular to grain in plane of bondline, E_y is the tensile modulus perpendicular to grain perpendicular to the plane of bondline, and G_{xy} is the shear modulus in rolling shear.

The delamination stresses at the bondline for flat-sawn Douglas-fir and oak laminates predicted by these models for a 16% moisture content change are compared to the strength of solid wood in Table 1.17. Obviously, the stresses predicted by a purely elastic model greatly exceed the strength of the wood. The model fails to consider the capability of the wood to deform viscoelastically, especially when the wood is wet. Nevertheless, failure would occur long before a 16% change in moisture content was reached.

McMillen (1955) measured the residual strain in successive slices of boards during drying to determine the differential drying stresses. Youngs and Norris (1958) developed an analytical model using

Table 1.17 Drying (Delamination) Stresses Calculated from a Model of Elastic Wood Behavior

	Average stress (lb/in.^{2})			
Species	Case 1 (shear)	Wood rolling shear strength[a]	Case 2 (cleavage)	Wood tensile strength
Douglas fir	800	300	1580	340
Oak	2020	800	3240	800

[a]Estimated.

simultaneous equations that predicted the stresses observed by McMillen. They applied the model to a 2- by 7-in. red oak board that had been drying under mild conditions for 4 days, when the tensile drying stresses in the outer shell are the most severe. The model predicted a reasonable tensile stress of 710 lb/in.^{2} on the wide tangential face. The actual tensile strength of the oak was 850 lb/in.^{2}, so the wood was near failure. The tensile stress on the narrow radial face was 160 lb/in.^{2}, and the maximum shear stress inside the piece was only 40 lb/in.^{2} The model demonstrates the severity of the tensile drying stresses on the wide face.

More recently, Kawai, Nakato, and Sadoh (1979a, 1979b) developed constitutive relations for drying stresses. Their model accounts for several important factors, such as the change in elastic properties with moisture content and the viscoelastic behavior of wood. The model requires knowledge of the mechanical properties of the wood, the basic shrinkage coefficients, the observed shrinkage, and the creep compliance. Kawai, Nakato, and Sadoh (1979a, 1979b) determined these terms for a fairly low-density wood (Hinoki) experimentally and then calculated the drying stresses under three different drying conditions. The maximum critical stress of 570 lb/in.^{2} occurred under low humidity (EMC = 11%) in the first minute or two of drying. Within 13 min, the stresses in the outer shell of the board had reversed tension to compression. This model could prove useful for determining the stresses that are likely to occur in laminated or edge-bonded wood constructions under drying conditions.

Differential shrinkage may also arise from:

1. More rapid drying on one side of the panel than the other.
2. More rapid drying from the end grain than from the side grain.
3. Or materials with different shrinkage coefficients when subjected to a moisture content change after bonding.

The first condition frequently occurs when one side of a panel is exposed to different conditions such as wetting, sunshine, or air movement, or if one side has a protective finish and the other does not. The second condition occurs because wood loses moisture roughly 20 times faster from the end grain than from the side grain. The third condition depends on how a bonded product is designed and constructed: for example, bonding a flat-sawn board to a quarter-sawn board, bonding plywood in which the grain directions of the face plies are not parallel, or joining species with different swell-shrink coefficients. Refer to Table 1.18 for a comparison of the different shell-shrink coefficients of many wood species, grain directions, and products. Figure 1.45 shows these and other examples of conditions that lead to differential shrinkage.

Table 1.18 Linear Expansion and Contraction of Selected Woods and Wood-Based Materials Between 30 and 90% Relative Humidity

Species or material	Plane[a]	Linear change (%)[b]
Wood species		
White ash	L	0.09
	T	3.7
	R	2.4
Hard maple	T	4.9
	R	2.2
Black cherry	T	3.5
	R	1.8
Yellow birch	T	4.7
	R	3.6
Black tupelo	T	4.3
	R	2.5
Silver maple	T	3.5
	R	1.4
Red oak	T	5.2
	R	2.2
Mahogany	T	3.4
	R	2.4
Material		
Plywood		<0.02
Particleboard		
Medium-density		0.20-0.60[c]
High-density		0.20-0.85
Insulation board		0.20-0.47
Medium-density fiberboard		0.35-0.62[d]
Hardboard		0.15-0.52
Waferboard		0.07-0.15
Oriented strandboard		
Parallel to panel length		0.05-0.10
Perpendicular		0.12-0.30

[a]T is tangential, R is radial.
[b]The range of values for wood-based materials reflects the influence of particle configuration, board construction, and manufacturing.
[c]The standard is 0.35 over a range of 50-90% RH (ANSI 208.1; ANSI 1989)
[d]The standard is 0.30 over a range of 50-90% RH (ANSI 208.2; ANSI 1980).

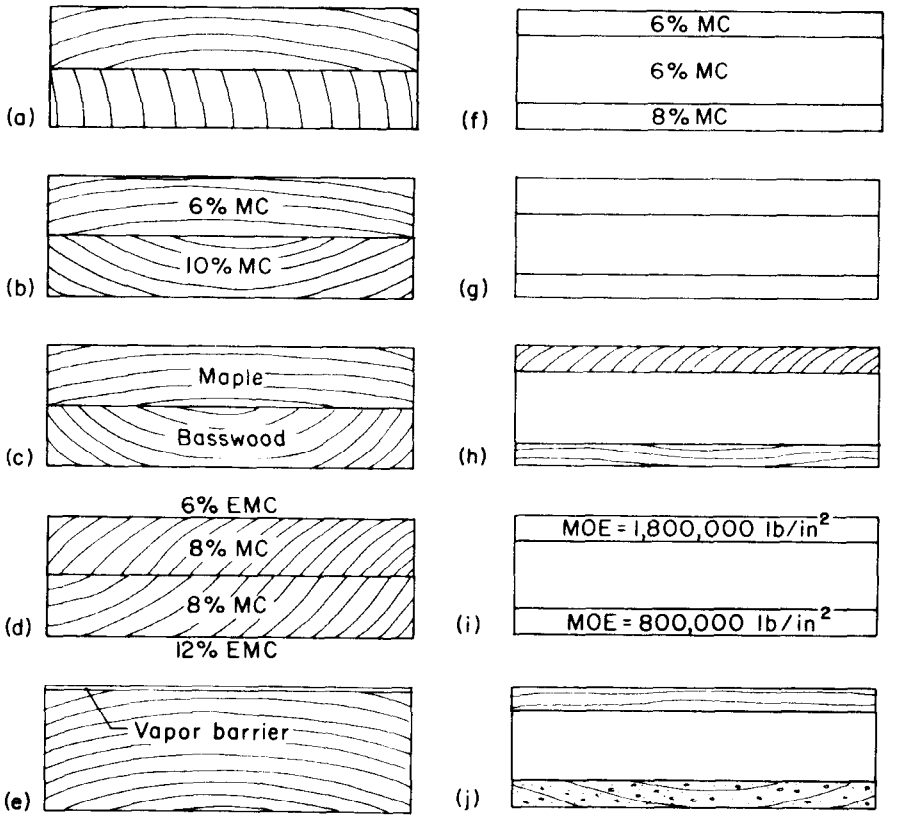


Figure 1.45 Examples of conditions leading to differential shrinkage, warping, and delamination stresses : (a) tangential compared to radial grain, (b) different moisture content at bonding, (c) species with different shrinkage coefficients, (d) different EMC content on opposite sides of laminate, (e) vapor barrier on one side, (f) outer plies not at same moisture content, (g) outer plies of different thicknesses, (h) one outer ply with steep grain angle or of different swell/shrink coefficient, (i) outer plies of different tensile modulus, and (j) grain angles of outer plies not parallel.

The geometry of the cross section of the laminate can also be a factor. Murthy and Chamis (1989) found that in a ±45°-fiber-oriented, reinforced, plastic laminate the width-to-thickness ratio (W/T) affected both the interlaminar shear stress and the interlaminar

normal stress. The normalized shear stress decreased rapidly as the width-to-thickness ratio increased from 0 to 4; at higher ratios, the shear stress was almost constant. The normalized normal stress changed from compression when W/T = 0 to a peak in tension when WIT = 4; thereafter, the stress decreased gradually to about 0 at W/T = 40.

Laufenberg (1982) studied the delamination behavior of a two-member Douglas-fir laminate in cyclic soak-dry treatments. He also applied finite element analysis to estimate the stresses in the bondline caused by shrinkage as a function of the growth-ring angle between the laminae. Changing the growth-ring orientation changed the swelling coefficient. The analysis showed the stresses are the highest at the outside edge of the laminate near the bondline when one lamina is flat-sawn and the other quarter-sawn. In this case, the maximum tension stress was 1600 lb/in.^{2}, and the shear stress was about 1270 lb/in.^{2} (Figure 1.46). Laufenberg also found that adjacent laminae whose growth-ring angles differed by more than 15° were likely to split or delaminate.

A major advantage of plywood is dimensional stability. The low shrinkage coefficient of wood along the grain is used to advantage. The bonding of alternating panel layers at right angles to each other results in a panel swell-shrink coefficient that is almost as low in all directions as the swell-shrink coefficient of the wood along the grain. But this achievement comes at the price of high shear and cleavage delamination stresses. Although the analysis of Murthy and Chamis (1989) suggests that there should be no tensile (cleavage) delamination stress at the edges of a panel with a WIT ratio >4, our observations suggest that such stress does arise. On the other hand, Heebink, Kuenzi, and Maki (1964). who studied the linear movement of plywood and flakeboard, conclude that the stresses induced by lateral swelling (primarily shear) are small. Here again, experience indicates that such stress may be significant. The plywood studied by Heebink, Kuenzi, and Maki (1964) was comprised of eight 1/16-in. veneers. The thicker the veneers, the greater the stresses and the greater the likelihood of delamination. The rule of thumb in the plywood industry is if plywood is made with veneers 1/16 in. thick or less, it will withstand the most severe environment without delaminating. If the veneers are 1/8 in. thick, delamination is more likely, and if the veneers are 1/4 in. thick, delamination is almost certain. Another way to look at the delamination of plywood is that as veneer thickness increases, the number of bondlines decreases so that more swelling or shrinking force is concentrated at each bondline.

In addition to the thickness of the individual laminae, the modulus of the wood and the tangential shrinkage coefficient also have a strong influence on delamination. The moduli change from high to

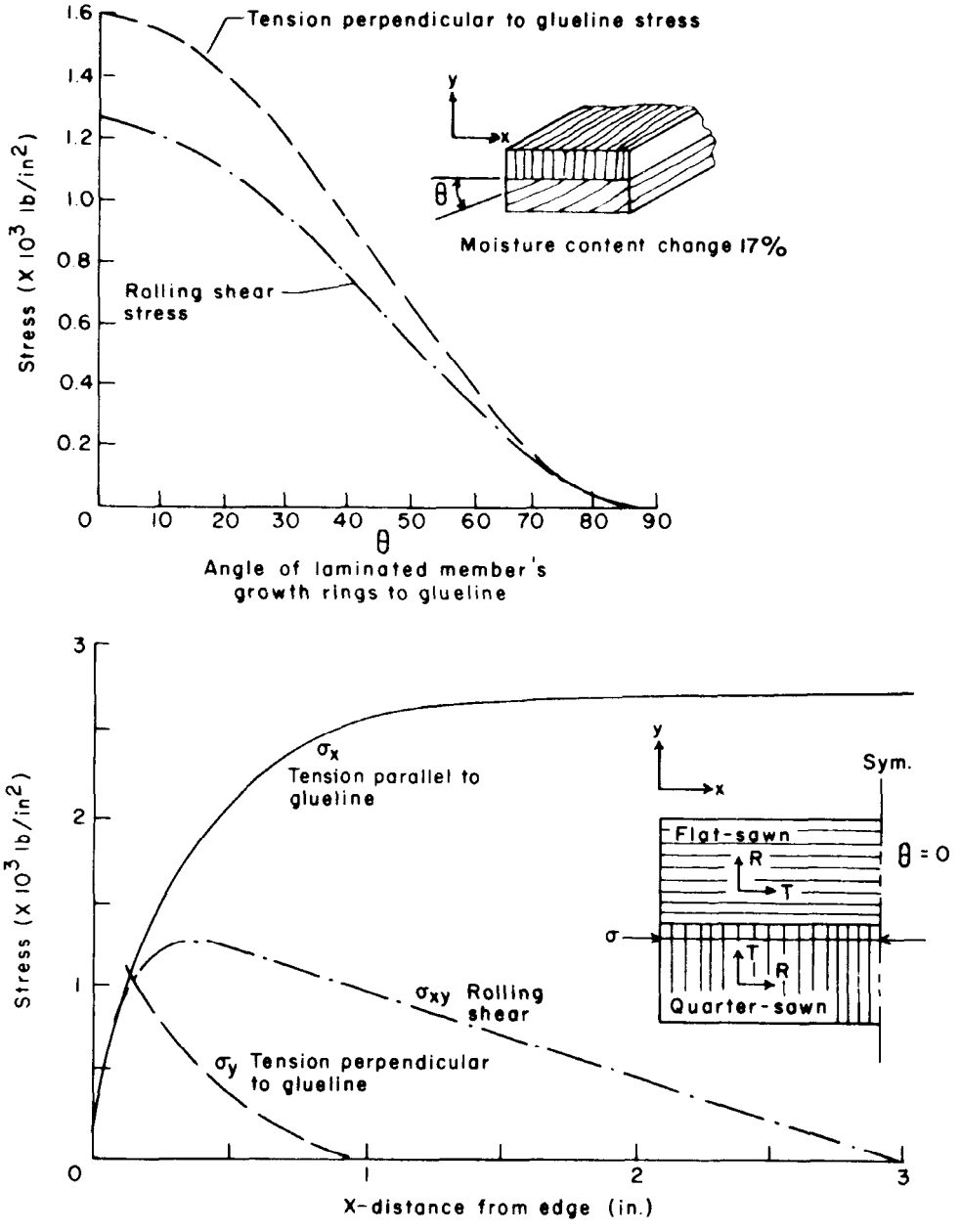


Figure 1.46 Predicted stresses in bondlines of a two-ply Douglas-fir laminate with a moisture content change of 17% (below fiber saturation): (top) maximum stresses as a function of the angle between the growth rings, (bottom) stresses in a quarter-sawn member laminated to a flat sawn member as a function of the distance from the edge.

low and shrinkage changes from low to high as the grain direction changes from parallel to perpendicular. Chugg and Parekh (1966) bonded 3/4-in. Douglas-fir and hemlock lumber with phenol-resorcinol-formaldehyde adhesive. The grain angle between the adherends varied from 0° (parallel grain) to 90° (perpendicular grain). The amount of delamination in small specimens exposed for several months outdoors increased dramatically as the angle between the grain directions of the two adherends increased from 0° to 90°. Some joints apparently failed in the wood, but this should be expected with well-made phenol-resorcinol bondlines.

The percentage of delamination after cyclic laboratory aging or actual service exposure is often used to evaluate the strength-related aspects of performance-initial bond quality, durability, and permanence. Although high strength and high percentage of wood failure are important and necessary for durable laminated timbers, such performance alone does not assure that the bonded joints will be durable in service (Dosker and Knauss 1944). High or low wood failure when the joint is loaded to failure means that the joint is stronger than the wood and should be better able to resist cyclic stresses than the wood. Other factors such as slow crack-growth resistance and aging are involved. Truax and Selbo (1948) studied laminated oak, maple, pine, and fir timbers and found that the percentage of delamination in the timber after a cyclic laboratory soak-dry treatment was a better predictor of actual outdoor experience of the timbers than either percentage of wood failure, or shear strength in dry or wet tests. The percentage of wood failure obtained in a dry shear test was a better indicator of weather resistance than shear strength, but only when adhesives of known durability were used. This seems to agree with the experience in the plywood industry (Raymond 1976). The percentage of wood failure in a dry shear test will not distinguish between durable/nondurable or permanent/nonpermanent adhesives.

