

Wood Adhesives

Bond Formation and Performance

Charles R. Frihart, Research Chemist

Christopher G. Hunt, Research Chemist

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A large portion of wood products made today are glued, or bonded, together. This is because bonding allows wood to be used in ways that would be impossible otherwise. We take wooden sheet materials, such as plywood, for granted, but they perform far better in some ways, and are far less expensive, than solid wood alternatives. Large structural pieces, such as the glulam skeletons in many buildings, would be impractical without adhesives. Everyday items such as wooden chairs would be extremely difficult to build without adhesives. In short, bonding wood products increases their value. This chapter is an introduction to wood bonding. Our primary goal is to provide an understanding of what makes good bonds and some principles that allow the reader to predict bond performance.

Bond Formation

Adhesives transfer and distribute loads between pieces of wood in a composite. This increases the strength, stiffness, and reliability of wood products. Another benefit of adhesives is that by adhering wood in crossing directions, such as plywood, the product has much lower swelling and shrinkage with changes in humidity or moisture. A good bond is like a strong chain across the adhesive-bonded joint (Fig. 10–1). The performance of a bonded joint depends on each link in the chain. If one is weak, the bond breaks. Therefore, it is important to understand the factors that contribute to the strength or weakness of the individual links (wood, adhesive, and interphase regions of wood and adhesive), and how they are controlled during product assembly.

Adhesion, or the hold an adhesive has on the wood, involves both mechanical and chemical factors. Because wood is porous, the surface at the microscopic level is very rough. This allows adhesives to form mechanical interlocks, where the adhesive wraps around cut surfaces and surrounds surface debris and damaged fibers. Ideally, the adhesive penetrates to sound wood, typically two to six cells deep. This penetration of adhesive into the cell wall microstructure increases the mechanical interlocking and the surface area for adhesive contact with the wood. With many adhesives, the most durable, water-resistant bonds develop when the adhesive not only flows deeply into cell cavities near the surface, but also enters, or infiltrates, the adjacent cell walls. The standard for excellent bonds is that the wood

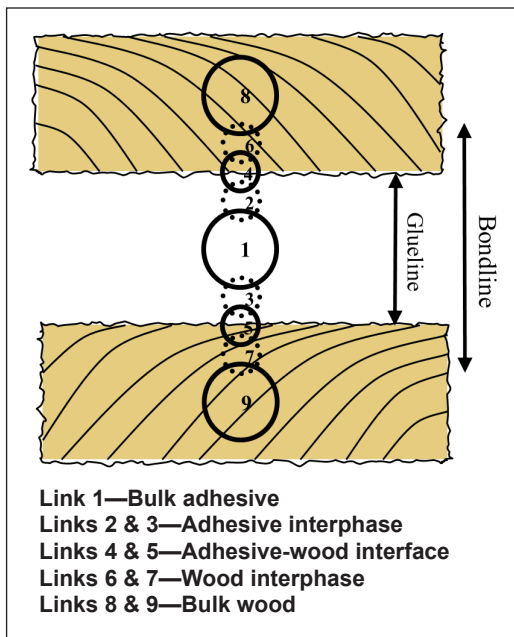


Figure 10–1. Imaginary links of adhesive bond between two pieces of wood. Although glueline and bondline are often used interchangeably, we recommend glueline for the pure adhesive phase (links 1–3) and bondline for the entire wood-adhesive interaction zone (zones 1–7). (Schematic adapted from Marra (1980).)

breaks well separated from the adhesive joint and that the bond strength is equal to or greater than the strength of solid wood.

Attractive forces between molecules of adhesive and wood contribute greatly to adhesion. Although covalent bonds—chemical bonds between the adhesive and wood—seem plausible with some adhesives, no evidence exists that they contribute to the strength of adhesive bonds. However, intermolecular attractive forces, such as Van der Waal’s forces, dipole–dipole forces, and hydrogen bonding, occur so frequently that they must be very important for bond strength, especially given the high contact area of the adhesive with the wood. With some wood surfaces, such as teak, wood extractives can interfere with direct adhesive contact, leading to a chemically weak boundary effect and poor bond strength.

Wetting

For maximum adhesive bond strength, the liquid adhesive must “wet,” or completely cover the wood surface at the molecular scale. Molecules of adhesive must come into direct contact with molecules of wood to provide the best mechanical interlock and intermolecular attraction between adhesive and wood. Wood surfaces may appear to be smooth and flat, but under a microscope, the surface is full of ridges, valleys, and crevices littered with loose fibers and other debris. Such surface conditions cause air pockets and blockages that prevent complete wetting by the adhesive

and introduce stress concentrations when the adhesive has cured. In addition, different characteristics of wood (such as grain angle, natural defects, and extractives) lead to widely different flow characteristics, wetting ability, and roughness. (Surface wetting is discussed in more detail in the section on Chemical Interference to Bonding, p. 10–4.) In addition to wetting, or completely covering these different surfaces, adhesives must be fluid enough and low enough surface energy to flow into the microscopic holes, or capillary structure of wood. Pressure enhances wetting by forcing liquid adhesive to flow over the surfaces, displace air blockages, and penetrate to the sound wood. With wood surfaces not being exactly parallel to the grain, cell lumens are open on the surface, effectively providing tunnels leading below the wood surface for adhesive to flow deeper into the wood.

Solidification

The adhesive bond forms once the adhesive solidifies, but full strength may take from hours to days to develop. The applied adhesive changes from liquid to solid by one or more of three mechanisms: (a) loss of solvent (including water) from adhesive through evaporation and diffusion into the wood, (b) cooling of a molten adhesive, or (c) chemical polymerization into cross-linked structures that resist softening when exposed to heat. Since water is a common carrier for most wood adhesives, loss of water and chemical polymerization often occur simultaneously.

Surface Properties of Wood for Bonding

Because adhesives bond by surface attachment, the physical and chemical conditions of the wood’s surface are extremely important for bond performance. The ideal wood surface is smooth, flat, and free of machine marks and other surface irregularities, including planer skips, chatter, and crushed, torn, or chipped grain. The cells on the surface should be cleanly cut, not crushed or burnished. Oils, from the machining or the wood, dirt, wood extractives, and other debris that could reduce the chemical forces between wood and adhesive (a weak boundary layer) (Fig. 10–1, links 4 and 5) can lead to premature wood failure.

Both mechanical and chemical properties of a wood surface influence the quality of adhesive bonds. Wood whose surface is highly fractured or crushed cannot form an ideal bond even if the adhesive forms a strong bond with the surface (Fig. 10–1, links 4 and 5). The weak wood underneath the surface is a weak link in the chain (Fig. 10–1, links 6 and 7) and a location of failure in the bonded assembly. In other cases, poor bond strength may be a result of the chemical properties of the surface. Sometimes natural extractives, over drying, or chemicals added to modify the wood change the surface chemistry enough to reduce bond performance. Physical damage

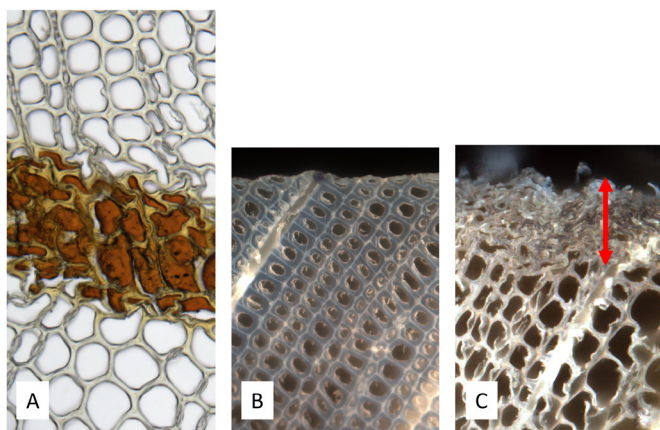


Figure 10–2. Cross sections of (A) southern pine bonded joint, (B) commercially planed surface, and (C) the same board after sanding with fresh 36-grit sandpaper. The brown band in A is phenol-formaldehyde adhesive, which contains water, alkali, and phenol, all of which soften wood. The clamping pressure was sufficient to crush the cells near the glue line, but after curing, the adhesive reinforced this damaged zone, producing a strong, durable bond. B shows a surface ideal for bonding. C shows the impact of sanding with new 36-grit sandpaper: the red arrow highlights the many layers of surface cells crushed by the sandpaper. Cell damage below the red arrow is from specimen preparation, not sanding. Each image is 0.26 mm (0.01 in.) wide. A: transmission image, B, C fluorescence images.

and chemical contamination of the wood surface interfere with essential wetting, flow, and penetration of adhesive. Sometimes chemical contamination reduces bond strength by preventing proper cure of the adhesive.

Lumber Surfaces

Surfacing or resurfacing the wood within 24 h before bonding provides a clean, easily wettable surface. In some situations, bonding within minutes of surface preparation gives noticeably better results because of the better surface wettability (see Chemical Interference to Bonding, p. 10–4). Surfacing just before bonding also minimizes the time for wood to change moisture content, and thus change size and possibly warp, cup, or twist, between the surfacing and bonding steps. Parallel and flat surfaces allow the adhesive to flow freely and form a uniformly thin layer that is essential to optimal adhesive performance.

Experience and testing have proven that a smooth surface cleanly cut with a knife, such as with a jointer or planer, is best for bonding (Fig. 10–2). Feeding a jointer too quickly, however, results in crushed cells on the surface and a shiny appearance called glazing. Not only are these crushed cells weaker, they also inhibit adhesive wetting and penetration. Crushed cells on the surface can be revealed by wiping a very wet rag over a surface, waiting for a minute or more, removing any remaining water with a dry paper towel, and comparing the roughness of the wet and dry surfaces. When

wetted, crushed cells spring back close to their original shape. Therefore, if the wetted area is much rougher than the dry area, the machining has crushed the surface. A weak joint will result if the adhesive does not completely penetrate and repair crushed cells to restore their strength.

To achieve higher production rates and possibly because of other considerations, sometimes precision sawing or even sanding are used. Well-maintained, properly operated saws regularly make surfaces good enough for even structural bonds (the highest level of performance). Although sanded surfaces do not produce optimum strength, sanding is sometimes used to prepare surfaces of solid wood for bonding. Because sanding is the only viable method for trimming the thickness of panels to tolerance, gluing panel faces often involves gluing to sanded surfaces. Because panel surfaces often have crushed cells and/or chemicals on their surface that interfere with wetting, sanded panels often glue more easily than unsanded panels.

Veneer Surfaces

The desired properties of wood veneer are similar to those of lumber, but manufacturing processes, including cutting, drying, and laminating into plywood or laminated veneer lumber (LVL), can drastically change physical and chemical properties of veneer surfaces. Special attention to these properties is required to ensure good bond strength.

The most common veneer is rotary cut, produced by holding the ends of a log and rotating it against a knife. This results in continuous sheets of flat-grain veneer. The log is soaked in warm water to soften the wood and make peeling easier. As the knife peels veneer from the log, it forces the veneer away from the log at a sharp angle, fracturing (checking) the veneer. This checked side is called the loose side, and the opposite side without checking is called the tight side. The direction and depth of checks strongly influence the shear strength of plywood in standard tests.

Sliced veneer is produced in long strips by moving a section of a log, called a flitch, against a knife. As in rotary cutting, the knife forces the veneer away from the flitch at a sharp angle, causing fine checking of the veneer. For book-matched face veneers, where grain patterns of adjacent veneers are near mirror images, half the veneer leaves will have their loose face exposed so the veneer must be cut as tightly as possible. Generally, hardwood face veneers are sliced to reveal the most attractive grain patterns.

Sawn veneer is produced in long narrow strips from flitches that have been selected and sawn for attractive grain patterns. The two sides of sawn veneer are free from knife checks, so either surface may be bonded with satisfactory results.

Veneer is dried soon after cutting, using continuous, high-temperature dryers. Drying temperatures range from 170 to 230 °C (330 to 446 °F) for short periods. Drying to very low moisture levels at very high temperatures or at moderate

temperatures for prolonged periods inactivates the veneer surfaces, causing poor wetting of veneer and poor bonding. Residues deposited on veneer surfaces from incomplete combustion of the fuel heating the dryer, such as soot, can also cause serious adhesion problems.

Veneer selected for its attractive appearance, or for use in sanded grades of plywood, should be uniform in thickness, smooth, and flat. Deep checks, knots, holes, decay, and face grain all can contribute to the grade. For lower grade plywood, defect standards are not as strict. For example, loosely cut veneer with deep checks and large defects is suitable for structural plywood. Lower grade veneer often requires more adhesive than does tightly cut veneer.

Chemical Interference to Bonding

Chemical interference that reduces the bondability of wood is more complicated and harder to detect than mechanical weakening of wood surfaces. This interference can be from natural causes (migration of extractives to the surface), inadvertent wood alteration (overdrying of the wood surface), or intentional alteration (wood modification). A simple water test can reveal potential surface inactivation, or problems in wetting and penetration. A drop of water or waterborne adhesive is placed in an area on the earlywood of a flat-grain surface that does not have checks or splits. A surface with good wettability and penetrability will absorb the drop within 20 s. If the drop spreads out but some water remains on the surface after 40 s, then the surface has good wettability but poor penetration and may be difficult to bond. If after 40 s the water drop retains much of its original shape with little spreading, then bonding problems from surface inactivation (poor wettability and penetrability) are very likely. Figure 10–3 shows how the inactivated surface of veneer can be restored by sanding to allow the droplet to spread out across the surface.

Naturally occurring extractives on wood surfaces contribute to surface inactivation through both physical and chemical means. Most, but not all, wood adhesives are waterborne; therefore, they are less likely to wet and penetrate extractive-covered surfaces. Particularly troublesome extractives are pitch, especially in the southern pines and Douglas-fir; oil, such as in teak; and waxes in composites and straw. When subjected to high temperatures during processing, extractives migrate to the surface, where they concentrate and physically block adhesive contact with wood. Furthermore, pitchy and oily extractives are hydrophobic (they repel water). The acidity of extractives of some oak species and tropical hardwoods can inhibit the chemical cure of some adhesives. In contrast, alkaline extractives can retard normal polymerization of an acidic adhesive, such as urea-formaldehyde, which can compromise the integrity of the adhesive film and bond.