Joint Design

Design is one of the most important factors that determine the strength of bonded wood joints and products. Surprisingly little information is available in the literature on this broad subject. Many designs have been arrived at after centuries of trial and error. Only recently have engineering practices been applied to the design of many types of wood joints; the design of composite materials other than plywood is still largely empirical. In this section we discuss the design of secondary joints, rather than primary joints between wood elements.

Secondary joints are those joints that connect wood and nonwood members to form an assembly or structure, such as a wood I-joist, an end-jointed member, a chair, or a building. In the broadest

sense, the adhesives used to bond assemblies are all structural adhesives. In a more restricted sense, a structural adhesive is one whose mechanical and chemical properties are known, thus allowing engineers or designers to apply engineering principles to the design of a structure. This type of engineering data is simply unavailable for almost all types of wood-bonding adhesives. Therefore, the Wood Handbook (Forest Products Laboratory 1987) categorizes adhesives according to their strength and rigidity into structural, semistructural, nonstructural, and unclassified categories. In addition, subcategories for resistance to stress, time, and service environment are used. The term assembly adhesive is often used to cover the broad range of structural, semistructural, and nonstructural adhesives that are used to bond all sorts of wooden assemblies, including buildings. The term construction adhesive applies more specifically to adhesives with gap-filling ability (usually elastomer-based, mastic-type adhesives) used for on-site building construction.

Butt Joints. The difficulty of developing the full strength of lumber in tension parallel to the grain was discussed earlier in this chapter. Schaeffer (1970a) used a variety of epoxy and phenol-resorcinol-formaldehyde adhesives and surface preparation techniques on southern pine, Douglas-fir, and eastern white pine. He obtained transverse butt-joint strengths ranging from 3000 to 10,000 lb/in.^{2} under very carefully controlled laboratory conditions. Most tensile strengths ranged from 3000 to 4000 lb/in.^{2} In a similar study a strength of 10,000 lb/in.^{2} was obtained but only with lower-density white pine (Schaeffer 1970b). This was enough to cause 100% wood failure in the white pine. No wood failure occurred in the Douglas fir and southern pine joints. However, finger joints prepared in the same study were approximately three times stronger than the best transverse butt joints. In light of this difficulty, transverse butt joints joining the end grain of the wood are seldom attempted.

The most common joint that is like the transverse butt joint is the 45° miter joint used in picture-frame construction. In this case, the joint need not develop the very high strength that would be needed to fail the wood in tension parallel to the grain. Only enough strength is required to resist the stresses created by normal handling of the picture frame.

The most severe stresses on the miter butt joint are usually those created by swelling and shrinking of the frame. Shrinkage tends to cause the frame to open at the inside of the miter. The anisotropic swell-shrink behavior of wood is responsible for this problem. As the wood shrinks, the frame members shrink in length only about 1/50 as much as in width. Conversely, the outside corners

open during swelling because the wood swells about 50 times more in width than in length (Figure 1.47). Consequently, wide picture frames are usually designed of two or more mating frames, each made of narrower moldings. The mating frames are then assembled

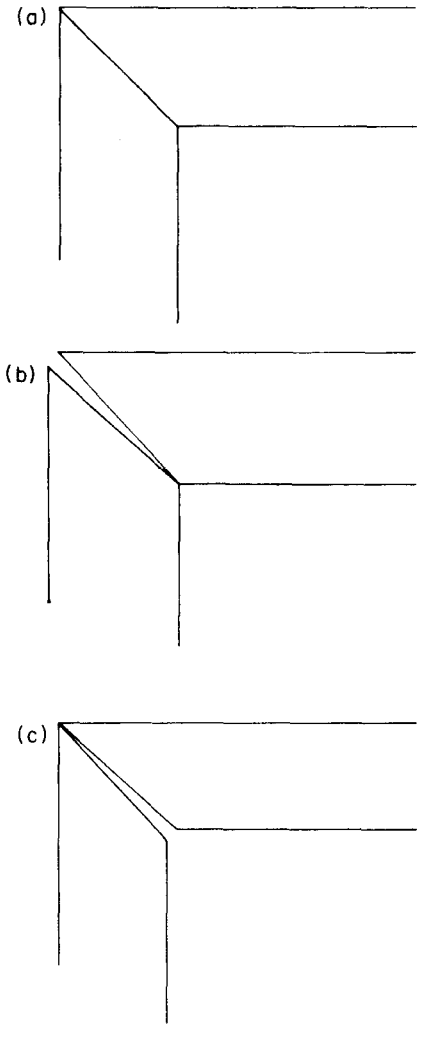


Figure 1.47 Mitered butt joint (a) as bonded, (b) failed as a result of anisotropic swelling, and (c) anisotropic shrinkage.

with nails that allow some movement at the corners without opening the bonded miter joints. Joints such as the gusseted butt joint, scarf joint, and finger joint (Figure 1.48) have been developed to overcome the deficiencies of bonded wood butt joints. These joints are strong because they have a high ratio of side-grain area to end-grain area, and also because the stress concentrations in the joint are lower.

Lap and Gusset Joints. The stresses in lap joints, including wood joints, generally are not uniform along the joint but increase toward the end (Goland and Reissner 1944). The stress at the end of a given joint that controls fracture and thus failure of the joint generally is not known. Therefore, various empirical methods have been developed for designing lap joints.

A generalized method for allowable design stresses for wood-bonding adhesives and the design of bonded joints has been developed by Krueger and Sandberg (1979). In the first step, the

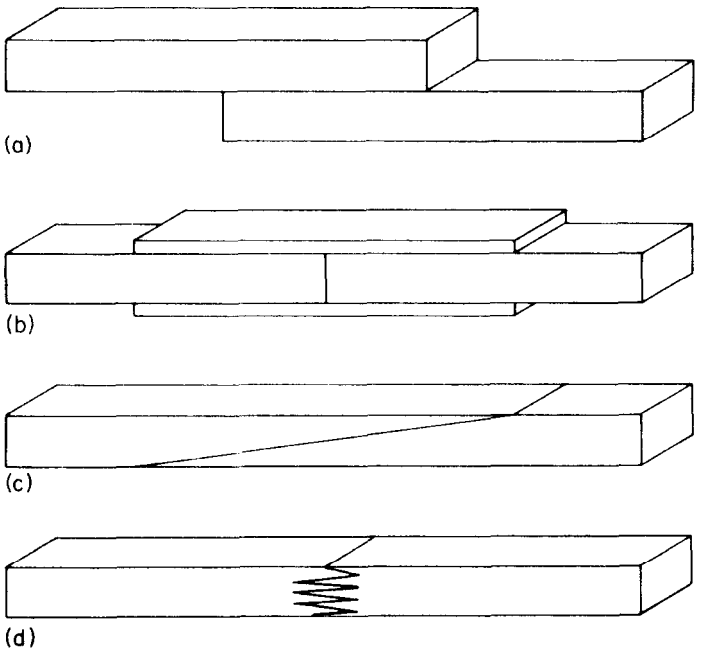


Figure 1.48 Common adhesively bonded end joints used with wood members : (a) lap, (b) gusseted-lap, (c) scarf, and (d) finger.

basic shear and tensile strengths of the adhesive are determined by standard test methods. In the second step, a series of reduction coefficients are determined for design, manufacturing, and service conditions. Among these coefficients are the characteristics of the wood, stress concentrations resulting from joint configuration and adherend and adhesive properties, duration of load, environment, quality control, and safety. Finally, these reduction coefficients are applied to the basic joint strength to reach an allowable working stress for design. This method is quite similar to that used for developing allowable stresses for wood members. The method along with illustrative examples of the design of lap joints is described by Krueger (1983).

Glos and Horstmann (1989) systematically studied the effects of varying side-grain to side-grain angle between the two adherends, length of overlap, shape of bonded area, wood density, type of adhesive, and length of unbonded-end distance on the strength of bonded lumber lap joints. All the factors studied had strong effects on strength except the shape of the bonded area, the width of the joint, and the method of clamping. Based on those effective relationships, the authors developed generally applicable design rules for glued wood (lumber) joints. The rules are in the form of a design factor equation similar in principle to the one developed by Krueger (1983), although Glos and Horstmann did not consider the effects of various environmental conditions, duration of load, and safety. The apparent specific application of this work is to the manufacture of bonded lumber trusses.

In bonded wood lap joints made with strong rigid adhesives, failure typically initiates at the ends of the overlap because of combined tension and shear stresses. This suggests that high stress concentrations at the ends of the lap control failure of the joint rather than plastic deformation of the materials. Walsh, Leicester, and Ryan (1973) demonstrated that fracture mechanics (stress concentration at a flaw) dominates the failure of practical lap joints in the range of two to eight times the thickness of the axial members. Using linear elastic fracture theory, these authors predicted the experimental strength of double-lap (gusseted-lap) joints based on the joint geometry and the wood elastic properties. They also developed a conservative design equation for double-lap joints based on the ratio of overlap length to axial-member thickness and the wood species strength determined from standard block shear tests:

$$\sigma_{nom}/\tau_y = (2W)^{-0.5}[1 + 1/8(L/W)]$$

for $L/W = 2-8$ and $T/W = 0.5-2$

where σ_{nom} is the allowable axial stress for member, τ_y the design shear stress for joint, L half the overlap length, W half the tension member thickness, and T the thickness of each splice plate.

Scarf Joints. The slope of the scarf is the major factor determining the strength of scarf joints. The rate of increase in strength diminishes as the slope decreases from 1-in-8 to 1-in-12. Eighty-five to 90% of the strength of the clear wood can be attained within this range of practical joints (Wardle 1967). At a slope of 1-in-20, properly cut and bonded scarf joints can attain 95% of the tensile strength of the clear wood. One hundred percent of the strength is apparently unattainable because of mismatch between the earlywood and latewood portions of the bonded members. The choice of slope obviously affects the amount of lumber required to make the joint. A slope of 1-in-12 requires about 18 in. of nominal 2-in. lumber, a considerable waste, especially if the lumber is a high-value structural grade.

Aside from considerations of slope, several other factors affect the performance of the joint. Lumber grading rules allow some slope of grain. If the surface of the scarf happens to be cut parallel to the slope of grain, the joint will be stronger than if the surface of the scarf happens to cut across the grain. The scarf surfaces must also be true plane surfaces, without torn grain, chatter marks, or other machining imperfections. Sanding the scarf weakens the joint. Longitudinal indexing of the two adherends for bonding presents a major problem in the mass production of scarf joints. End notches and steps are sometimes used for indexing. However, both techniques result in significant stress concentrations that detract from the joint strength. End notches (steps located at the surface) are especially damaging. These notches may reduce strength to 65% of the solid wood. Aluminum nails and wood dowels are probably the preferred methods for indexing. Both techniques require careful positioning of the two adherends for drilling or nailing. If the adherends have different thicknesses, the scarf may shift slightly as pressure is applied. A slight overlap of the scarf resulting in somewhat higher pressure than desired is preferable to a slight underlap, which results in much lower pressure than required (Wardle 1967).

Finger Joints. A finger joint is, in a sense, a folded scarf joint. Finger joints are normally used for end joining lumber to make longer lengths, although these joints are also used in box corners and some furniture assembly. The mating surfaces of the two adherends are shaped in a mating finger (usually tapered) configuration, mated, and bonded with adhesive. The joint has several significant advantages and disadvantages over the scarf joint. The first advantage

is that the finger joint wastes less material than does the scarf joint. Instead of 18 in., as little as 1.5 in. of wood is wasted to make a structural joint. Even less wood is wasted in nonstructural joints. Second, the interlocking feature of the mating fingers eliminates the problem of indexing encountered in scarf joints. On the other hand, the first disadvantage of finger joints is that such joints necessarily have many points of stress concentration, one at each finger tip, that reduce the structural efficiency below that attainable with a scarf joint. The second disadvantage is the expense, care, and frequency required to properly maintain the special cutters that cut the fingers. These cutters dull rather quickly, especially on dense wood, and the proper shape of the fingers is critical to maintaining the proper shape and fit of the joint for good bonding.

The design of the finger joint is of the utmost importance in determining the strength of structural joints. The same considerations of slope that control the strength of scarf joints affect that of finger joints: that is, flatter slopes (higher finger length to pitch ratios) yield higher strengths. However, there is a point of diminishing return. As the slope decreases, the number of fingers increases when the finger length is held within practical limits. The pitch or, in other words, the distance between the fingers becomes very small. Furthermore, each finger tip creates a stress concentration when load is applied to the joint. The high frequency of stress concentrations associated with the closely spaced fingers creates a plane of weakness that causes the joint to fail at a lower average stress than would a joint with optimal slope and pitch. Failure of such a joint would most likely be catastrophic as well. Page (1959) found that strength increased 50% as the slope decreased from 1-in-4 to 1-in-6 (finger length and tip thickness were held constant). A further decrease to 1-in-8 increased strength another 20%. Slopes of 1-in-10 and 1-in-16 failed to increase strength further. Selbo (1964) reported little gain in strength with slopes flatter than about 1-in-12.

After the slope is selected, a finger length must be selected that will provide sufficient shear strength to equal or exceed the tensile strength of the solid member. This length will be least three to four times the pitch. Selbo (1964) found little gain beyond a ratio of 4:1. Wardle (1967) pointed out that fingers must be shorter than the valleys to prevent crushing of the tips and splitting in the valleys.