Overdrying and overheating interfere with adhesion by causing extractives to diffuse to the surface, by reorienting

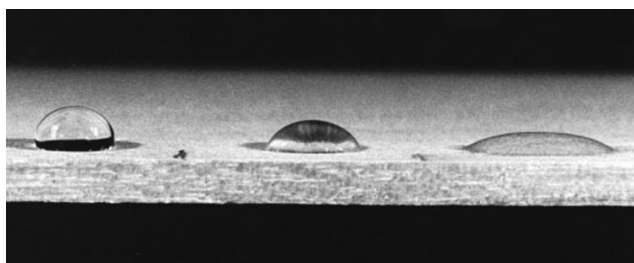


Figure 10–3. A simple water drop test shows differences in wettability of yellow birch veneer surface. Three drops were applied to surface simultaneously and then photographed after 30 s. The left drop retained a large contact angle on an aged and unsanded surface; the center drop had a smaller contact angle and improved wettability after the surface was renewed by two passes with 320-grit sandpaper to cut through the deactivated surface; the right drop showed a small contact angle and good wettability after four passes with the sandpaper.

surface molecules to expose less polar portions, and by oxidizing or pyrolyzing (starting to burn) the wood. Airborne chemical contaminants can also inactivate a wood surface.

To reduce decay in service, wood is treated with a variety of preservatives, and these treatments may inhibit adhesive cure and/or decrease the ability of the adhesive to wet the wood. Poor wetting reduces the contact area, and thus the bond strength, between adhesive and wood. By understanding the properties of these treated woods, adhesive companies have been able to alter the adhesives and bonding process to provide sufficiently durable products.

The most common fire-retarding chemicals used for wood are inorganic salts based on phosphorous, nitrogen, and boron. These acid-based salts release acid at elevated temperatures to decrease flammable volatiles and increase char in wood, thereby effectively reducing flame spread. The elevated temperature and moisture conditions of hot-press curing can release some of these acids, inhibiting the cure of alkaline phenolic adhesives. Alkaline resins can still make durable bonds if the wood is pretreated by priming with certain alkaline aqueous solutions or by selecting appropriate adhesives.

Chemical modification of wood reduces moisture-related dimensional changes and slows decay. The commercial modified wood available today is either thermally treated, acetylated, or furfurylated. The bondability of modified wood is not well studied except in the case of acetylated wood. These modifications alter the basic wood properties and consequentially alter the ability of adhesives to interact with the wood. A major impact is to reduce water absorption by reducing the polarity of the wood. Thus, for bonding, adhesive selection may depend more on the modification method than the original species. We recommend consulting the wood supplier for advice on bonding, and practicing with the wood, before committing to a particular approach.

Bonding of Wood Composite Products and Nonwood Materials

The surfaces of wood composites such as plywood, strandboard, particleboard, fiberboard, and hardboard generally have poor wettability relative to that of freshly cut wood surfaces. Surfaces of these materials may appear glazed or shiny, indicating that they have been inactivated. During hot pressing, resinous extractives and added waxes migrate to the surface, adhesive on the outer surfaces of particles and fibers cures, and caul release agents remain on the surfaces—all of which reduce wetting by waterborne adhesives. Surfaces of composite products typically are more difficult to bond than surfaces of solid wood products. Lightly sanding with 320-grit sandpaper to cut through the inactivated surface often improves adhesion to composite panel products having poor wettability (Fig. 10–3). Too much sanding can create an uneven surface and perhaps produce too much loose-fiber debris that can interfere with adhesion. Furthermore, the internal strength of composites often limits the strength of adhesive bonds.

Products incorporating wood composites bonded to metal or plastic are becoming more common for higher performance, but they present special challenges. Metal foils and plastic films laminated to wood composites do not require high cohesive strength for indoor applications, but the adhesives still must be compatible with both wood and nonwood surfaces. If a structural bond is required between wood and metal or plastic, then only epoxy, polyurethane, and other isocyanate-based adhesives may be sufficiently compatible. Even then, good adhesion often requires cleaning of the nonwood surfaces to remove contaminants. Application of coupling agents, primers, or other special treatments may be required to chemically activate the surfaces.

The difficulty with bonding metals to wood is often metal surface inactivation. The surface energy of clean metals is higher than that of wood, but with exposure to air, metals quickly adsorb contaminants and form metal oxides to produce a low-energy, weak boundary layer at the surface. A series of cleaning procedures is required to regenerate the high-energy surface and create microscale roughness necessary for structural bonding. Steps in surface preparation may include abrasion by sandblasting, cleaning with liquid or vapor organic solvents, alkaline washing, chemical etching, and/or priming with adhesive solutions or coupling agents.

Plastic surfaces are difficult to bond because they are generally low energy and hydrophobic. Plastics are organic polymers that may be either thermoplastic (soften on heating) or thermosetting (cross-linked and resist softening on heating). Thermoplastics generally are not as strong and stiff as wood, but the properties of thermoset materials approximate and even exceed the mechanical properties of wood. Reinforcing plastics with fibers, such as fiberglass, further increase strength and stiffness. Reinforced plastics

that are effectively bonded to wood can be strong and cost-effective structural composites. Traditional waterborne wood adhesives do not bond well to plastics because they are polar and hydrophilic. Epoxies, polyurethanes, and isocyanate-based adhesives can bond many plastics to wood. Adhesion to plastic surfaces occurs primarily by physical intermolecular attraction forces and, in some cases, hydrogen bonding. Abrading and chemical etching of plastic surfaces increase adhesion by providing some mechanical interlocking. Coupling agents have molecules that can react with both the adhesive and the surface, making them particularly useful for bridging dissimilar materials. Plasma or flame treatment of plastic surfaces can clean and activate surfaces for enhanced adhesion. Grafting of monomers onto cleaned plastic surfaces by means of plasma polymerization can create a polar surface that is more compatible with adhesives.

Physical Properties of Wood for Bonding

Density and Porosity

Surface properties are not the only factors to control bonding in wood. Bond quality is also affected by the bulk physical properties of wood, particularly density, porosity, moisture content, strength, and swelling–shrinking properties.

Solid wood cell walls generally have a density of $1,500 \text{ kg m}^{-3}$ (94 lb ft^{-3}), regardless of the wood species. However, the bulk density of wood varies between species because of the amount of void volume. Wood density changes widely between wood species. Within a piece of wood, there are often large differences in density between earlywood and latewood. Many other factors also result in density variation, even within a single tree. High-density wood has thick walls and small lumina (the hollow centers of cells), whereas low-density wood has thin walls and large lumina. Thus, higher density wood contains more material per unit of volume and can carry more load.

Bonded wood assemblies typically increase in strength with wood density up to a range of 700 to 800 kg m^{-3} (44 to 50 lb ft^{-3}) at a moisture content 12%. Below this density level, adhesion is usually easy, and the strength of the wood limits the assembly strength. Above this density level, high-strength joints with high wood failure are harder to produce consistently. Wood failure refers to the percentage of the total failure area that is wood, rather than adhesive failure. High wood failure is preferred, especially in U.S. standards, because there is no ambiguity about whether a bond is well formed. Counterintuitively, flexible adhesives such as polyurethane can sometimes produce bonds with higher strength due to adhesive deformation, but lower wood failure due to a less stressed adhesive–wood interphase.

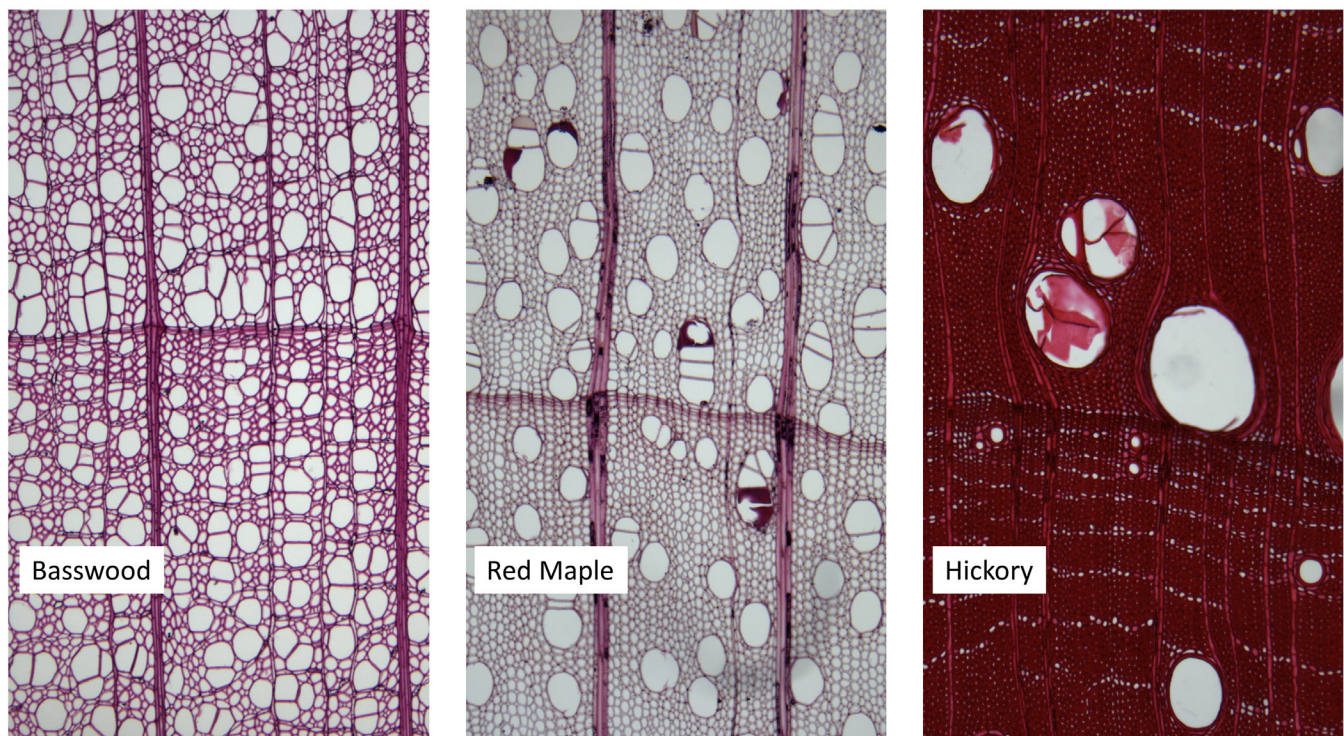


Figure 10–4. Cross sections of three different species showing openness of cellular structure. Bonding from any of the sides becomes progressively more difficult with progress through the series basswood, red maple, hickory. Images approximately 850 μm (0.033 in.) across, stained cross sections in transmission.

High-density woods are difficult to bond for several reasons. Because of their thicker cell walls and smaller diameter lumens, adhesives do not easily penetrate the wood void spaces, limiting mechanical interlock. Much greater bonding pressure is required to compress the stronger, stiffer, high-density wood to provide close contact between wood surfaces and adhesive. High-density woods are strong and allow high loads to be placed upon the bondline. Finally, high-density woods tend to swell and shrink more with changes in moisture content than do low-density woods. This puts far higher loads on the bondline simply from moisture changes and also increases the problem of boards changing shape between surface preparation and bond cure.

Wood density and anatomy control wood porosity, which usually affects penetration and bond performance. To attain the highest joint strength, the adhesive must penetrate and interlock several cells deep into sound, undamaged cell structure. In wood, porosity varies according to the grain direction. End-grain surfaces (butt joints) are many times more porous than radial or tangential surfaces. Adhesives penetrate so easily into the open lumens perpendicular to the grain that overpenetration often occurs when gluing end-grain. Overpenetration occurs when voids form in the glue line because too much adhesive has moved into the wood structure. This overpenetration and the high strength of wood in the longitudinal direction are primary reasons why it is so difficult to form strong, load-bearing bonds in butt joints. Across the grain, there are fewer and smaller

paths for adhesive flow, so overpenetration generally is not a problem with a properly formulated adhesive, assuming it is applied correctly.

The porosity and resulting adhesive flow into wood vary greatly, both between hardwoods and softwoods and within each of these groups. Figure 10–2A shows adhesive penetration in a softwood, southern pine. Softwoods contain mostly longitudinal tracheid lumens connected by bordered pits. Pits are the small openings between cells that permit lateral transfer of fluids in living trees. Adhesives can use the network of pits to penetrate deeply, even in tangential and radial directions.

Figure 10–4 shows the large differences in lumen volume and distribution of volume across the annual ring in three hardwood species. In hardwoods, the thin-walled, relatively large longitudinal vessels have porous end walls, so adhesives can penetrate deeply along the end grain. Where two vessels are in lateral contact, numerous inter-vessel pitting can occur, which allows for lateral flow between vessels. The remaining thick-walled fibers have relatively few pits for lateral transfer of adhesive. Some species, such as red oaks, have large numbers of radially oriented rays that, along with easy flow through vessels, are prone to overpenetration. Adhesives for large customers may be formulated specifically for hardwoods or softwoods, and for specific species within the groups, and have adjustable properties for specific manufacturing situations.

Moisture Content and Dimensional Changes

Water occurs naturally in living trees and affects wood properties and adhesive bonding strength dramatically. Depending on extractive levels and morphology, wood cell walls typically swell while taking up 25% to 30% of their dry weight in water. As wood dries below 25% to 30% moisture, it shrinks and becomes stiffer. At higher moisture levels, excess water simply fills lumens and makes wood heavier. Wood in service will shrink and swell as it loses and takes on moisture from the air; under typical indoor conditions, wood contains 5% to 12% moisture. The shrinking and swelling (dimensional changes) are different for the three principal directions in wood. Longitudinal dimensional change (along the grain, or up and down in the standing tree) is the least and usually amounts to less than 0.2% between fiber saturation and oven dry in normal wood. Tangential dimensional change is the greatest, typically 6% to 12%, whereas radial dimensional change is typically about half the tangential movement. Wood with low density tends to have the smallest dimensional change. Compression wood (softwoods), tension wood (hardwoods), and juvenile wood (the first few rings in the center of a tree), are prone to more longitudinal shrinkage, resulting in more warp, bow, and twist of the wood. Chapter 4 discusses wood moisture relations in detail.

Wood dimensional changes that accompany variations in moisture content have broad-ranging and important consequences on the performance of bonded joints. As the wood in bonded assemblies swells and shrinks, internal stresses develop that can damage the adhesive bond and/or the wood itself. Damage may occur when moisture content changes in adjacent pieces of wood that have different swelling–shrinkage coefficients. This can arise with different species; variation in heartwood, sapwood, or juvenile wood content; or grain type, such as radial grain bonded to tangential, or end grain bonded to cross grain. Large stresses can occur when different parts of an assembly have different moisture contents. Dimensional changes associated with water are a common cause of adhesive failure. Moisture-driven stresses can be minimized by bonding pieces of wood with compatible grain directions, low shrinkage coefficients, and like species of similar moisture content, and by bonding at the moisture content expected during service.