After slope and finger length, the finger tip thickness is the most important factor that determines joint strength. The thinner the finger tip, the higher the strength. Selbo (1963) reported that increasing the tip width from 0.045 in. to 0.090 in. while maintaining the same pitch (spacing between fingers) reduced the

tensile strength by 20%, although the actual percentage of reduction depended on the finger pitch and slope. Based on relationships such as shown in Figure 1.49, Selbo concludes that if maximum strength is needed, the fingers should be designed with tips as

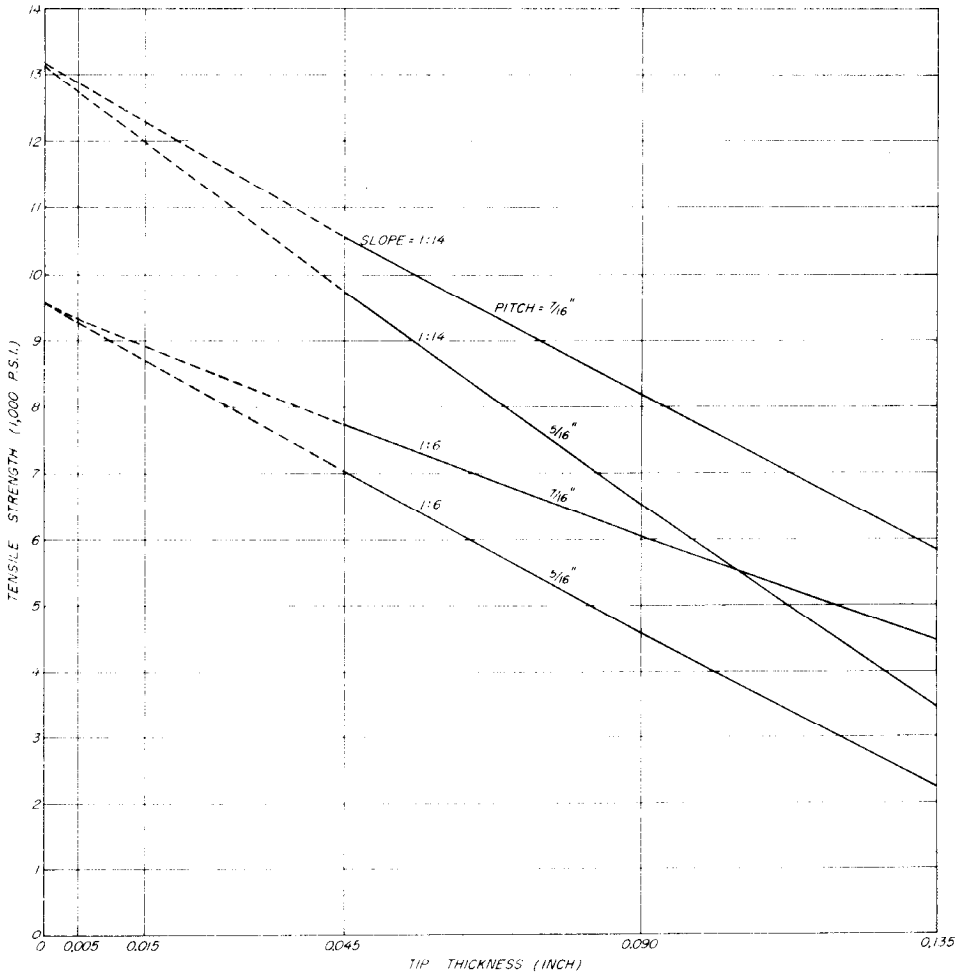


Figure 1.49 The effect of tip thickness on the tensile strength of finger joints in Douglas-fir. (Dashed lines represent extrapolated data.) (From Selbo 1963.)

thin as is practically possible. The minimum thickness of a tip depends considerably on the species and density of the wood, which control the rate of tool dulling. Sharper tip cutters tend to dull more rapidly in production, especially when cutting dense wood. Richards (1963) reported that finger cutters with tip thickness down to 0.032 in. are stable and suitable for commercial production of finger joints up to about 1.5 in. in length.

The flat area at the end of each finger, which corresponds to the tip thickness, forms a narrow butt joint. Adhesives have much different elastic properties than does the wood parallel to the grain. Therefore, an adhesive joint perpendicular to the grain (a butt joint) presents a severe discontinuity in a wood member in tension parallel to the grain. Butt joints are notoriously weak relative to the wood strength parallel to the grain. Under an axial load, butt joints fail at a relatively low load level in relation to the wood strength. Failure of the butt-joint portion of the finger joint worsens the already severe stress concentrations at the finger tips. These severe stress concentrations cause the finger joint to fail at an average stress level well below that obtainable with a good scarf joint.

Special joints called impression finger joints were developed to minimize finger tip thickness. Impression finger joints are prepared by machining small fingers and then molding them to a sharp point by pressing them into a heated die (Strickler 1967, Richards 1963). Richards (1963) showed that the strength of sharp-tipped joints increased from 30 to 85% depending on species compared to the strength of joints made with normal tip thickness of 0.030-0.040 in. Very dense species are apparently unsuited to impression forming without preslitting the wood (Carruthers 1968). Even with low to moderate density species, impression joints are not practicable for several reasons; an important reason is economics. The extra cost of fabricating impression-type finger joints is not justified by the increased strength obtained when considering the strength of most construction lumber grades. A blunter, but more economical, machined finger tip provides sufficient strength for most grades of lumber that contain knots and other allowable defects. As very-high-strength, low-variability lumber products such as laminated veneer lumber (LVL) and Paralam are used in engineered structures, impression finger joints might prove cost-effective. On the other hand, such lumber products are readily produced in virtually any length desired without the need for secondary joining.

When the finger tip occurs at the outer edge of a finger joint, the flat area at the tip forms a notch in the surface of the member. Such notches are especially harmful stress concentrations and should be avoided by careful machining before finger jointing. or, if possible, they should be feathered out by planing the member after finger jointing.

In practice, fingers for nonstructural joints such as used in millwork are short (1/4 to 5/8 in.). Recently, a trend toward the shorter length has been driven by the cost of lumber. Fingers for structural joints are longer, ranging from 1 to 2.5 in.; again, industry tends to manufacture the shorter length. Joint efficiencies of 50-85% are possible with production-type finger joints. These and many other factors of finger joint design, production, and use are discussed in an extensive literature review (Jokerst 1981).

Assembly Joints. Assembly joints are commonly used in furniture and millwork manufacture, although they are by no means limited to these industries. Dowel joints and mortise and tenon joints are the most common examples of assembly joints. Other types include gusset or double-lap joints, corner joints, and finger joints. Assembly joints are used to fasten wood members with their grain angles at an angle to each other, as in picture-frame or chair construction. The joints were developed to compensate for the fact that adhesive bonds are stronger than wood in tension perpendicular to the grain and weaker than wood in tension parallel to the grain. As in other types of joints, the most successful assembly joints transfer stress through shear rather than tension to develop high joint strengths.

Within limits, the strength of a dowel joint may be increased by increasing the shear area. The shear area is a function of the dowel diameter and length, and of the number of dowels or of the width and length of the tenon. Two strength-limiting factors are the end grain that is present in end-grain to side-grain joints and the stress concentrations that occur at the ends of the dowel or tenon. The bond to the end-grain portion of the dowel hole or mortise in the side-grain member contributes less to strength than does the side-grain portion. The amount of side-grain surface is paramount. This is especially true in mortise and tenon joints, where the wide face of the tenon largely controls joint strength. Other design factors are the clearance between the dowel or tenon and the mating surface; whether the dowels are smooth surfaced or embossed with parallel or spiral grooves; and the clearance between the end of the dowel and the bottom of the hole, or between the tenon and the mortise. Many other variables in the bonding process also influence joint strength, such as the type of adhesive, the moisture content of the wood and the dowels, and the surface quality of the dowel or tenon and the mating hole or mortise.

Possibly the most important design factors that contribute to the strength of assembly joints are the shear area and the depth of insertion of the dowel or tenon into the opposite member. The strength of dowel joints increases approximately linearly with the circumference of the dowel. Eckelman cited by De Bat (1969) reports that dowel joint strength is directly proportional to dowel

diameter. The strengths of 1/4-, 3/8-, and 1/2-in. dowels inserted to the same depth yielded strengths of 1000, 1625, and 2200 lb, respectively. Thus, if other factors such as insertion depth and the species and design of the dowel are held constant, a 1/2-in. dowel will be about twice as strong as a 1/4-in. dowel. The strength of a given dowel joint increases at a decreasing rate as the depth of insertion increases. Eckelman cited by De Bat (1969) has shown that the strength of single joints made with 1/4-, 3/8-, and 1-2-in. dowels levels off at about 2, 3, and 4-1/2 in., respectively. Further increases in the depth of dowel insertion provide little increase in strength. As a rule of thumb, the strength does not increase beyond a depth of insertion of about four times the dowel diameter. The same rule may hold for the ratio of tenon thickness to depth of insertion. However, assembly joints have the additional variable of tenon width.

Clearance is another important factor in designing both dowel joints and mortise and tenon joints. In general, the strongest joints are obtained when the dowel or tenon fits the hole exactly. Eckelman (1969) reported that the strongest joints had at most a 0.001-in. clearance. Sparkes (1966a, 1969) found the strongest joints when the hole equaled the dowel diameter ±0.005 in. Joints made with oversized dowels were as strong as exact-sized dowels as long as the bondline was not starved. Smooth dowels produce the highest strength under ideal bonding conditions. However, in production, grooved dowels are required to allow air to escape during dowel insertion and to allow the adhesive to squeeze up between the dowel and the surface of the hole. Joints made with grooved and spiral-surfaced dowels were only about 89% as strong as joints made with smooth dowels (Eckelman and Hill 1971). Fine grooves are better than coarse. Sparkes (1966a) stated that grooved dowels should be about 0.020 in. oversize. Aside from these conditions and adhesive and bonding considerations, the single most important factor in designing and obtaining high-strength dowel joints and mortise and tenon joints is ensuring that the grain direction is as parallel to the long axis of the dowel or tenon as possible.

The type of adhesive and the gap-filling capability and solids content of the adhesive apparently interact with the type of dowel and the clearance between the hole and the dowel (Sparkes 1969, Eckelman 1979). Gap-filling adhesives and higher solids content apparently give the best results.

Eckelman (1969, 1989) developed an equation for predicting the strength of single-dowel joints :

$$F_2 = -0.834D(L^{0.89})(0.9S_1 + S_2)abc$$

where F_2 is withdrawal strength (lb), D is dowel diameter (in.), L is depth of penetration of dowel in the piece (in.), S_1 is shear

strength parallel to grain of wood member (lb/in.^{2}), S_2 is shear strength parallel to grain of wood dowel (lb/in.^{2}), a is the correction factor for adhesive type, b the correction factor for dowel-hole clearance, and c the correction factor for type of dowel (smooth, multi, spiral).

Although this relationship describes the performance of a single dowel, the number and spacing of dowels is an important factor in furniture construction. The most common and economical joint is made with two dowels. For extreme service conditions, the use of three dowels will increase joint strength by about 15%. The actual amount of strength increase depends on the joint geometry (Sparkes 1970). The wider the joint and the further apart the dowels, the greater the resistance to in-plane bending (for example, the bending of the joint between the rail and rear legs of a chair). One caution : The further apart the dowels, the greater the danger that shrinkage in service will cause the rail to split between the dowels.

Dowel joints are more economical to manufacture than mortise and tenon joints, and are used for most applications. However, a mortise and tenon joint is stronger than a dowel joint. Sparkes (1970) found that mortise and tenon joints were about 38% stronger than dowel joints when dowel spacing was equivalent to tenon width. Increasing the tenon width, similar to increasing the spacing between dowels, is the most effective means for increasing the strength of a mortise and tenon joint. Depth of insertion and tenon length are also important. In chair construction, maximum joint strength is achieved by inserting the tenon to within 0.20 in. of the opposite surface of a continuous cross-member, such as the back leg of a chair. Where the cross-member ends at the tenon (where a chair rail connects to the front chair leg), extending the tenon too far through the leg may invite splitting (Sparkes 1970).

These factors and many other factors in the design of solid wood and particleboard assembly joints are discussed in Eckelman's (1989) extensive review of the world literature relating to various types of assembly joints.

C. Stability and Related Criteria

Adhesive Stability

Wood adhesives are often classified according to the stability of their strength in various service environments. Physical stability is the resistance of a material to the temporary or reversible environmental effects (temperature, moisture, or stress). Chemical stability is the resistance of a material to permanent or irreversible environmental effects. We will use the terms *durability* for physical stability

and *permanence* for chemical stability. In terms of wood adhesive performance, adhesive stability may be defined as

Durable : Stronger, more rigid than wood, more stable under reversible environmental effects.
Nondurable : Weaker, less rigid than wood, less stable under reversible environmental effects.
Permanent: More stable than wood under irreversible environmental effects.
Nonpermanent : Less stable than wood under irreversible environmental effects

Figure 1.50 illustrates the relationships between these types of performance and the performance of wood. These relationships provide a system for categorizing adhesives according to their strength and resistance to the environment, which was first suggested by

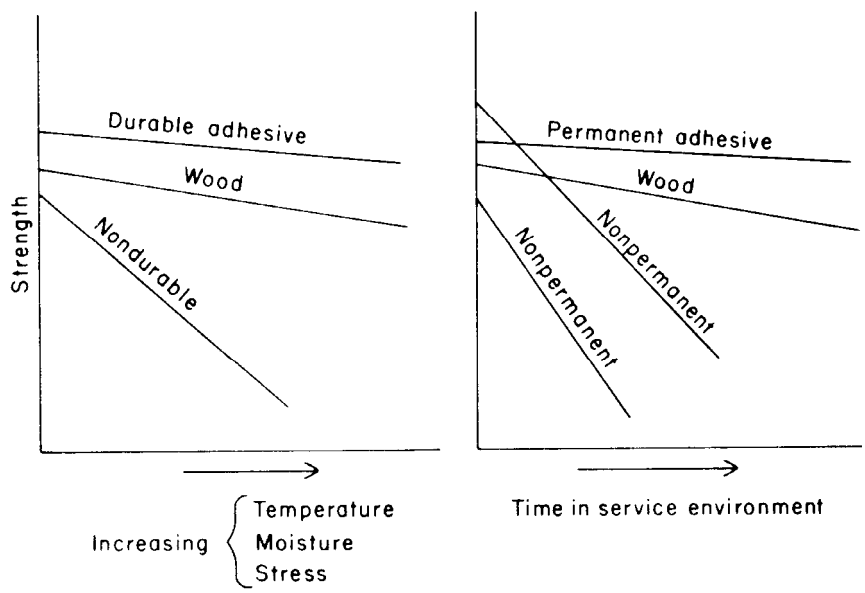


Figure 1.50 Illustration of durable and nondurable and permanent and nonpermanent behavior of adhesives in comparison to the behavior of wood.

Kreibich (1981). By this system, the common wood adhesives are classified as follows :

Durable/permanent	Resorcinol-formaldehyde Phenol-formaldehyde Phenol-resorcinol-formaldehyde Melamine-formaldehyde Isocyanate Epoxy Emulsion-polymer-isocyanate
Durable/nonpermanent	Epoxy Emulsion-polymer-isocyanate Cross-linking poly(vinyl acetate) Melamine-urea-formaldehyde Urea-formaldehyde
Nondurable/permanent	Casein Poly(vinyl acetate) Rubber or synthetic elastomer based
Nondurable/nonpermanent	Hot melt Rubber or synthetic elastomer based

Epoxy and emulsion-polymer-isocyanate are included in two categories. Although all adhesive properties are subject to some variability depending on how they are formulated and how the bonds are prepared, these particular adhesives are subject to widely varying properties based on user discretion. Rubber and synthetic elastomer-based adhesives, such as construction mastics and contact adhesives, are subject to extremely wide variation in the manufacturer's choice of elastomer, additives, and compounding procedures, which strongly affect permanence.

Durability. The initial quality of bonded joints or products is usually determined by a strength test or a determination of the percentage of wood failure. These tests are conducted on dry or wet specimens. The level considered to indicate satisfactory initial bond quality may be an in-house standard or it may be prescribed in a published product standard. Many standards listed in the Appendix (Tables 1.20 and 1.21) prescribe lower limits for strength and percentage of wood failure as proof of bond quality. The use of elevated water or temperature levels in some standards also screens the durability characteristics of the adhesive and the adhesive bond.

The environment, particularly temperature and moisture, strongly affects the adhesive and the properties of the wood. As described

in previous sections, an increase in the moisture content of wood from 6% (oven-dry weight basis) to water-soaked will decrease the shear strength parallel to the grain by 30-60% and decrease the tensile strength perpendicular to the grain by 0-65%. The amount of strength reduction is species dependent, and in fact, the tensile strength perpendicular to the grain of a few species actually increases with increasing moisture content. Temperature has little effect on strength in the range from -50 to 20°C. However, an increase from 20 to 50°C decreases shear strength and shear modulus parallel to the grain by 25% and tensile strength perpendicular to the grain by 10-30%, depending on the moisture content. The strength and stiffness of a material may return to their original levels when conditions return to normal, as long as fracture has not occurred, or if the yield point of the material has not been exceeded.