Adhesives

Composition

During the 20th century, wood adhesives shifted from natural to synthetic organic polymers. A polymer is a large molecule constructed of many small repeated units. Natural polysaccharide and protein polymers in blood, hide, milk, soybean, starch, dextrin, and other biomass have been used as adhesives for centuries. These polymers are still

in use today, although they have been largely replaced by petrochemical- and natural-gas-based systems. The first wood adhesives based on synthetic polymers were produced commercially during the 1930s. Synthetic polymers can be made stronger, more rigid, and more durable than wood, and generally have much greater water resistance than traditional adhesives from natural polymers. However, recent advances in biomass-based adhesives have made them more competitive with fossil fuel-based adhesives

Whether a synthetic adhesive is thermoplastic or thermosetting has a major influence on its performance in service. Thermoplastics are long-chain polymers that soften and flow on heating, and then harden again upon cooling or drying. They generally have less resistance to heat, moisture, and long-term loading than do thermosetting polymers. Common thermoplastic adhesives for wood include uncross-linked poly(vinyl acetate) emulsions, elastomerics, contacts, and hot-melts. Thermosetting polymers make excellent structural adhesives because almost all undergo irreversible chemical change when cured, and on reheating, they do not flow again. These cross-linked polymers can have high strength and resistance to moisture and other chemicals, and are rigid enough to support large, long-term loads without deforming. Phenol-formaldehyde, resorcinol-formaldehyde, melamine-formaldehyde, urea-formaldehyde, isocyanate, polyurethane, and epoxy adhesives are examples of thermosetting polymers.

As applied, adhesives usually contain a mixture of several chemically active and inert materials, each added for specific properties such as working characteristics, shelf life, strength properties, or durability. Solvents dissolve or disperse adhesive polymers, act as carriers of polymer and additives, aid in wetting, and control flow and penetration of the adhesive. Water is the carrier for most wood adhesives, primarily because water readily absorbs into wood, is inexpensive, and does not have adverse effects on the environment. Organic solvents are still used with elastomeric and contact adhesives, although waterborne versions are becoming more prevalent in the marketplace. Reinforcing fibers, mostly inert organics, can enhance mechanical properties of the adhesive film, especially toughness, impact resistance, and shrinkage. Fillers of both organic and inorganic origins contribute to rheological control of the fluid system, particularly in reducing the spread and penetration of the adhesive into wood. Extenders are like fillers, in that they control flow and working characteristics, but are different in that they do not reduce bond strength.

Certain chemicals are added to plasticize adhesive polymers, enhance tackiness, improve heat resistance, or lower costs. Plasticizers, such as dibutyl phthalate, are used to soften the brittle vinyl acetate homopolymer in poly(vinyl acetate) emulsion adhesives. This is necessary to facilitate adhesive spreading and formation of a flexible adhesive film from the emulsion at and below room temperature. Phenolic

polymers are used as tackifiers and adhesion promoters in neoprene and nitrile rubber contact adhesives. Reactive polymeric fortifiers, such as melamine-formaldehyde, can be substituted into urea-formaldehyde adhesives to improve resistance to moisture and heat. Adding some phenol-formaldehyde to resorcinol-formaldehyde adhesives reduces adhesive costs, without sacrificing adhesive strength and durability.

Catalysts are chemicals used to accelerate the rate of chemical reaction of polymeric components. Acids, bases, salts, peroxides, and sulfur compounds are a few examples of catalysts. Catalysts do not become a part of the final polymer; they simply increase the rate of reaction. Hardeners are reactive components that do become a part of the final polymer. Examples are an amine hardener added to epoxy, and formaldehyde added to resorcinol—both produce cross-linking reactions to solidify the adhesive. For curing urea-formaldehyde and melamine-formaldehyde adhesives, what are often called hardeners are actually catalysts, because they speed up cure the adhesive but do not become part of the polymer. Other chemicals, such as antioxidants, acid scavengers, preservatives, wetting agents, defoamers, or colorants, may be added to control or eliminate some of the undesirable characteristics of certain adhesive formulations.

Strength and Durability

In building construction, adhesives that hold up the building during its life are considered structural. These adhesives generally are stronger and stiffer than the wood that they bond. Structural bonds are critical because bond failure could result in serious damage to the structure or its occupants. Examples of structural applications include glue-laminated beams, prefabricated I-joists, laminated veneer lumber, cross-laminated timber, mass plywood, and stressed-skin panels. Structural adhesives that maintain their strength and rigidity under the most severe cycles of water saturation and drying are considered fully exterior adhesives. Adhesives that lose strength faster than wood under severe conditions, particularly water exposure, are considered interior adhesives. Between exterior and interior adhesives are the intermediate adhesives, which maintain strength and rigidity in short-term water soaking, but deteriorate faster than wood during long-term exposure to water and heat. Unfortunately, adhesives that are the strongest, most rigid, and most resistant to deterioration in service are typically the least tolerant of wide variations in wood surface condition, wood moisture content, and assembly conditions, including pressures, temperatures, and curing conditions.

Semi-structural adhesives impart strength and stiffness to an adhesive-bonded assembly, and in some instances, they may be as strong and rigid as wood. However, semi-structural adhesives generally do not withstand long-term static loading without deformation. They are capable of short-term

exposure to water, although some do not withstand long-term saturation, hence their limited exterior classification. Another semi-structural adhesive application is the nailed-glued assembly where failure of the bond would not cause serious loss of structural integrity because the load would be carried by mechanical fasteners.

Nonstructural adhesives typically support the dead weight of the material being bonded and can equal the strength and rigidity of wood in dry conditions. Nonstructural adhesives often lose strength and sometimes stiffness when exposed to water or high humidity. Two major markets for nonstructural adhesives are furniture and cabinet assembly.

Elastomeric construction adhesives are categorized as nonstructural but are normally used for field assembly of panelized floor and wall systems in light-frame construction. These adhesive joints are much stiffer than mechanically fastened joints, resulting in stiffer panels. In addition to the adhesive, mechanical fasteners are used to carry the load in case of adhesive failure.

Some adhesives could be easily included in more than one category because they can be formulated for a broad range of applications. Isocyanate and polyurethane adhesives are examples. Polymeric methylene diphenyl diisocyanate (pMDI) with a low molecular weight develops highly durable bonds in structural strandboard, even though strandboard products deteriorate from swelling and shrinkage stresses. One-part polyurethane adhesives provide durable adhesive films, but as molecular weight increases, adhesion to porous wood generally decreases and bonds become increasingly susceptible to deterioration from swelling and shrinkage stresses. Soybean-based adhesives have limited wet strength on their own, but cross-linking agents are added to increase water resistance for nonstructural uses.

Selection

Many factors need to be considered when selecting the best adhesive for a particular application. The adhesive must be applied, wet the surface, penetrate into the wood, cure, and maintain strength for sufficient time under different loads and environmental conditions. Table 10–1 describes the typical form, properties, preparation, and uses of common adhesive families. Manufacturers and adhesive suppliers should completely review the product, its intended service environment, and all production processes and equipment before choosing an appropriate adhesive. Whatever the approach to adhesive selection might be, the following points are important.

Strength—The amount of load the adhesive is required to carry must be considered.

Durability—The kind of environment the bond will be exposed to (liquid water, humidity, heat, cold, chemicals, light, loading level) and the length of exposure will determine durability.

CHAPTER 10 | Wood Adhesives: Bond Formation and Performance

Table 10–1. Working and strength properties of adhesives, with typical uses

Type	Typical user	Form and color	Preparation and application	Strength properties	Typical uses ^a
Hot melt	Woodworker, industrial	Solid blocks, pellets, ribbons, rods, or films; solvent-free; white to tan; near colorless bondline	Solid form melted for spreading; bond formed on solidification; requires special application equipment for controlling melt and flow	Develops strength quickly on cooling; lower strength than conventional wood adhesives; moderate resistance to moisture; gap-filling with minimal penetration	Edge-banding of panels; plastic lamination; patching; film and paper overlays; furniture assembly; general purpose home and shop
Isocyanate [Iso], [pMDI]	Woodworker, industrial	Liquid containing isomers and oligomers of methylene diphenyl diisocyanate; light brown liquid and clear bondline	Adhesive applied directly by spray or spread; reactive with water, producing CO ₂ gas (foaming), excellent spreading over surfaces, cured with heat under pressure in panel products	High dry and wet strength; very resistant to water and damp atmosphere; can reduce moisture swelling of wood, adheres to metals and plastics	OSB, particleboard, fiberboards, woodworker
Poly(vinyl acetate)emulsion [PVA, PVAc]	Woodworker, industrial	Liquid ready to use; often polymerized with other polymers; white to tan to yellow; colorless bondline	Liquid applied directly; cures at room temperatures	High dry strength; low resistance to moisture and elevated temperatures; joints yield under continued stress	Furniture; flush doors; plastic laminates; panelized floor and wall systems in manufactured housing; general purpose in home and shop; also known as “white glue”
Cross-linkable poly(vinyl acetate) emulsion [PVAX]	Woodworker, industrial	Liquid, similar to poly(vinyl acetate) emulsions but includes copolymers capable of cross linking with a separate catalyst; white to tan with colorless bondline	Liquid emulsion mixed with catalyst; cure at room temperature or at elevated temperature in hot press or radio-frequency press	High dry strength; improved resistance to moisture and elevated temperatures, particularly long-term performance in moist environment	Interior and exterior doors; molding and architectural woodwork; cellulosic overlays
Polyurethane [PU]	Woodworker, industrial	Low-viscosity liquid to high-viscosity mastic; supplied as one part (1K) or two-part (2K) systems, color varies from clear to brown; colorless bondline	Adhesive applied directly to one surface, preferably to water-misted surface; reactive with moisture on surface and in air; cures at room temperature	High dry and wet strength; resistant to water and damp atmosphere; limited resistance to prolonged and repeated wetting and drying; gap-filling, widely used for structural applications in Europe	General purpose home and shop; construction adhesive for panelized floor and wall systems; laminating plywood to metal and plastic sheet materials; specialty laminates; installation of panels, LVL and glulam in Europe, and CLT assembly
Epoxy	Woodworker, historical, niche	Liquid resin and hardener supplied as two parts; completely reactive leaving no free solvent; clear to amber; colorless bondline	Resin and hardener mixed by user; reactive with limited pot-life; cured at room or elevated temperatures; only low pressure required for bond development	High dry to wood, metal, glass, and plastic; formulations for wood resist water and damp atmospheres; delaminate with repeated wetting and drying; gap-filling	Repair of laminated beams and architectural components, general home and shop, historical in boats, airplanes, sports equipment

Table 10–1. Working and strength properties of adhesives, with typical uses—con.

Type	Typical user	Form and color	Preparation and application	Strength properties	Typical uses ^a
Elastomeric mastic (construction adhesive)	Construction	Putty-like consistency, synthetic or natural elastomers in organic solvent or latex emulsions; tan, yellow, gray	Mastic extruded in bead to framing members by caulking gun or like pressure equipment; nailing required to hold materials in place during setting and service	Strength develops slowly over several weeks; dry strength lower than conventional wood adhesives; resistant to water and moist atmospheres; tolerant of outdoor assembly conditions (wet/frozen lumber); gap-filling	Lumber to plywood or OSB in floor and wall systems; laminating gypsum board and rigid foam insulating; assembly of panel system in manufactured homes
Elastomeric contact	Industrial, construction	Viscous liquid, typically neoprene or styrene-butadiene elastomers in water emulsion; tan to yellow	Liquid applied directly to both surfaces, partially dried after spreading and before pressing; roller-pressing at room temperature produces instant bonding	Strength develops immediately upon pressing, increases slowly over a period of weeks; dry strengths much lower than those of conventional wood adhesives; low resistance to water and damp atmospheres; creep under static load	On-the-job bonding of decorative tops to kitchen counters; factory lamination of wood, paper, metal, and plastic sheet materials
Cross-linked soybean [soy]	Industrial	Creamy tan/white viscous fluid	Soy flour mixed with water and cross-linking chemicals to provide wet strength, applied to wood and hot pressed	Good dry strength, acceptable wet strength	Interior plywood, engineered wood flooring; potential for use in particleboard and fiberboard
Emulsion polymer isocyanate [EPI] and polymer emulsion polyurethane (PEP)	Industrial	Liquid emulsion and separate isocyanate hardener; colorless	Emulsion and hardener mixed by user; reactive on mixing with controllable pot-life and curing time; cured at room and elevated temperatures; radio-frequency curable; high pressure required	High dry and wet strength; very resistant to water and damp atmosphere; very resistant to prolonged and repeated wetting and drying; adheres to metals and plastics	I-joist assembly, laminated beams for interior and exterior use; lamination of wood to metals and plastics; doors and architectural materials, structural insulated panel (SIP) assembly
Melamine-formaldehyde [MF] or melamine-urea-formaldehyde [MUF]	Industrial	Powder or liquid with blended catalyst; white to tan; colorless	Mixed with water; cured in hot press with platens at 120 to 150 °C (250 to 300 °F) and lower internal temperatures; particularly suited for fast curings	High dry and wet strength; very resistant to water and damp atmospheres	Melamine-urea primary adhesive for durable bonds in hardwood plywood; end-jointing and edge-gluing of lumber; and scarf joining softwood plywood; LVL and glulam in Europe, and CLT assembly

CHAPTER 10 | Wood Adhesives: Bond Formation and Performance

Table 10–1. Working and strength properties of adhesives, with typical uses—con.