This behavior is illustrated in the effects of swelling and shrinking stress of ponderosa pine and hard maple shear-block specimens on the strength of four adhesives shown in Figure 1.51 (Gillespie 1976). The wood was conditioned at 27°C and 65% RH (moisture content about 10-11% EMC) before bonding. After bonding, the specimens were divided into four groups-two groups for swelling tests and two for shrinking tests. The two groups for swelling tests were soaked (moisture content greater than 30% EMC). One of these groups was tested; the other group was reequilibrated at 27°C and 65% RH (about 12% EMC) and then tested. The two groups of specimens for shrinking tests were treated similarly except that they were dried instead of soaked.

A dense wood like hard maple, with a high swell-shrink coefficient and high modulus, produces a greater nonrecoverable effect upon adhesives and joint strength than does a lower density wood like ponderosa pine. This can be seen by comparing the magnitudes of the strength reductions for pine (Figure 1.51a) and maple (Figure 1.51b). Figure 1.51 also shows differences in the abilities of semirigid and rigid adhesives to accommodate the swelling and shrinking stresses of the two different types of wood and to recover strength when restored to the original conditions at bonding. In response to swelling of pine (Figure 1.51a), all adhesives with the exception of uncatalyzed poly(vinyl acetate) recovered virtually all their strength after soaking. In the pine, strength loss caused by shrinkage stress was minimal and the wood for all practical purposes completely recovered. Hard maple adherends (Figure 1.51b) have a higher swell-shrink coefficient and modulus than ponderosa pine. In this case, both the poly(vinyl acetate) adhesives and the gap-filling phenol-resorcinol-formaldehyde (PRF) adhesives withstood the shrinkage stress and recovered completely upon return to the original bonding conditions. However, joints

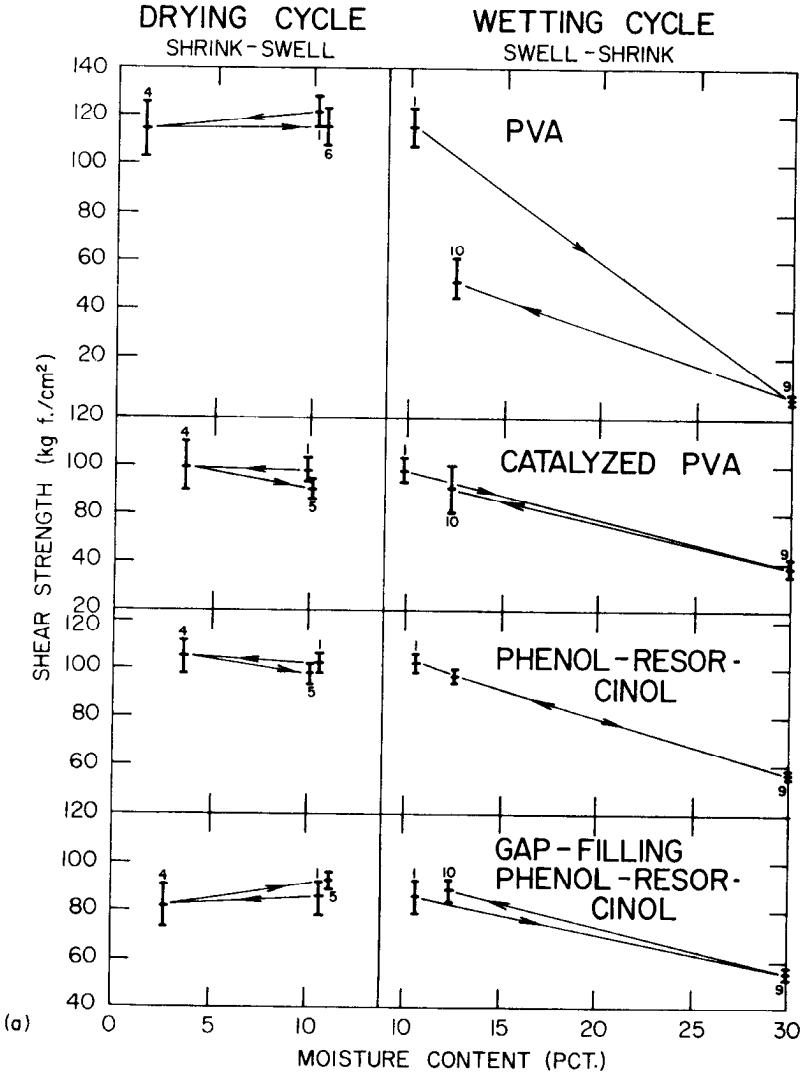


Figure 1.51 Recoverable and nonrecoverable effects of internal stress on joint strength: (a) ponderosa pine joints showing shrinkage effects on the left and swelling effects on the right.

formed by the more brittle conventional PRF adhesive suffered a permanent loss in strength as a result of shrinkage stress. In this case, the wood near the bondline may have been damaged

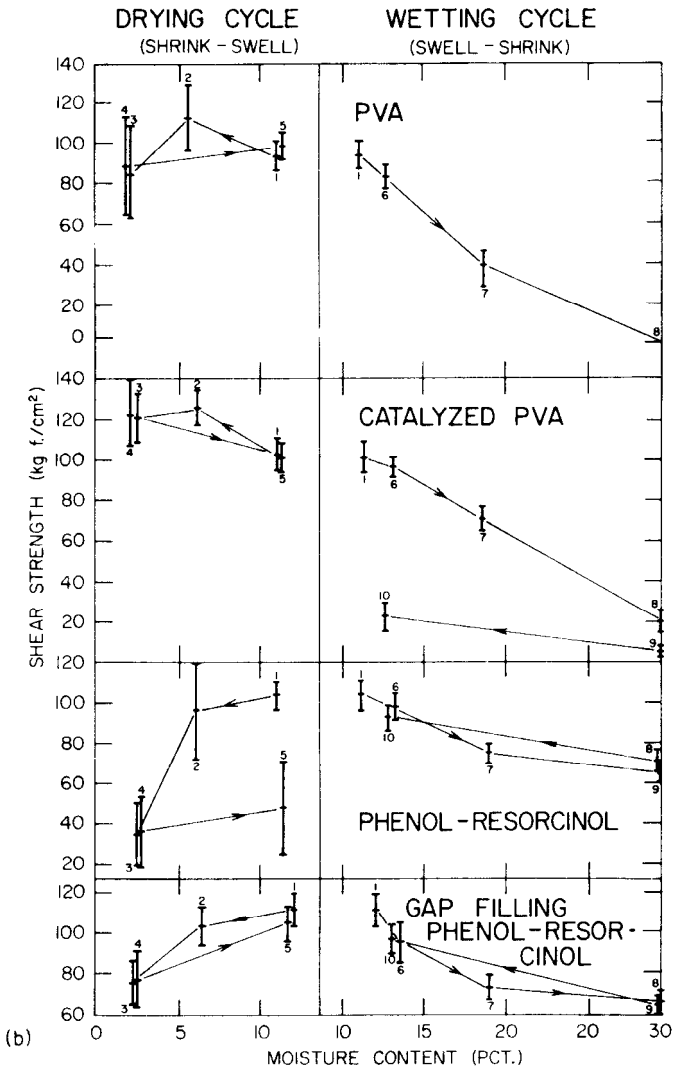


Figure 1.51 (Continued.) (b) Hard maple joints showing shrinkage effects on the left and swelling effects on the right.

rather than the adhesive. Swelling stress generated by the maple specimens destroyed or substantially weakened the two poly(vinyl acetate) adhesives, but the strength loss of both types of PRF

joints was largely recoverable (Figure 1.51b). Similar behavior by bonded joints or adhesive films has been observed in several studies (Heim, Knauss, and Seutter 1922; Tellman, Kutscha, and Soper 1967; Irle and Bolton 1988; Sakuno and Goto 1982, 1983).

Heim, Knauss, and Seutter (1922) considered the effect of internal stress on the strength of bonded joints of nine hardwood species with moderately high density. The sources of stress were (1) difference in moisture content of adherends at time of bonding, (2) uniform moisture content change in adherends of unequal density after bonding, and (3) uniform moisture content change in joint formed of a plain-sawn adherend and a quarter-sawn adherend after bonding. When the strength of bonded joints is reduced by internal stress caused by a moisture content shift (other variables eliminated), the strength initially drops but then recovers over time if the moisture content remains constant at the new level. Once the two adherends equilibrate at the new moisture content level, they will be equally affected by subsequent moisture content changes. However, strength loss caused by differential shrinkage as a result of differences in density or the plane of cut (quarter-sawn compared to flat-sawn lumber) will likely reoccur with subsequent moisture content shifts (Heim, Knauss, and Seutter 1922; Sanborn 1945).

As noted earlier, the relationship between adhesive properties and temperature, moisture, and stress levels is important in selecting an adhesive and in designing the joint or structure. The designer must know what strength or stiffness to expect of the joint or product if it becomes wet or is heated above normal temperature.

The effects of moisture change after bonding upon the strength of joints formed by various types of durable and nondurable adhesives are summarized in Figure 1.52. In the case of durable adhesives (UF, PRF, gap-filling PRF, XPVA), an increase in moisture content causes an assembly of unlike materials to deform visibly but the strength is controlled by the moisture-strength relationship of the wood. A decrease in moisture content increases the strength of the wood and the strength of bonded joints if shrinkage is unrestrained. However, moisture loss causes shrinkage, and if the design of the joint or structure restrains shrinkage, significant internal stresses develop. The wood may even crack; even if it does not crack, the internal stress will reduce the apparent strength of durable adhesive joints (Figure 1.52, UF, PRF). In effect, if shrinkage is restrained, internal stress lowers the strength of the joint below the level expected from the moisture-strength relationship of the wood (Gillespie 1976).

In the case of nondurable adhesives (epoxy, PVA, casein), an increase in moisture content will cause less deformation of a bonded product of unlike materials than occurs with a durable adhesive; as

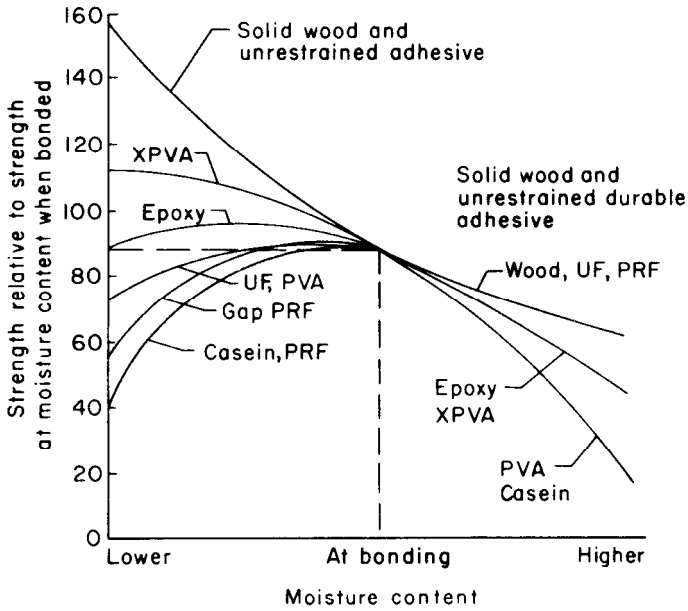


Figure 1.52 Schematic of the effect of moisture content on wood and joints bonded with various adhesives.

the adhesive absorbs moisture, it becomes less rigid and more deformable. Strength is controlled by the strength-moisture relationship of the adhesive (Figure 1.52, epoxy, UF, PRF). A decrease in moisture may actually have less effect on strength than is the case with a durable adhesive because the nondurable adhesive can deform to relieve some internal stresses without fracturing (Figure 1.52, compare XPVA and epoxy against UF, PRF, and gap-filling PRF).

Permanence. All organic materials deteriorate or age according to their inherent structure and the surrounding environment. The rate of deterioration may vary with time. A permanent adhesive, joint, or product shows no greater deterioration during its life in the service environment than does solid wood of the same species.

Many adhesives and bonded products have decades of documented performance in many environments. Assuming that the adhesive is used properly, the long-term performance of similar products can be predicted with some certainty. For example,

well-designed joints made with any commonly used woodworking adhesive, including animal glue and poly(vinyl acetate), will retain their strength indefinitely if the moisture content of the wood does not exceed approximately 15% and the temperature remains within the range of human comfort. However, some adhesives deteriorate when exposed either intermittently or continuously to temperatures much above 100°F for long periods.

Low temperatures (down to about -65°C) seem to have no significant effect on strength of bonded joints with phenol-formaldehyde, urea-melamine-formaldehyde, cross-linked poly(vinyl acetate), and casein adhesives. In tests of saturated specimens, specimens bonded with urea-formaldehyde and phenol-resorcinol-formaldehyde were initially stronger than solid wood specimens and specimens bonded with phenol-formaldehyde, urea-melamine-formaldehyde, and cross-linked poly(vinyl acetate) and casein. The urea-formaldehyde and phenol-resorcinol-formaldehyde adhesives lost considerable strength when subjected to alternating ambient subzero exposure. The solid wood specimens and specimens bonded with phenol-formaldehyde, urea-melamine-formaldehyde, and cross-linked poly-(vinyl acetate) did not lose strength (Steiner and Chow 1975). The authors suggest the greater sensitivity of the specimens bonded with urea-formaldehyde and phenol-resorcinol-formaldehyde was due to their greater rigidity.

Joints and products that are well made with phenol-formaldehyde, resorcinol-formaldehyde, or phenol-resorcinol-formaldehyde adhesives have proved more permanent than wood when exposed to warmth and high humidity, water, alternate wetting and drying, and temperatures sufficiently high to char the wood. These adhesives are adequate for use in products that are exposed indefinitely to the weather (Figure 1.53).

Joints and products bonded with melamine- formaldehyde, melamine-urea-formaldehyde, and urea-formaldehyde adhesives, though well made, have proven less permanent than wood. Melamine-formaldehyde when properly cured is only slightly less durable than phenol-formaldehyde or resorcinol-formaldehyde, and it is still considered acceptable for structural products. Melamine-urea-formaldehyde is significantly less durable than these adhesives, and urea-formaldehyde is quite susceptible to degradation by heat and moisture and shrinkage stresses in weathering (Figure 1.53).

Joints or products bonded with nondurable adhesives, like poly-(vinyl acetate), hot-melt adhesives, and natural resins, will not withstand prolonged exposure to water or high moisture content, or repeated high-low moisture content cycling in joints between adherends of high-density woods. However, if properly formulated, these adhesives are permanent in a dry environment. Examples of

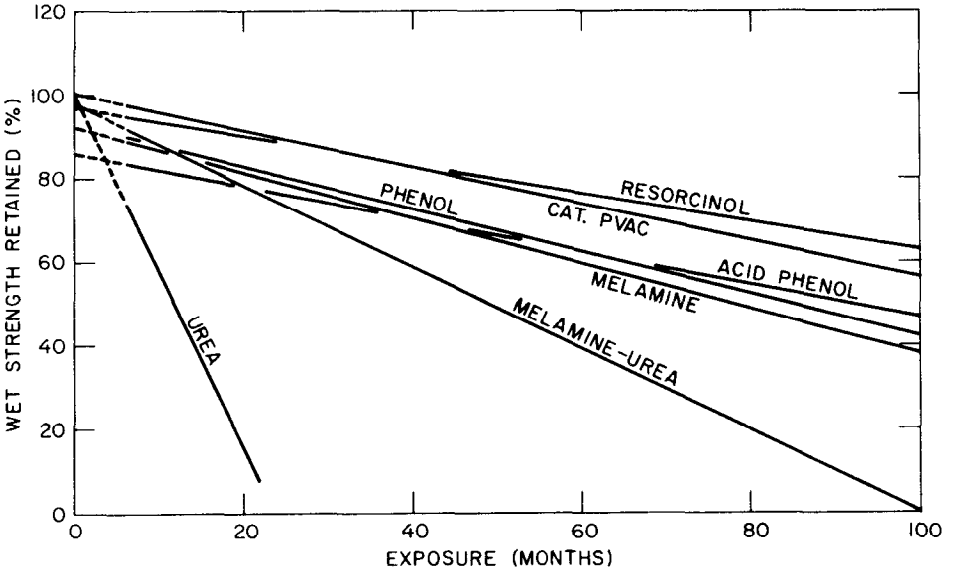


Figure 1.53 Comparison of the permanence of common wood adhesives in yellow birch (ASTM 1989g) plywood shear specimens in full outdoor exposure.

such permanence are found in the intact veneered artifacts from ancient Egyptian tombs (Knight and Wulpi 1927).