Type	Typical user	Form and color	Preparation and application	Strength properties	Typical uses ^a
Phenol-formaldehyde [PF]	Industrial	Liquid, powder, and dry film; dark red–black bondline	Liquid blended with extenders and fillers by user; film inserted directly between laminates; liquid or powder applied directly to wood in composites; all formulations cured in hot press, typically at 120 to 150 °C (250 to 300 °F)	High dry and wet strength; very resistant to water and damp atmospheres; more resistant than wood to high temperatures and chemical aging	Primary adhesive for extreme exterior durability: OSB, plywood, hardboard
Lignin, soy, or tannin incorporated into phenol-formaldehyde	Industrial	Like PF	Engineered to behave like PF	Good dry strength; moderate to good wet strength; durability improved by blending with phenolic adhesive	Very small markets as of 2020, but significant potential
Resorcinol-formaldehyde [RF] and phenol-resorcinol formaldehyde [PRF]	Industrial	Liquid resin and powdered hardener supplied as two parts; phenol may be copolymerized with resorcinol; dark red bondline	Liquid mixed with powdered or liquid hardener; resorcinol adhesives cure at room temperatures; phenol-resorcinols cure at temperatures from 21 to 66 °C (70 to 150 °F)	High dry and wet strength; very resistant to moisture and damp atmospheres; more resistant than wood to high temperature and chemical aging	Primary adhesives for laminated timbers and assembly joints that must withstand severe service conditions
Urea-formaldehyde [UF]	Industrial	Powder and liquid forms; white to tan resin with colorless bondline	Powder mixed with water, hardener, filler, and extender by user; some formulations cure at room temperatures, others require hot pressing at about 120 °C (250 °F)	High dry and wet strength; moderately durable under damp atmospheres; moderate to low resistance to wetting and temperatures in excess of 50 °C (122 °F)	Dominates interior panel market (medium density fiberboard; particleboard, European hardwood plywood); very low cost; degrades over time to emit formaldehyde; new formulations emit far less
Animal, protein	Historical	Clear to tan to dark; thick liquid	Often heated to apply; sets upon cooling and loss of water	Typically not water resistant but strong when dry	Furniture
Soybean protein	Historical	Powder with added chemicals; white to tan, similar color in bondline	Mixed with cold water, lime, caustic soda, and other chemicals; applied and pressed at room temperatures, but more frequently hot pressed when blended with blood adhesive	Moderate to low dry strength; moderate to low resistance to water and damp atmospheres; moderate resistance to intermediate temperatures	Plywood for interior use

^aCLT, cross laminated timber; LVL, laminated veneer lumber; OSB, oriented strandboard.

Wetting—As discussed in the introduction, the chemistry of the surface and adhesive must be compatible. A waterborne adhesive on an oily surface is unlikely to spread out unless the adhesive contains surfactants, organic solvents, or other materials to help it spread and make molecular contact with the wood surface.

Timing—Several timing factors must be considered. Pot life refers to how long a batch of adhesive is usable after being made. Open time is the time between applying the adhesive and joining the pieces. Closed time refers to the time between joining the pieces and applying heat or pressure for completing the assembly. Clamp time is how long the finished piece must remain clamped. Increasing temperature usually shortens set and cure time. After pressing, adhesives typically need hours or weeks to develop full strength.

Consistency—The consistency, or viscosity, of the adhesive must be compatible with the application equipment, whether it be brush, spatula, roller, extruder, curtain coater, spray, or powder metering device. In addition, the adhesive must be fluid enough to enter the void spaces in the wood, but not so fluid that most of the adhesive is squeezed deep into the wood or out of the glue line, causing a starved joint.

Mixing—If water, hardener, catalyst, filler, extender, or other additive are used with a resin, appropriate equipment must be available to produce a uniform product.

Clamping—Pressure must be applied to joints to ensure close contact between the parts. Typically, most wood adhesives do not fill gaps well and high pressure may be required to form tight joints. Pressure also helps the adhesive to wet and penetrate the wood surface by forcing it into the void spaces of wood. However, too high a pressure, such that the adhesive largely squeezes out, should be avoided.

Temperature—Higher temperature increases the rate of chemical reactions, evaporation, and diffusion. Therefore, higher temperature reduces pot life, open and closed assembly times, and clamping time. Phenol-formaldehyde, melamine-formaldehyde, urea-formaldehyde, and isocyanate adhesives must be cured at high temperatures and require expensive, heated presses. Poly(vinyl acetates), epoxy, polyurethanes, resorcinol-containing adhesives and many isocyanates cure well at room temperature, but can often develop higher strength upon heating.

Moisture content—Many adhesives need low wood moisture content to properly penetrate wood (12% wood moisture content is a typical specification). However, isocyanates and polyurethanes need some water to cure and may even perform better at higher moisture content. Inexpensive wood moisture content meters are widely available.

Color and finishing properties—In furniture and interior millwork where appearance is critical, adhesive color, ability to absorb stains and finishes, and freedom from

bleeding and staining are critical factors. Adhesives used in the furniture industry are usually formulated to produce either a tan or colorless joint.

Ease and simplicity—One-part adhesives, such as poly(vinyl acetate), hot-melt, and adhesive films, are the simplest to use because there is no chance for error in weighing and mixing components. Waterborne adhesives are easy to clean up. Two- or multiple-part adhesives require careful measuring and mixing of components and may require special solvents for cleanup after bonding. High water resistance often means more difficult cleanup when cured.

Cost—The cost of adhesive, related application equipment, and labor can be significant. On the other hand, the value of the bonded product is often many times more than the adhesive plus wood.

Safety and environment—Many adhesives cure by chemical reactions and therefore are hazardous in the uncured state. Even waterborne adhesives can have organic chemical components that evaporate, causing health concerns for workers and consumers. The most common exposure routes are through the skin or through inhalation of evaporated components. Formaldehyde hardener for resorcinol, phenol, melamine, and urea adhesives is a severe irritant. Amine hardeners in some epoxy adhesives are strong skin sensitizers. Chemical sensitivity can be caused by repeated exposure to uncured adhesives. Aerosols and skin contact of uncured isocyanates are a significant health hazard. Organic solvents in adhesives have largely been replaced by water through a combination of regulation and technological improvements in waterborne systems.

Health, Safety, and Shelf-Life

Health and safety regulations require that toxic and hazardous chemicals have a visible label to warn of their dangers. Material safety data sheets (MSDS) along with instructions are provided with adhesive products to advise of proper handling procedures, protective gear and clothing (classified as personal protective equipment, PPE), and procedures for dealing with disposal, spills, and fire, and to offer guidance for first-aid and professional treatment of injuries. The statements made in this book concerning the safety of adhesives and effects on the health of the user are general and not meant to be all-inclusive. The user should consult the MSDS and follow the manufacturer's instructions and precautions before using any adhesive.

Uncured adhesives may be harmful and require safety precautions, whereas cured adhesives are usually safe for human contact. A notable exception is urea-formaldehyde adhesive, which can release low concentrations of formaldehyde gas from bonded wood products, especially under hot, moist conditions. The carcinogenic formaldehyde can react with proteins in the body to cause irritation and inflammation of membranes of eyes, nose, and throat. In

most industrialized countries, regulations now require extremely low formaldehyde emissions and mandate regular testing of wood panel products in production. These regulations and the resulting innovations in the industry have produced clear reductions in formaldehyde emissions from wood products. Phenol(resorcinol)-formaldehyde adhesives, which are used to manufacture plywood, strandboard, and laminated beams, also contain formaldehyde. After curing, however, the highly durable phenol-formaldehyde, resorcinol-formaldehyde, and phenol-resorcinol-formaldehyde polymers do not chemically break down in service; thus, no detectable formaldehyde is released. Cured melamine-formaldehyde polymers do not release formaldehyde either, though they are not quite as durable as the others previously mentioned. Ultra-low emitting formaldehyde (ULEF) adhesives are formulated to reduce formaldehyde emissions. Uncross-linked poly(vinyl acetate), isocyanate, and soy adhesives address the formaldehyde issue by having no added formaldehyde (NAF). Unless detailed knowledge of the safety of the adhesive is available, it should be assumed that uncured adhesives could be harmful at high concentrations or with chronic exposure. As commercial adhesive formulations change frequently, so can their safety profile.