At present, some isocyanate, epoxy, cross-linked poly(vinyl acetate), and emulsion-polymer-isocyanate adhesives may be sufficiently permanent to use on lower density species under exterior conditions. Some elastomer-based adhesives may be sufficiently permanent for protected exterior use with lower-density species in nonstructural applications, or in semistructural applications when used in conjunction with approved nailing schedules, or even in structural applications in properly designed joints (Krueger and Sandberg 1979, Hoyle 1976). Those adhesives that cure chemically but still remain flexible seem the most permanent.

These conclusions generalize adhesive performance by generic type. Individual formulations of a given type of adhesive may vary greatly depending on manufacturing and use variables, and on the wood or other materials that are bonded. The performance of new adhesives or new materials, or combinations of materials,

even when made with well-established adhesives, is always subject to suspicion until proven in actual service. The reason for suspicion is that numerous interactions can occur between the physical and chemical characteristics of the wood, the type of adhesive, and the environment.

Certain adhesives such as urea-formaldehyde are more affected by cyclic bondline stress than are other adhesives. Dense woods, as discussed previously, can be expected to increase the rate of degradation in cyclic conditions as a result of the greater stress placed on the bondline. The shrinkage stresses developed by dense woods bonded with stronger, crack-resistant adhesives like phenol-resorcinol-formaldehyde degrade the wood more than the bondline (Figure 1.54).

Each species of wood has its own chemical characteristics. Wosparkik (1984) studied the effects of several wood characteristics, including extractive content, total acid content, pH, acid buffering capacity, and soluble acid content, in varous constant dry- or wet-aging and cyclic aging treatments upon joints formed by various adhesives. The results revealed numerous interactions between these characteristics and the type of accelerated test. Acidic woods and adhesives can be expected to increase the rate of hydrolysis of the wood itself, and particularly of hydrolysis-sensitive adhesives like urea- and melamine-formaldehyde. Urea-formaldehyde is extremely sensitive to acidity and buffering capacity in moist environments. Adhesives like epoxy and isocyanate are insensitive to the acidic characteristics of the wood.

Dimensional Stability

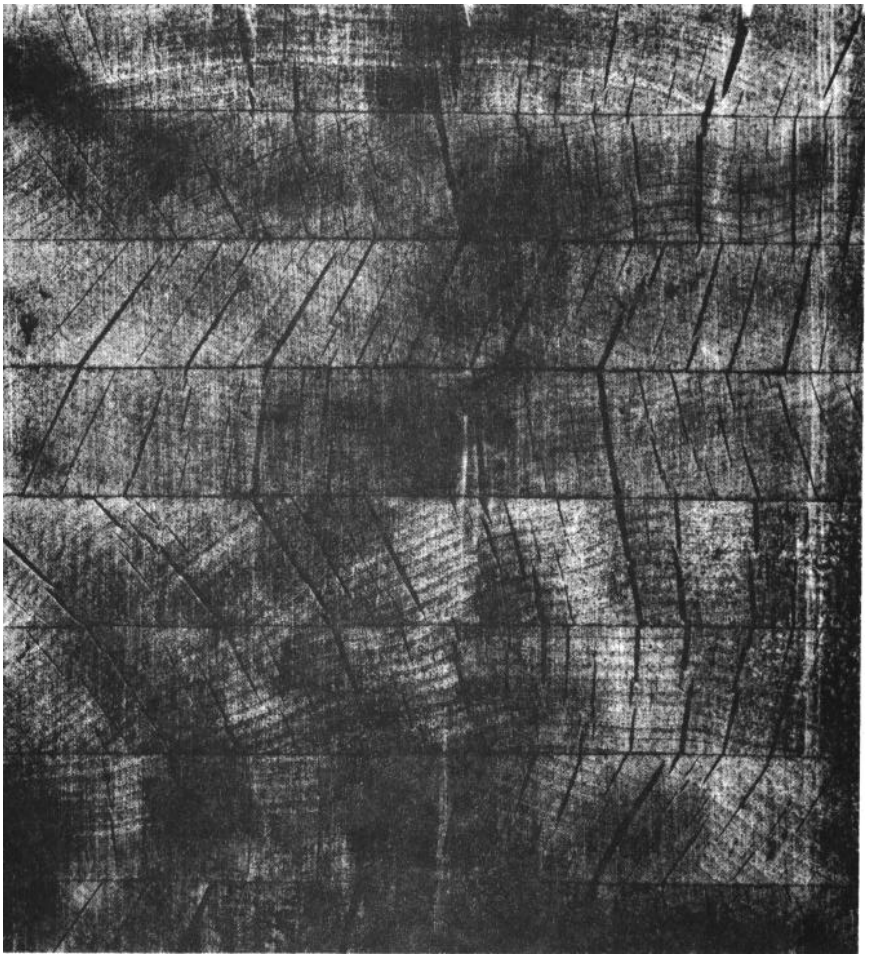
The shape and appearance of the bonded product or structure are an extremely important performance criterion in bonded products like furniture. Unacceptable changes in shape or appearance are common and sometimes difficult to analyze and control. Dimensional instability is seldom caused directly by the adhesive, but rather indirectly by the rigidity of the adhesive connection. As discussed previously, a flexible adhesive can sometimes minimize dimensional instability by relieving the internal stresses that cause warping or distortion, but other factors are far more powerful. More often, unacceptable dimensional changes are caused by a combination of (1) poor design of the bonded material or structure, (2) failure to control the properties of the wood or wood-based materials, and (3) failure to control the moisture condition of the individual pieces when they are locked together by the adhesive.

Design. Proper design can accommodate much of the inevitable and nonuniform dimensional changes of wood. The choice of wood

or wood-based material or plane of cut controls to a great degree the dimensional stability. And finally, selecting the proper moisture content for the intended service environment and assurance of uniform moisture content among individual members at the time of bonding is critical not only to dimensional stability but also to the strength of the bond.

1. Balanced design. Balanced design applies to reconstituted wood panels, composite panels formed of wood and other panel materials, and even laminated lumber. This term means that the panel or laminate must be symmetric about the center line of the panel. or, as shown in Figure 1.55, that A = E and B = D. Symmetry goes beyond thickness. It includes the species of wood or type of material and all the attendant mechanical properties, especially the swell-shrink coefficient and modulus (Figure 1.45f-j). The simplest way to balance the design is to use the same material, grain direction, and thickness on both sides of the center line. A more flexible but complicated technique that uses different materials requires knowledge of the material properties to determine the weighted swelling and shrinking of individual plies (Forest Products Laboratory 1978).

   In plywood, moisture imbalance (Figure 1.45b,f) and grain direction deviations (Figure 1.45h,j) are among the common causes of warping (Forest Products Laboratory 1966). In kitchen countertops, a high-pressure laminate bonded to the top surface only, creates an imbalance in swell-shrink coefficients of the outer portions of the countertop and also in the rate of moisture content change (Figure 1.45e) (Heebink 1960). In laminated door stiles, imbalance is caused by laminating strips of lumber with different swell-shrink coefficients of moisture contents (Figure 1.45c,f). In furniture panels, imbalance can be caused by grooving one side of an otherwise balanced panel. Imbalance can also occur even if the face and back laminae have exactly the same mechanical and physical properties if the laminae are stored and bonded at different EMCs (Figure 1.45b). When the face and back reach a common EMC after bonding, they will have different levels of internal stress, which cause the panel or laminate to warp. These are a few examples of the types of problems arising from faiure to consider material properties in the design of bonded wood panels and materials.
2. Minimizing and averaging. Tangentially sawn (flat-sawn) boards warp more than radially sawn (quarter-sawn) boards; they tend to cup (become concave) on the side toward the outside of the log, and wide tangentially sawn boards warp more than narrow tangentially sawn boards. Lumber panels made from narrow tangentially sawn boards alternating with the growth rings up

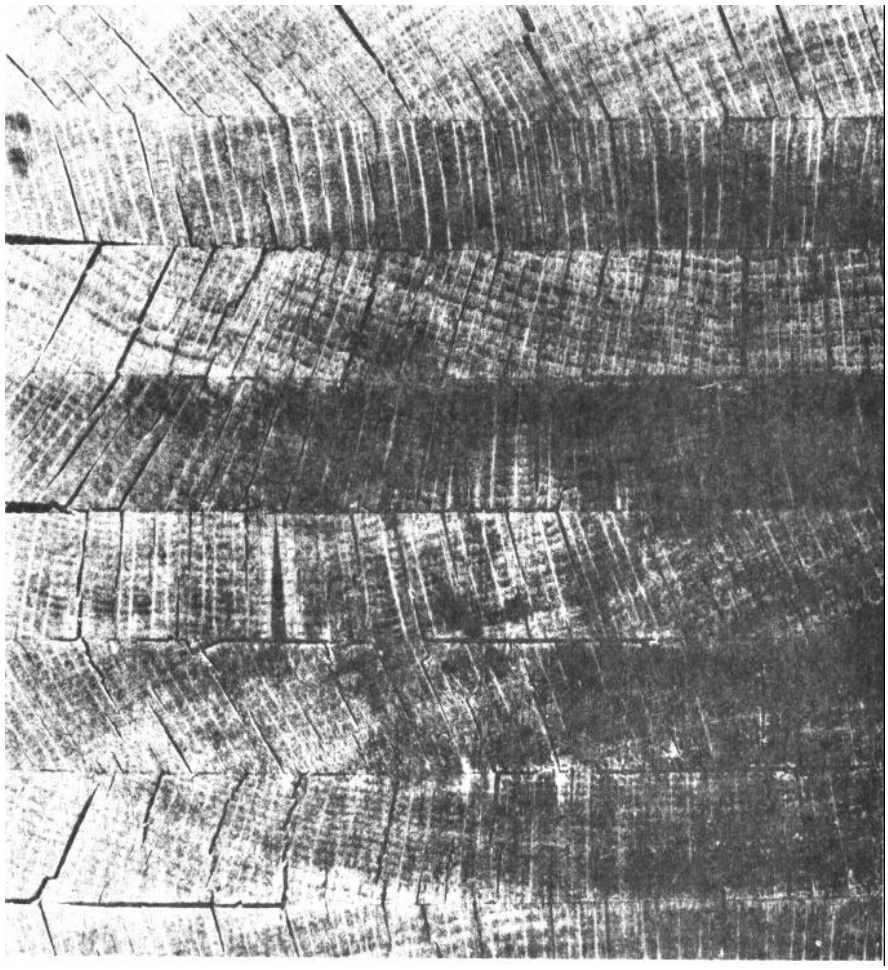


(a)

Figure 1.54 Laminated oak beam end sections showing adhesive bondlines more resistant to cracking under shrinkage stress than the wood (a) and less resistant (b).

and down (Figure 1.56) will warp considerably less than a panel made with wide tangentially sawn boards, or narrow tangentially sawn boards whose growth rings are all aligned in the same direction.

3. Sorting and selecting. Warp, sunken boards, and telegraphing in furniture panels can be minimized by sorting and selecting



(b)

Figure 1.54 (Continued).

lumber to eliminate mixing tangentially sawn and radially sawn boards, boards of different species, or boards with different moisture contents from occurring in the same panel.

4. Free movement. When movement cannot be restrained by balanced design or minimizing and averaging, the design must allow free swelling and shrinking within the limits expected in service. Some examples of products that require free movement

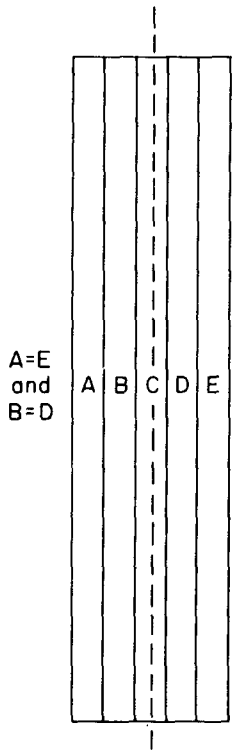


Figure 1.55 Five-layer panel showing symmetry and balanced construction.

are tabletops, end-banded lumber panels, and floating, raised-panel doors. The frame of the floating-panel door is quite stable in width and length because most of each dimension is comprised of longitudinal grain with its attendant low swell-shrink coefficient. However, the panel enclosed by the frame has a large dimension across the grain, and it swells and shrinks considerably in that direction. Proper design prohibits bonding the panel to the frame and, in fact, allows room for the panel to move freely within the frame.

By contrast, a poor design leads to dimensional instability. For example, if lumber stiffeners are bonded to the underside of an edge-glued lumber tabletop or if the top is bonded to the apron of the table, warp can develop. A tabletop has a very large dimension across the grain, in the direction of maximum

Figure 1.56 Method of alternating growth ring orientation in narrow boards to minimize warping of an edge-bonded panel.

swelling and shrinking. Restraining one side by bonding it to a rigid cross-member will surely cause the top to warp or crack. Tabletops and other wide members must be held in place with fasteners that will allow free movement with changing moisture content.

Swell-Shrink Coefficient. When a choice is possible, it is better to choose the wood species, plane of cut, or material with the lowest swell-shrink coefficient because moisture content changes and thus dimensional changes in service are inevitable. The smaller the dimensional change of a wood material for a given unit of moisture content change, the more stable the final product. Referring to Table 1.18, which shows the percentage of linear change that accompanies a change in relative humidity from 30 to 90%, a glued panel or structure of radially sawn black tupelo (linear change of 2.5%) will be more dimensionally stable than a panel of tangentially sawn hard maple (linear change of 4.9%).

Factors other than the swell-shrink coefficient of the wood species affect the swell-shrink behavior of the reconstituted material. For example, the thickness swelling and shrinking of veneer or reconstituted panel products such as plywood, particleboard, and flakeboard are controlled by factors that lead to compression set during bonding and springback forces after removal from the press. Among these factors are the particle configuration, moisture content of the particles at pressing, temperature at pressing, and resin content. Plywood and flakeboard are slightly less stable than solid wood of the same species along the grain, but far more stable than solid wood across the grain. The linear expansion and contraction of various types of plywood and reconstituted panel materials relative to each other and to solid wood varies with the number and arrangement of the plies in plywood, and with the flake or particle geometry and orientation, presence or absence of layering, number of layers, and resin content in particleboards and flakeboards. Particleboards and flakeboards with randomly oriented particles have approximately the same linear swell-shrink coefficient in all directions, parallel to the plane of the board. Oriented strandboard with three to five aligned layers swells more across the panel than does

plywood or flakeboard and less along the panel than does flakeboard (Table 1.18). In the examples given in Table 1.18, the waferboard (0.07-0.15% linear expansion) is less dimensionally stable than plywood (< 0.02%), but in turn more stable than medium density fiberboard (0.35-0.62%). These are but a few examples of how the wood species and panel construction and manufacture can affect the dimensional stability of the bonded products and structures.

Tables of shrinkage coefficients for additional solid wood species are given in the Wood Handbook (Forest Products Laboratory 1987). Additional information on the dimensional stability of various types of reconstituted panels may be found in Suchsland (1972), Hse (1975), and Lehmann and Hefty (1973). Suchsland and McNatt (1985, 1986) presented an excellent treatise on how these and other factors lead to unacceptable dimensional stability of laminated wood panels.

D. Appearance

Discoloration

The chemicals that constitute an adhesive, such as the resin, solvents, plasticizers, antioxidants, and fillers, may interact with the wood or with the finish or coating to produce a color change that is unacceptable to the user. The combination of wood with many new and different materials through adhesive bonding has provided the opportunity for unexpected and unwanted interactions. Two examples are the caustic in phenol-formaldehyde adhesives used for exterior-type structural panels, and certain solvents, antioxidants, and plasticizers used in elastomeric-based adhesives.

The caustic is thought to contribute to the excellent durability of panels bonded with phenol-formaldehyde adhesive by acting as a plasticizer for both the wood and the adhesive. However, it has several unwanted side effects. First, a panel made with an alkaline phenol-formaldehyde adhesive is more hygroscopic, thus worsening the already excessive swelling of flakeboard panels. Second, the caustic may migrate to the surface of an exposed panel, causing a brown discoloration on white painted surfaces and white discoloration on dark surfaces. Third, the caustic may dissolve certain paints and finishes (Sell 1978).

Solvents, plasticizers, and antioxidants used in plywood patching compounds and construction adhesives have the ability to migrate from the adhesive or patching compound into adjacent materials. When such chemicals migrate into decorative vinyl floor and wall coverings, they discolor the vinyl material when it is exposed to ultraviolet light. Little is known about the exact mechanism of the discoloration.

Visible Joints

Visible joints are those that contrast with the adjoining wood. This problem is usually associated with the visible edges of the bondlines in stained products or products finished with a transparent coating. The contrast may be between a light-colored wood and a dark adhesive, or between a dark wood and a light-colored adhesive. Contrast may also be caused by the shadow cast by a bondline that is out of the plane of the wood surface.

In the first case, dark adhesives such as phenol-formaldehyde and resorcinol-formaldehyde must sometimes be used to obtain high durability and permanence. The only solution to the problem of visible joints is to hide the contrast by applying a dark stain or painting the surface. The user has several other choices when the highest durability and permanence are not required. Melamine-formaldehyde, melamine-urea-formaldehyde, cross-linked poly(vinyl acetate), and isocyanate cross-linked emulsion polymer adhesives are light colored and are capable of highly durable and permanent bonds.

The second case of visible joints, that of dark wood and a light bondline, is usually encountered with dark furniture woods or wood covered with a dark stain. The adhesive does not absorb the stain or finish to the same extent as the wood and therefore creates a contrast that is evident in finished furniture, especially tabletops. The finish solvent system may be incompatible with the adhesive. Certain solvent systems may partially dissolve non-cross-linked adhesives, such as poly(vinyl acetate), which are widely used in furniture manufacture. The adhesive bond may be destroyed at the surface, leaving the bondline as a trough, or swelling of the adhesive may create a ridge at the bondline. Either defect is clearly visible on a glossy furniture surface.

The third case of visible joints, which is similar to the last example, is called a sunken bondline. For example, a sunken bondline can be caused by machining too soon after bonding. During bonding, the wood in contact with the wet adhesive absorbs water from the adhesive. Although only a small amount of water is absorbed, the water causes the wood on either side of the adhesive layer to swell. Eventually, the water dissipates further into the wood and finally into the air, but this may take several hours. If under the pressures of production the surface is unwisely planed before the moisture dissipates, then the wood immediately adjacent to the adhesive layer will shrink after planing, leaving a trough at the bondline. Sunken bondlines are very evident on a glossy tabletop, but they may become visible only after the finish is applied.

E. Performance Evaluation

Adhesives and adhesively bonded joints and materials are subjected to many forces that cause degradation: water and water vapor, heat, cyclic internal stress, static and dynamic external loads, microorganisms, air pollutants, and ultraviolet light. The intensity of each force varies in a given service environment, creating an infinite variety of degradation processes. These forces may interact with an enhanced negative effect on a bonded joint. Moreover, each adhesive responds differently to each force. Under such circumstances, it is understandable that no laboratory exposure treatment has yet been developed that will predict the behavior of even a single product in more than one limited environment. Nor is it likely that such a test will ever be developed (Gressel 1986).

The safest path for evaluating the performance of a new adhesive or bonded material has three steps:

1. Establish the ultimate strength and durability of the adhesive.
2. Establish the permanence of the adhesively bonded joint or material made with commercial adherends.
3. Develop the range of permissible bonding conditions for quality control.

Plans for broad-scale testing programs such as this have been suggested by several researchers (Sell 1978; Millett, Gillespie, and River 1977; Krueger and Sandberg 1979; Caster 1983).

Bond Strength and Durability

The durability of adhesives-that is, the resistance of an adhesive to the reversible effects of heat and moisture-is normally evaluated by a simple shear or tension test of small specimens. The specimens are conditioned to equilibrium under the required temperature and moisture conditions and then tested immediately. Often, the selected temperatures are those reported for various interior or exterior portions of buildings in service. For example, although roof surfaces may reach 160°F or higher, the wood moisture content will be low in a roof exposure. The strength and the amount of wood failure on the failed surface determined from these tests are often compared to some internal or published standard for acceptable performance. High strength and high percentage of wood failure suggest that a bonded joint is able to withstand the swelling and shrinkage stresses exerted by the wood adherends in service. However, strength and wood failure of dry or wet unaged specimens are not in themselves sufficient evidence of adhesive bond permanence.

Bond Permanence

Permanence is measured by the loss or rate of loss of some property, usually a mechanical property, against the time or number of treatment cycles of an accelerated laboratory or outdoor exposure. The time- or cycle-dependent changes may be chemical or mechanical. New adhesives or products, even products made with adhesives of proven permanence, do not have a history of long-term performance in service environments and can vary in permanence according to the bonding procedure described earlier. For the sake of economics, an estimate of their permanence is usually required in the shortest possible time. Many accelerated-aging tests have been developed to help make these estimates, but no single treatment or test method has been proven to definitively predict service life in every environment. There are simply too many variables to contend with. The treatments and tests that have proven most useful fall into two categories: single-test comparative methods and multiple-test rate methods.

Comparative Methods. Comparative methods usually compare the performance of an unknown adhesive or bonded product against that of a well-known adhesive or product, or against some industry-accepted standard. Both the unknown and the known specimens are usually subjected to severe swelling and shrinkage stresses, and possibly to a thermal or chemical stress before testing. Comparative methods have been used at least since the very earliest days of this century, but especially since the development of durable and permanent synthetic resin adhesives.

Over the last 50 years, the percentage of wood failure in plywood tensile shear specimens after a cyclic boil-dry-boil treatment (U.S. Department of Commerce 1983) has been proven to adequately indicate the weathering resistance of North American softwood plywood bonded with phenol-formaldehyde adhesive (Figure 1.57) (Perkins 1950, Findley 1964). Raymond (1976) pointed out, however, that although the test is fast, it is not applicable without recalibration for a new adhesive or veneer. For example, the test did not predict the poor weathering resistance of plywood made with a blood-extended phenol-formaldehyde adhesive (Perkins 1950). The blood-extended phenol-formaldehyde adhesive may have been attacked by microorganisms in service that could not be predicted by the boil-dry-boil wood failure criteria for permanence. Nor did the boil-dry-boil wood failure criteria accurately predict the poor performance of phenol-formaldehyde adhesive bonds in plywood made with face veneers of certain tropical species (Wilkie and Wellons 1978).

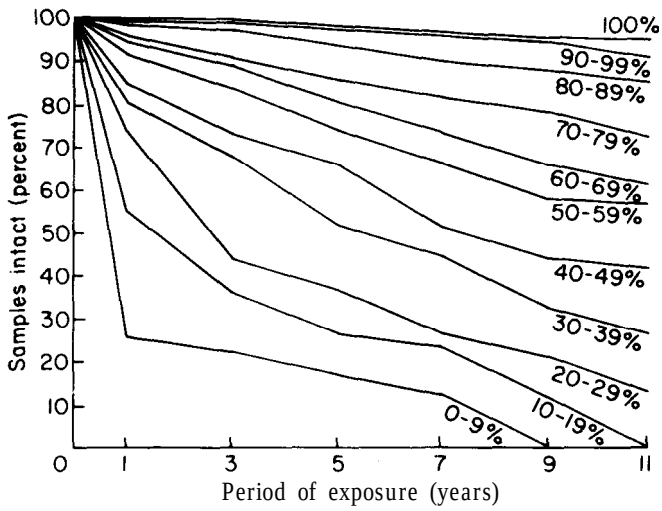


Figure 1.57 Plywood panel durability (percentage of panels not showing delamination) as a function of outdoor exposure time. Individual curves represent the amount of wood failure in small plywood shear test specimens that were soaked, dried, and tested before outdoor exposure of larger panel (after Perkins 1950).

Truax and Selbo (1948) found that the amount of delamination of small beam sections under cyclic soaking and drying treatment correlated with the delamination of laminated timbers in outdoor exposure. Those results formed the basis for evaluating the suitability of adhesives for structural timbers for exterior use (ASTM 1989c). Interestingly, the original 180-day test has been shortened over the years (by using more stressful conditions) to the point where it now can be completed in 1-3 days (Selbo 1964, ASTM 1989e). Two other widely used comparative tests that exemplify the cyclic soak-dry and boil-dry-boil treatments are the ASTM D 1037 (ASTM 1989b) and French V313 tests (AFNOR 1979).

The ASTM D 1037 and French V313 tests have a long history of satisfactory service against which to judge the efficacy of the comparative test. Notwithstanding this lengthy historical record, researchers generally agree that these tests will sort the best adhesive from the worst and will even correlate the durability of a group of known adhesives with. a given outdoor environment, Unfortunately, whether this correlation translates to some other adhesive, wood product, or environment is always questionable. Furthermore,

a high percentage of wood failure considered regardless of the attendent joint strength can be misleading. Biological, physical, or chemical damage to the wood may not be evident to the evaluator. Such damage will ensure a high percentage of wood failure, but it will severely reduce the permanence of the joint regardless of the adhesive bond quality. This subject is discussed more fully in Section III.

Rate Methods. The rate of chemical or mechanical degradation usually varies with time. Comparative methods only provide an indication of performance at one instant in time. Nothing is learned of the degradation rate before or after that time. For additional time and money, rate methods provide insight into mechanism and time effects of the degradation process. They also can be used in comparison tests of unknown and known materials, and they have some predictive capabilities. Three different rate methods developed in recent years are the rate-process method (Gillespie 1965), the automatic boil test (Caster and Kulenkamp 1976), and the XENOTEST (Deppe 1981).

The rate-process method measures the thermal and chemical aging resistance of a wood-adhesive system in the absence of stress. First, the degradation rate is determined at several elevated, constant temperatures. Second, the relationship of rate to temperature is determined (Gillespie 1965). Third, the rate at normal service temperature is predicted from the relationship determined in step two. The whole process is based on the assumption that the degradation mechanism does not change in the interval. The rate-process method has been used with some success to forecast the service life of a wide variety of woods and adhesives in dry, moist, and wet conditions (Gillespie 1965; Gillespie and River 1976; River 1984; Rodwell 1988; Sasaki, Kaneda, and Maku 1976; Khrulev and Dudnik 1982).

In the rate-process method, treatment times vary from a few hours at the highest temperature to a year at the lowest temperature. Heat accelerates the hydrolytic effect of water. The concentration of water increases the sensitivity of the degradation rate to temperature. Because the rate-process method does not account for the effects of stress, the method is probably most suitable for adhesives that are either quite resistant to cyclic-stress effects or that will be used in a stable environment. Researchers are continuing to develop a theoretical basis for incorporating stress into the rate-process method (Caulfield 1985, Papazian 1983).

The automatic boil test encompasses the major degrading factors of heat, moisture, and stress in a cyclic treatment. Each cycle consists of (1) submersion of specimen in boiling water for 10 min,

(2) drying in circulating air at 23°C for 4 min, and (3) drying in circulating air at 107°C for 57 min. Treatments of permanent adhesives may run for 800 or more cycles, with periodic tests to establish the rate of degradation. The performance of solid wood specimens bonded with several common wood adhesives and exposed to this treatment has been correlated with performance in four outdoor exposures over a 12-year period (Caster 1980). For permanent adhesives, such as phenol-formaldehyde, approximately 41 cycles is the equivalent of 1 year of outdoor aging. Work is continuing to develop a similar correlation for reconstituted wood panel materials (Caster 1986).

The XENOTEST is a weatherometer test method developed in Germany for reconstituted panel products. The test attempts to combine all the major degrading factors, including stress and ultraviolet light, into an accelerated exposure system that uses normal service temperatures and environmental conditions. The rationale is that the results obtained with boil-dry and other harsh treatments depend on the type of adhesive, whereas outdoor exposures are too variable as well as time consuming (Deppe 1975, Sell 1978). The XENOTEST attempts to overcome these problems by accelerating the frequency (although reducing the duration) and the persistence of change rather than by fluctuating temperature and moisture levels. The conditions of the XENOTEST are (1) water spray at 18°C, (2) ultraviolet irradiation and drying at 35°C and 18% relative humidity, and (3) freezing at -12°C. These conditions are repeated but varied in a very detailed series of cycles designed to replicate the climatic conditions of Western Europe. The rates of degradation of coated and uncoated panels exposed outdoors for 3-6 years visually correlate quite well with the rates of degradation over 12-24 weeks of XENOTEST exposure (Deppe 1981).

Estimates of long-term performance in outdoor service are often obtained by placing specimens in outdoor exposure without a protective finish. However, at least 5 years of exposure are necessary to distinguish between adhesives as different in permanence as urea- and phenol-formaldehyde. Outdoor exposures are intensified by using small specimens with a high percentage of edge to surface, by facing the specimens south at an angle perpendicular to the noonday sun, and by exposing the specimens without protective covering or coating.

Wood Selection

The evaluation of adhesive performance has two aspects: (1) determination of the ultimate strength and durability of the adhesive and (2) determination of the adhesive's ability to form a good joint with the commercial substrate and of the permanence of the joint or bonded product.

Ultimate Strength and Durability. In the United States, hard maple and yellow birch have been the traditional substrates for more than 70 years for evaluating the ultimate strength and durability of wood-bonding adhesives. Hard maple lumber is used for the ASTM D 905 shear-block specimens for room-temperature curing adhesives (Figure 1.58a) (ASTM 1989f). Yellow birch veneer is used for ASTM D 2339 two-ply lap-shear specimens (Figure 1.58b) (ASTM 1989h) and, more commonly, for ASTM D 906 plywood shear specimens (Figure 1.58c) (ASTM 1989g) for both cold- and hot-

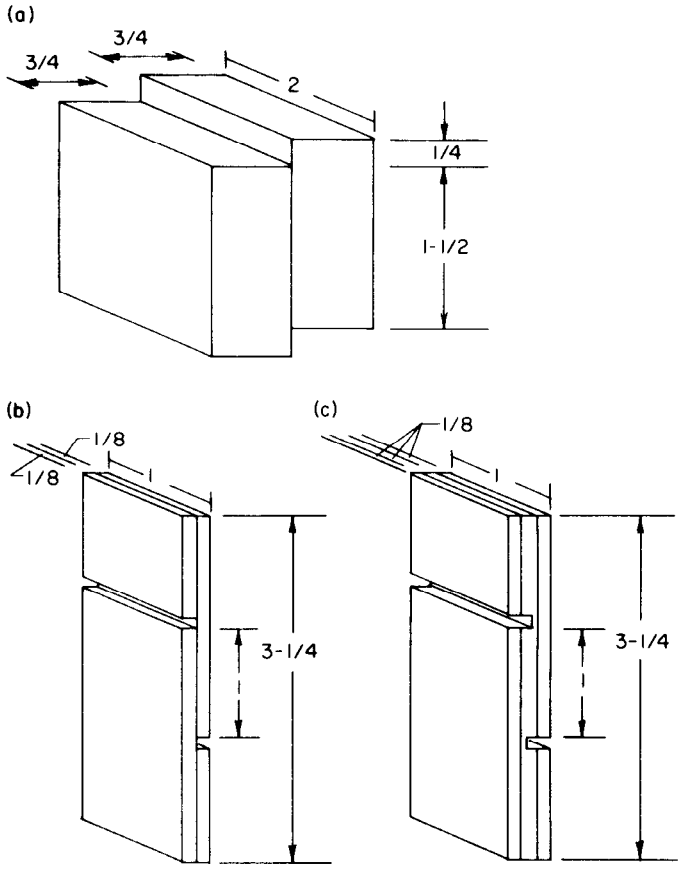


Figure 1.58 Standard adhesive joint strength test specimens: (a) block shear (ASTM 1989f), (b) tensile lap shear (ASTM 1989h), (c) tensile plywood shear (ASTM 1989g).

press-type adhesives. Hard maple is among the most dense and difficult to bond of the North American commercial woods. Average shear stresses as high as 3000-4000 lb/in.^{2} can be applied to the adhesive with ASTM D 905 hard maple specimens. Although yellow birch is similar to hard maple in density, it is slightly weaker in shear strength. We are not sure why yellow birch is used in preference to maple in plywood-type specimens. One reason may be that yellow birch checks less in peeling and produces veneer with better surface quality than does hard maple. Yellow birch ASTM D 906 three-ply specimens made with 1/8-in. veneers are capable of about 700 lb/in.^{2} The ASTM D 2339 two-ply specimens made with 1/8-in. yellow birch veneer and 1/2-in. lap are capable of ≥1500 lb/in.^{2} Because of their high density and swell-shrink coefficients, both hard maple and yellow birch provide an extreme challenge to an adhesive in a soak-dry or boil-dry treatment used for assessing durability and permanence in cyclic conditions. Oak is also frequently used in ASTM D 905 specimens for challenge tests.

The wood pieces selected for strength and durability tests should be equal to or above the average specific gravity for the species, straight-grained, and free of defects such as knots, decay, cross grain, and discolorations. In the case of plywood specimens, veneer should also be free of cracks or severe lathe checks and rough surfaces.

Product Qualification and Permanence. The second approach for evaluating adhesive performance requires selecting a wood that the adhesive will be used with in a commercial product. In this case, the strength and durability characteristics of the adhesive may have previously been established using a tested species and tests described above. The user needs to learn if a given species affects the bond quality and permanence of the adhesive and bond because of the species-peculiar chemical and physical characteristics. In many other commercial products, softwoods and medium-density hardwoods are used. These woods, with some exceptions (like the southern pines), do not present as great a mechanical challenge to the adhesive. Each wood differs in its effect on the ability of the adhesive to form a strong bond. Commercial wood-bonding processes such as plywood and particleboard production are highly tuned to match the adhesive to the chemical and physical properties of the wood that affect the bond-formation process. Testing the processing viability of an adhesive with maple does not assure that the adhesive will be effective with aspen. Extending the idea of testing processibility as a function of ultimate strength and durability of the adhesive is the growing trend to use particulate mixtures of various species in reconstituted wood products. As the

substrate to be bonded becomes more complex, the ability to form a quality bond with permanent qualities must be assessed.

F. Standard Performance Tests and Specifications

Strength and Durability

Examples of test requirements for the ultimate strength and durability of adhesives are found in the following standard specifications:

ASTM D 4689, Standard specification for adhesive, casein-type.
ASTM D 4317, Standard specification for poly(vinyl acetate)-based adhesives.
ASTM D 3498, Standard specification for adhesives for field-gluing plywood to lumber framing for floor systems.

Performance specifications that require strength tests at elevated temperatures or elevated temperature plus humidity include the following :

ASTM D 2559, Standard specification for adhesives for structural laminated wood products for use under exterior (wet-use) exposure conditions.
ASTM D 3110, Standard specification for adhesives used in nonstructural glued lumber products.
PS 1-83, U.S. Product standard for construction and industrial plywood.

The performance requirement is usually a minimum strength value based on the shear strength of the solid wood or a minimum percentage of wood failure (typically between 70 and 85%). These performance standards and others are summarized in the Appendix.

Permanence

Several methods for testing permanence have been standardized in the United States:

ASTM D 1037, Evaluating the properties of wood-base fiber and particle panels (accelerated aging).
ASTM D 3434, Multiple cycle (automatic) boil-dry test.
ASTM D 3632, Oxygen-pressure aging test.
ASTM D 4502, Heat and moisture aging test.
ASTM D 4783, Resistance of adhesive preparations in container to attack by bacteria, yeast, and fungi.

ASTM D 4300, Effect of mold contamination on permanence of adhesive preparations and films.
ASTM D 4680, Creep and time to failure of adhesives in static shear.

Performance levels have been established for interior or exterior exposures in some of these methods or in product specifications that cite the methods. Some methods have predictive capabilities that might be used to establish a minimum expected service life.

G. Measures for Improving Bond Performance

Materials

Wood density affects the ease of obtaining a high-quality bond and the stress placed on the bond by cyclic moisture changes. The swelling and shrinking coefficient, along with density, affects the magnitude of the dimensional change and the internal stress during cyclic moisture changes. The most effective way to ensure good performance is to use the lowest-density wood that will meet the other mechanical and physical requirements. Usually, choosing a lower-density wood will result in a lower swell-shrink coefficient as well.

Design

Bonded wood and wood products may experience unavoidable moisture content changes in service. With an understanding of how wood and bonded joints and products respond to moisture content change, products and structures can be designed and constructed to eliminate or minimize dimensional distortion or cracking where changes are unavoidable. In addition, buildings can be designed to shield the bonded joint or material from direct exposure to the weather. Covered bridges are the classic example of a structure designed to protect structural members and joints from the weather. Another example is laminated beam construction in which the tops and ends of the beams are not exposed directly to the weather.

Coatings

Coatings can reduce the amplitude of a short-term cycle of moisture content and consequently the internal stresses in the wood and the joint. Coatings can also limit the maximum moisture content of a joint exposed directly to rain and snow. However, with a few exceptions, coatings will not prevent the change of moisture content under prolonged exposure to very damp or very dry conditions. In exterior service, bonded materials will swell and shrink, which may, in turn, crack even the best coatings and allow water to penetrate the interior.

Encasing the member in aluminum or glass is an effective though impractical method for preventing moisture content change. Paraffin wax, though seldom used, is the most effective and practical method. Three coats of aluminum-flake-filled varnish is second only to paraffin in effectiveness; however, it is seldom used where the natural beauty of the wood is desired. The most effective commercial treatments and their moisture-excluding effectiveness ratings are shown in Table 1.19.

Treatments

Creosote and other oil-borne preservative treatments will also reduce the amplitude of short-term cycles of moisture content by slowing penetration and diffusion rates. Treating the wood before bonding is the most effective method, but the treatment chemicals often interfere with bonding. Carefully selected adhesives and bonding conditions are required to obtain adhesive bonds that are as durable as

Table 1.19 Moisture Excluding Effectiveness (MEE) of Selected Wood Coatings[a]

Coating	Number of coats	MEE[b] 1 day	7 days	14 days
Paraffin (dip)	1	100	97	95
Epoxy (two-part)	2	98	88	78
Aluminum pigmented varnish	2	97	87	77
Enamel (soya/tung/alkyd)	2	96	83	70
Oil-base house primer paint	1	85	46	24
Polyurethane varnish	2	83	43	23
Lemon oil polish	1	<1	<1	<1
Nitrocellulose lacquer	2	70	22	8
Latex wall paint	2	11	0	0

[a]Source: Feist, Little, and Wennesheimer (1985).
[b]MEE = [(U - C)/C] × 100 where U is weight of moisture absorbed by uncoated wood and C is weight of moisture absorbed by coated wood.

the treated wood. Nevertheless, many creosote- and oil-borne-treated glued-laminated wood structures have performed splendidly for 40 years or more in the most severe conditions.

As with coatings, most treatments will not prevent moisture content change if conditions producing change persist for a long period. Treatments such as poly(ethylene glycol) and acetylation have proven effective at minimizing the amplitude of moisture content change even over long periods (Stamm 1964a; Rowell 1982b, 1984). Unfortunately, these treatments are at present uneconomical for most products. Treating times are slow because wood is relatively impermeable. The chemicals are often expensive, and weight percentage gains of 10-30s are necessary to achieve meaningful improvement in dimensional stability. Therefore, very little wood is treated-only wood used for special high-value products (Rowell 1982b). Chemically bound treatments such as acetylation also have a distinct disadvantage for adhesive bonding. The treated wood is quite hydrophobic. Water-based resins have difficulty wetting the surface and penetrating the wood, and thus they cannot establish strong adhesion to the wood (Rowell, Youngquist, and Sachs 1987). Current research at the USDA Forest Service Products Laboratory is aimed at overcoming this difficulty.

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APPENDIX : SUMMARY OF REPRESENTATIVE DURABILITY SPECIFICATIONS AND QUALITY ASSURANCE STANDARDS FROM VARIOUS COUNTRIES

This appendix includes representative specifications and standards from the United States, Great Britain, Canada, Japan, and South Africa. Many of these specifications and standards may be outdated; however, they represent classic specifications or standards that have served the wood products industry for many years. Unfortunately, English translations of many well-known standards from Germany and France were unavailable to us.

Tables 1.20 and 1.21 list the specification or standard designation, the types of product or products to which the specification or standard applies, and a brief statement of the performance required by the specification or standard.

The source and title of each specification or standard are listed after the tables. The number following the hyphen or colon in the specification or standard generally indicates the year of adoption or latest revision of the copy of the standard available to the authors. For example, ANSI/AITC A190.1-1983 was adopted in 1983.

Table 1.20 Durability Specifications for Wood Adhesives

Specification[a]	Product	Exposure
ASTM D 2559	Structural laminate Wet-use adhesive	Dry Cyclic VPSD Dead load
CSA 0112.7	Resorcinol and phenol resorcinol (cold press)	Dry Cyclic VPSD
CSA 0112.6	Phenol and phenol-resorcinol (hot press)	Dry 48-h Soak Boil/dry/boil
ASTM D 3110	Nonstructural laminates Wet-use adhesives	Dry Boil/oven-dry/ boil VPS
	Dry-use adhesive	Dry 3-Cycle soak/oven-dry Heat (74°C)
	Nonstructural finger joints Wet-use adhesive	Dry Boil/oven-dry/boil VPS
	Dry-use adhesive	Dry 3-Cycle soak-dry Heat (74°C) Moist heat (60°C, 16% EMC)
ASTM D 3498	Plywood subfloor adhesive	Wet lumber (at bonding) Frozen lumber (at bonding) Dry lumber (at bonding) Gap filling Moisture resistance Oxidation resistance Mold resistance Bacterial resistance

Requirement
Shear strength less than tabulated value for species; wood failure >75%
End-grain delamination <5% for softwoods, <8% for hardwoods
Less than 3.55-mm slip from 14, 12.7-mm-long joints
Shear strength >19 MPa
End-grain delamination <8% for any species or specimen
Plywood shear strength >2.5 MPa
Plywood shear strength >2.5 MPa
Plywood shear strength >2.5 MPa
Shear strength >60% tabulated value for species, wood failure >60%
Shear strength >50% tabulated value for species, wood failure >50%
Shear strength >50% tabulated value for species, wood failure >50%
Shear strength >60% tabulated value for species, wood failure >60%
Shear strength >30% tabulated value for species, wood failure >30%
Shear strength >40% tabulated value for species, wood failure >40%
Tensile strength >13.8 MPa, wood failure >60%
Tensile strength >11.0 MPa, wood failure >50%
Tensile strength >11.0 MPa, wood failure >50%
Tensile strength >13.8 MPa, wood failure >60%
Tensile strength >11.0 MPa, wood failure >30%
Tensile strength >11.0 MPa
Tensile strength >5.2 MPa
Shear strength >1.03 MPa
Shear strength >0.69 MPa
Shear strength >1.03 MPa
Shear strength >0.69 MPa
No delamination
No fracture on flexure
No strength loss
No strength loss

(continued)

Table 1.20 (Continued).

Specification[a]	Product	Exposure
ASTM D 3930	Manufactured home adhesive	Low temperature (at bonding) Dry lumber (at bonding) Gap filling High temperature Oxidation resistance Film Bonded joint Creep resistance Structural adhesive Semistructural adhesive Mold resistance Type I qualification (interior/exterior) D 3110 cyclic boil-dry D 3110 cyclic VPSD Type II qualification (interior/ weather-protected exterior) VSD Type III qualification (interior only) Moist heat (32°C, 85% RH)
ASTM D 4689	Casein	Dry 48-h Soak
CSA 0112.3	Casein	Dry 48-h Soak
BS 1444	Casein	Dry 24-h Soak
ASTM D 4690	Urea-formaldehyde adhesive	Dry 48-h Soak
CSA 0112.5	Urea-formaldehyde adhesive	Dry 48-h Soak

Requirement
No minimum, report the average shear strength
No minimum, report the average shear strength No minimum, report the average shear strength No minimum, report the average shear strength
No break on flexure Shear strength >50% of original dry shear strength
Shear slip <0.152 mm Shear slip <1.27 mm No growth
No minimum, report the average shear strength No minimum, report the average shear strength
No minimum, report the average shear strength
No minimum, report the average shear strength
Block shear strength >19.3 MPa, plywood shear strength > 2.34 MPa Block shear strength >0.94 MPa
Block shear strength >19 MPa, plywood shear strength >2.34 M Plywood shear strength >1 MPa
Tensile shear strength >4.32 MPa Tensile shear strength >0.72 MPa
Block shear strength >19.3 MPa, plywood shear strength >2.3 MPa Block shear strength >1.93 MPa
Block shear strength >19 MPa, plywood shear strength >2.3 MPa Plywood shear strength >1.9 MPa

(continued)

Table 1.20 (Continued).

Specification[a]	Product	Exposure
ASTM D 4317	Polyvinyl acetate adhesive (Wet-use)	Dry Dry at 160°F 48-h Soak Boil-dry-boil
	(Intermediate)	Same as Type I except no boil-dry-boil exposure
	(Dry-use)	Same as Type II except no 48-h soak exposure
CSA 0112.4	Polyvinyl acetate adhesive (dry-use)	Dry Heat (71°C)
CSA 0112.8	Polyvinyl acetate (Intermediate)	Dry 48-h Soak Heat (82°C)
	(Wet-use)	Dry 48-h Soak Heat (82°C) Boil-dry-boil
BS 4071	Polyvinyl acetate	Dry Creep
CSA 0112.1	Animal glue	Dry
CSA 0112.2	Starch glue	Dry
JIS K 6801	Urea-formaldehyde (Room temperature setting)	Dry Soak (60°C), 3 h
	(hot-press)	Dry Soak (60°C), 3 h

Requirement
Block shear strength >19.3 MPa, plywood shear strength 2.75 MPa Plywood shear strength >1.72 MPa Plywood shear strength >1.72 MPa Same wood failure requirements as in Technical and Type I hardwood plywood (see HP 1983, Table 1.21).
Same requirements as Type I for Type II required exposures
Same requirements as Type II for Type III required exposures
Block shear strength >19 MPa Plywood shear strength >1.7 MPa tested hot
Block shear strength >19 MPa, plywood shear strength >2.6 MPa Plywood shear strength >1.9 MPa Plywood shear strength >2.6 MPa
Block shear strength >19 MPa, plywood shear strength >2.6 MPa Plywood shear strength >1.9 MPa Plywood shear strength >2.6 MPa Plywood shear strength >1.9 MPa
Failing load >1334 N Support 446-N load for 7 days without failure
Block shear strength >14 MPa, wood failure >50%
Block shear strength >14 MPa, plywood shear strength >2 MPa
Block shear strength >9.81 MPa Block shear strength >5.88 MPa
Plywood shear strength >1.18 MPa Plywood shear strength >0.98 MPa

(continued)

Table 1.20 (Continued).

Specification[a]	Product	Exposure
JIS K 6802	Phenol-formaldehyde	
	(Room temperature setting)	Dry Boil/oven-dry/boil
	(Hot-press)	Dry Boil/oven-dry/boil
JIS K 6804	Polyvinyl acetate	
	(Room temperature setting)	Dry Soak (30°C), 3 h
	(Cold setting1	Dry Soak (30°C), 3 h
JIS K 6806	Emulsion polymer isocyanate	
	Structural exterior	
	(Room temperature setting)	Dry Boil/oven-dry/boil
	(Hot-press)	Dry Boil/oven-dry/boil
	Nonstructural interior	
	(Room temperature setting)	Dry Soak (60°C), 3 h
	(Hot press)	Dry Soak (60°C), 3 h
BS 1204	Part II, close contact type	
	Weather/boil proof	Boil, 6 h Soak, 16-24 h Mycological resistance
	Boil resistant	Boil, 3 h Soak, 16-24 h Mycological resistance
	Moisture resistant	Soak 67°C, 3 h Mycological resistance
	Interior	Soak, 16-24 h

[a]Source and title follow Table 1.21.

Requirement
Block shear strength >9.81 MPa Block shear strength >5.88 MPa
Plywood shear strength >1.18 MPa Plywood shear strength >0.98 MPa
Block shear strength >9.81 MPa Block shear strength >3.92 MPa
Block shear strength >6.86 MPa Block shear strength >1.96 MPa
Block shear strength >9.81 MPa Block shear strength >5.88 MPa
Plywood shear strength >1.18 MPa Plywood shear strength >0.98 MPa
Block shear strength >9.81 MPa Block shear strength >5.88 MPa
Plywood shear strength >1.18 MPa Plywood shear strength >0.98 MPa
Plywood shear strength >2.24 MPa Plywood shear strength >3.45 MPa Plywood shear strength >2.75 MPa
Plywood shear strength >1.72 MPa Plywood shear strength >3.45 MPa Plywood shear strength >2.75 MPa
Plywood shear strength >2.06 MPa Plywood shear strength >2.75 MPa
Plywood shear strength >3.45 MPa

Table 1.21 Quality Assurance Standards for Wood Joints and

Specification[a]	Product	Exposure
AITC A190.1	Structural laminated timber	
	Exterior (wet use)	Dry
		Cyclic VPSD (cyclic delamination)
	Interior (dry use)	Dry
SABS 096	Structural finger joints	
	Interior (dry use)	16- to 24-h Soak
		Hot water soak
	Exterior (wet use)	16- to 24-h Soak Hot water soak 3-h Boil
PS 1-83	Softwood plywood (Exterior use)	Vacuum/pressure-soak Boil/oven-dry/boil
HP 1983	Hardwood plywood Technical and Type I (exterior use)	Dry Boil/oven-dry/boil

Wood-Based Materials	Requirement[b]
	Block shear strength greater than tabulated value for species, wood failure >80% for softwoods and nondense hardwoods and >60% for dense hardwoods End grain delamination; <8% for softwoods, <5% for hardwoods
	Shear strength requirement same as for wet-use, wood failure >80% for softwoods and nondense hardwoods, >40% for dense hardwoods
	Wood failure >10% regardless of strength Tensile strength >22.4 MPa when wood failure 10-29% Tensile strength >20.0 MPa when wood failure 30-49% Tensile strength >16.8 MPa when wood failure 50-69% Tensile strength >13.6 MPa when wood failure 70-89% Tensile strength >11.4 MPa when wood failure 90-100%
	Wood failure >10% regardless of strength Tensile strength >22.4 MPa when wood failure 10-29% Tensile strength >20.0 MPa when wood failure 30-49% Tensile strength >16.8 MPa when wood failure 50-69% Tensile strength >13.6 MPa when wood failure 70-89% Tensile strength >11.4 MPa when wood failure 90-100%
	Wood failure >10% regardless of strength Tensile strength >22.4 MPa when wood failure 10-29% Tensile strength >20.0 MPa when wood failure 30-49% Tensile strength >16.8 MPa when wood failure 50-69% Tensile strength >13.6 MPa when wood failure 70-89% Tensile strength >11.4 MPa when wood failure 90-100%
	Wood failure >85% Wood failure >85%
	Wood failure >50% if strength <1.72 MPa Wood failure >30% if strength >1.72 but <2.41 MPa Wood failure >15% if strength >2.41 MPa

(continued)

Table 1.21 (Continued).

Specification[a]	Product	Exposure
HP 1983	Type II (exterior use)	3-Cycle soak/oven-dry
	Type III (interior use)	2-Cycle soak-dry
ANSI A208.1	Particleboard	
	Type 1-M-1 (interior)	Dry
	Type 2-M-2 (exterior)	Dry Dry after accelerated aging
BS 5669	Particleboard	
	Type I (standard interior)	Dry 1-h Soak
	Type III (improved moisture resistance)	Dry 1-h Soak 24-h Soak
DIN 68 763	Particleboard	
	(Exterior use)	Dry 24-h Soak
	(Furniture)	Dry 24-h Soak
APA ARP 108	Composite and non-veneer sheathing	Dry 6-Cycle vacuum/ soak-dry
CS 251-63	Hardboard	
	Standard	Dry
	Tempered	Dry
CS 0115-M1982	Hardwood and decorative plywood	
	Exterior	Soak-dry then 2 cycles boil-dry at 63°C
	Interior	3 Cycles soak-dry at 50°C

Requirement[b]
Edge delamination <6.3 mm deep by 50 mm long
Edge delamination <6.3 mm deep by 50 mm long
MOR >11.0 MPa, MOE >2241 MPa, IB >0.41 MPa
MOR >17.2 MPa, MOE >3103 MPa, IB >0.41 MPa MOR >8.6 MPa, MOE >1552 MPa, IB >0.20 MPa
MOR >13.8 MPa, MOE >2,000 MPa, IB >0.34 MPa TS <12% (6- to 19-mm-thick board)
MOR >19.0 MPa, MOE >2,750 MPa, IB >0.5 MPa TS <8% (6- to 19-mm-thick board) TS <8%
MOR >18 MPa, IB >0.15 MPa (13- to 20-mm-thick board) TS <12%
MOR >18 MPa, IB >0.35 MPa (13- to 20-mm-thick board) TS <15%
No minimum, report average bending strength for material meeting full panel performance requirements Bending strength >50% of the above dry bending strength
MOR >34.5 MPa, tensile strength >17.2 MPa, IB >690 kPa MOR >48.3 MPa, tensile strength >24.1 MPa, IB >1,034 kPa
No delamination
Delamination <50 mm long or 3 mm deep

(continued)

Table 1.21 (Continued).

Specification[a]	Product	Exposure
CAN3-0188.2-M78	Waferboard	Dry 2-h Boil
CS 0153-M1980	Poplar plywood Exterior	Boil-dry-boil (63°C dry) Either VSP, or Soak, or 3 Cycles ice-boil (10 min each) Heat (open flame)
	Interior	Cyclic soak-dry (5)
	Scarf/finger joints	Dry
CS 0122-M1980	Structural glued laminated timber	Dry
		Dry
		VPSD (RT dry) (3) (cyclic delamination)
CAN3-0188.1-M78	Mat-formed particle-board Interior Grade L-1 Grade S	 Dry Dry
CSA 0121-M1978	Douglas-fir plywood	Boil-dry-boil (63°C dry) Either VSP, or Soak, or 3 Cycles ice-boil (10 min each) Heat (open flame)
BS 1088: 1966	Hardwood plywood Marine grade	Boil 72 h or steam under pressure, 12 h

Requirement[b]
MOR >14.0 MPa, MOE >2.7 GPa, IB >280 kPa
MOR >7.0 MPa
Wood failure >80%
Wood failure >80%
Wood failure >80%
Wood failure >80%
No delamination
Delamination <50 mm long or 3 mm deep
Average tensile strength >75% average tensile strength of unjointed panel
Average block shear strength >6 times species allowable shear strength in longitudinal shear
Average wood failure >80%
Average tensile strength of finger joints >3 times species allowable bending stress for highest grade of species group
Delamination <10% of bondlines on end grain
MOR >16.5 MPa, MOE >2.5 GPa
MOR >12.0 MPa, MOE >1.10 MPa, IB >350 kPa
Wood failure >80%
Wood failure >80%
Wood failure >80%
Wood failure >80%
No delamination
On a visual wood failure scale of 0-10 (highest quality), average of all specimens >5, no specimen <2

(continued)

Table 1.21 (Continued).

Specification[a]	Product	Exposure
BS 1455	Hardwood plywood (weather/boil proof)	Boil 72 h or steam under pressure
SABS 1089	South African pine stock glulam timber	Dry Cyclic VPSD (cyclic delamination)
BS 4169	Structural glued-laminated timber	Dry
		Cyclic VPSD (cyclic delamination)
BS 6566: 1985	Plywood (Weather/boil proof)	72-h Boil or steam at 0.20 N/mm^2 pressure
	(Cyclic boil-resistant)	Boil/oven-dry/boil
	(Moisture resistant)	3-h Soak, warm water
	(Interior)	24-h Soak

[a]Source and title follow Table 1.21.
[b]TS is thickness swell; MOR is modulus of rupture; MOE is modulus of elasticity.

Requirement[b]
On a visual wood failure scale of 0-10 (highest quality) average of all specimens >5, no specimen <2
Block shear strength >5.0 MPa, wood failure >75% Delaminated on end grain <5% of total bondline
Block shear strength >3 times allowable shear stress for softwoods Block shear strength >3.5 times allowable shear strength for hardwoods Delamination on end grain <10% of total bondline
Shear strength >2.5 MPa and wood failure ≥15%. or 2.5 MPa ≥ shear strength >1.7 MPa and wood failure ≥25%, or 1.7 MPa > shear strength >0.7 MPa and wood failure >50%, or 0.7 MPa ≥ shear strength >0.35 MPa and wood failure ≥75%
Same requirements as Weather/boil proof
Same requirements as Weather/boil proof
Same requirements as Weather/boil proof

Specification: Source and Title for Tables 1.20 and 1.21

American National Standards Institute
1430 Broadway
New York, NY 10018

ANSI/AITC A190.1-1983 American National Standard for Wood Products-Structural Glued Laminated Timber
ANSI/HPMA HP 1983 American National Standard for Hardwood and Decorative Plywood
ANSI/A208.1-1989 American National Standard-Wood Particleboard

American Plywood Association
P.O. Box 11700
Tacoma, WA 98411

APA PRP-108 Performance Standards and Policies for Structural-Use Panels

American Society for Testing and Materials
1916 Race Street
Philadelphia, PA 19103

ASTM D 2559-84 Standard Specification for Adhesives for Structural Laminated Wood Products for Use Under Exterior (Wet-Use) Exposure Conditions
ASTM D 3110-88 Standard Specification for Adhesives Used in Nonstructural Glued Lumber Products
ASTM D 3498-76 Standard Specification for Adhesives for Field-Gluing Plywood to Lumber Framing for Floor Systems
ASTM D 3930-85 Standard Specification for Adhesives for Wood-Based Materials for Construction of Manufactured Homes
ASTM D 4317-88 Standard Specification for Polyvinyl Acetate-Based Emulsion Adhesives
ASTM D 4689-87 Standard Specification for Adhesive, Casein-Type
ASTM D 4690-87 Standard Specification for Urea-Formaldehyde Resin Adhesives

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NOTE-All ASTM specifications and standards may be found in the current American Society for Testing and Materials, Annual Book of Standards, Vol. 15.06.

British Standards Institution
2 Park Street
London, W.1 A2BS
England

BS 1088: 1966 Specification for Marine Plywood Manufactured from Selected Tropical Hardwoods
BS 1204:1979 Specification for Synthetic Resin Adhesives (Phenolic and Aminoplastic) for Wood. Part 1. Specification for Gapfilling Adhesives. Part 2. Specification for Close-Contact Adhesives
BS 1444 Specification for Cold-Setting Casein Adhesive Powders for Wood
BS 1455 : 1972 Specification for Plywood Manufactured from Tropical Hardwoods
BS 4071:1966 Specification for Polyvinyl Acetate (PVA) Adhesives for Wood
BS 4169: 1970 Specification for Glued-Laminated Timber Structural Members
BS 5669:1979 Specification for Wood Chipboard and Methods of Test for Particleboard
BS 6566:1985 Plywood

Canadian Standards Association
178 Rexdale Boulevard, Rexdale
Ontario, Canada M9W 1R3

CAN3-0188.1-M78 Interior Mat-Formed Particleboard
CAN3-0188.2-M78 Waferboard
CSA 0112.1-M1977 Animal Glues for Wood
CSA 0112.2-M1977 Starch Glues for Wood
CSA 0112.3-M1977 Casein Glues for Wood
CSA 0112.4-M1977 Polyvinyl Adhesives for Wood
CSA 0112.5-M1977 Urea Resin Adhesives for Wood (Room- and High-Temperature Curing)
CSA 0112.6-M1977 Phenol and Phenol-Resorcinol Resin Adhesives for Wood (High-Temperature Curing)
CSA 0112.7-M1977 Resorcinol and Phenol-Resorcinol Resin Adhesives for Wood (Room- and Intermediate-Temperature Curing)
CSA 0112.8-M1977 Polyvinyl Adhesives-Cross Linking, for Wood
CSA 0115-M1982 Hardwood and Decorative Plywood
CSA 0121-M1978 Douglas-Fir Plywood
CSA 0122-M1980 Structural Glued-Laminated Timber
CSA 0153-1963 Poplar Plywood
CSA 0251-63 Hardboard

DIN Deutsches Institute fur Normung e.V.
DIN - Normen in Fremdsprachen
1 Berlin 30, Burggrafenstrasse 4-7
Germany

DIN 68763 Particleboard: flat-pressed panels for building construction

Japanese Standards Association
1-24, Akasaka 4-Chrome, Minato-Ku,
Tokyo 107, Japan

JIS K 6801 Urea Resin Adhesives for Wood
JIS K 6802 Phenol Resin Adhesives for Wood
JIS K 6804 Polyvinyl Acetate Emulsion Adhesive for Woods
JIS K 6806 Water-Based Polymer-Isocyanate Adhesives for Wood

National Institute of Standards and Technology
Route I-270 and Quince Orchard Road,
Gaithersburg, MD 20899

PS 1-83 U.S. Product Standard for Construction and Industrial Plywood

Council of the South African Bureau of Standards
Private Bag X191, Pretoria 0001
Republic of South Africa

SABS 096-1976 Code of Practice for the Manufacture of Finger-Jointed Structural Lumber
SABS 1089-1976 Specification for SA Pine Stock Glued Laminated Timber (Stock Glulam)

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