Diisocyanates are sensitizers that are capable of causing occupational asthma. They also are highly reactive chemicals that polymerize rapidly on contact with strong alkali, mineral acids, proteins, water, and many other materials. Because polymeric methylene diphenyl diisocyanate (pMDI) adhesives develop strong and durable bonds with wood, they have gained acceptance in composite wood products. Any isocyanate is potentially hazardous if mishandled, but the low vapor pressure of pMDI means it does not evaporate quickly. pMDI adhesives require strict attention to adequate ventilation and use of personal protective equipment to remove airborne pMDI on dust particles. Emulsion polymer isocyanates (EPI), polymer emulsion polyurethanes (PEP), and polyurethanes also contain the reactive isocyanate group, and so chronic contact with these uncured adhesives should be avoided. Properly cured isocyanate-containing adhesives are not considered hazardous in bonded wood products.

Thermoplastic adhesives are generally of low toxicity, but any added solvents may carry health concerns. Construction and contact adhesives contain organic solvents with low flash points. When used in small, unventilated spaces, the solvent can accumulate in the air and cause an explosion if ignited. Some adhesive producers offer less flammable formulations based on chlorinated solvents. Solvents in these adhesives are generally toxic, but harmful effects can be avoided by providing adequate ventilation and following the manufacturer's safety instructions.

The human respiratory system cannot handle fine dust, even from wood. Use dust masks and adequate ventilation when

creating or handling fine dusts, especially when spraying chemicals.

Disposal and storage life are often covered in MSDSs. For liquid adhesives, disposal can become complicated because the adhesive ages and partially cures, and this semisolid material still has the hazards of the uncured adhesive but is more difficult to handle. Fully cured adhesives tend to be the safest because the reactive groups no longer exist.

Bonding Process

Moisture Content Control

After wood and adhesive selection, the next most important factor contributing to trouble-free service of adhesive bonds is control of wood moisture content before, during, and after the bonding process. Moisture content strongly affects the final strength and durability of joints, development of surface checks in wood, and dimensional stability of the bonded assembly.

The moisture in wood, combined with water in adhesive, will greatly influence the wetting, flow, penetration, and cure of waterborne wood adhesives. In general, adhesives are designed to provide the best bonds when the wood is between 6% and 14% moisture content. Special formulations are often used for applications outside this range. Aqueous adhesives tend to interact with the wood and dry out prematurely when applied to wood below 6% moisture content. Wood absorbs water from the adhesive so quickly that adhesive flow and penetration into the wood are drastically inhibited, even under high pressure. Wood may become so dry below 3% moisture content that it temporarily resists wetting.

Wood with too much moisture is also difficult to bond with normal waterborne adhesives. Water and low-molecular-weight portions of the adhesive migrate more slowly into wet wood cell walls than into drier cell walls. This leaves the adhesive more prone to squeeze-out when pressure is applied. In many adhesives, low-molecular-weight components infiltrating the cell walls are necessary for long-term durability. Control of moisture content is particularly critical when the adhesive is cured in a hot press because the excess moisture turns to high-pressure steam inside the product. This pressurized steam can blast channels through the wood composite or cause large internal voids, called blows, in panel products. Even if blows do not occur, excess moisture within thermosetting adhesives can prevent complete cross-linking, thereby weakening the adhesive.

Large changes in moisture content after bonding will cause shrinking or swelling that can seriously weaken both the wood and adhesive bond and can cause warping, twisting, and surface irregularities. Therefore, wood products should ideally be bonded at the same equilibrium moisture content (EMC) that the product will experience

in service. If the predominant relative humidity (RH) of the air in an environment is known, one can estimate the EMC of the wood by using Table 4–2. Interior RH levels in buildings depend on climate, season, moisture-generating activities, and operation of conditioning equipment. With the exception of dry climates, air-conditioned spaces are often around 45% to 55% RH, giving wood an EMC of approximately 8% to 10%. During winter in the northern states, indoor heating lowers air humidity so that the wood EMC drops to around 4%, but the moisture levels within the exterior walls can be higher. EMC of wood outdoors is generally higher, ~12%, but with large variation depending on the climate and local conditions. The average moisture content for exterior wood in most of the United States is 8%. Average moisture content increases to 11% along the Atlantic and Gulf coastal regions; in the arid southwest, the EMC is relatively low at 6%. For wood outdoors, local environment is key. Wood close to the ground, a common source of moisture, and wood in the shade, are typically wetter than wood away from moisture sources and exposed to moving air and sunlight. Products manufactured in humid environments and then moved to dry conditions, especially northern states where EMC drops very low in winter, can experience warping, splitting, delamination of joints, or other noticeable appearance defects. Manufacturers and importers of bonded wood products must be aware of these regional and seasonal variations to condition the wood and bond it at moisture content levels consistent with air humidity conditions of the service region.

Adhesive often contributes moisture to a product. In particleboard or fiberboard, the water in the adhesive can be 3% to 7% of the wood weight. During hot pressing, some water evaporates. To minimize deformation and prevent steam blisters or blows upon removal from the hot press, the total moisture content of the assembly should not exceed 10%. Moisture content of 3% to 5% in veneer at the time of hot pressing is satisfactory for hardwood plywood intended for furniture and interior millwork and for softwood plywood intended for construction and industrial uses. When radio-frequency-curing adhesives, low moisture content in the wood is necessary to prevent arcing. Often lumber with moisture content of 6% to 7%, assuming 1% to 2% will be added by aqueous adhesives, is satisfactory for cold pressing of furniture and interior millwork. Laminated lumber (glulam) for exterior use should contain 10% to 12% moisture before bonding. Because there is relatively little adhesive, it only contributes about 1% to the total moisture content.

Lumber that has been kiln dried to the approximate average moisture content intended for bonding may nonetheless vary in moisture content level between boards and within individual boards. Large differences in moisture content between adjacent or within boards can result in considerable stress on the common joint after bonding as the boards equalize toward a common moisture content. This internal

stress can reduce the amount of load that can be applied before fracture. For best results, keep differences in moisture content less than about 5% for lower density species and 2% for high-density species.

Surface Preparation

The section “Surface Properties of Wood for Bonding” covers the detailed relationships between surface condition and adhesive bond performance. Wood surfaces are best prepared for maximum adhesive wetting, flow, and penetration by removing all materials that might interfere with bond formation to sound wood. Ideally, wood should be surfaced immediately before applying adhesive. This short time not only minimizes the opportunity for extractives and other contaminants to degrade the bonding surface, but also minimizes the opportunity for wood to change moisture content, and thus shape, after the flat surface has been prepared. Some standards require no more than 24 h between surfacing and bonding, especially for structural products. Particularly with high-extractive-content woods, such as southern pines, times as short as 15 min may be necessary for the best bonds. In addition to improving bond quality, properly prepared surfaces also facilitate uniform adhesive spread rate.

Spreading of Adhesive

Regardless of method used for bonding, the purpose in spreading the adhesive is to evenly apply enough adhesive so that under pressure, the adhesive will flow into a uniformly thin layer and penetrate adequately. The amount of adhesive needed will depend on wood species, surface quality, moisture content, type of adhesive, temperature and humidity of the air, assembly time, and application of adhesive to one or both surfaces. Adhesives can be spread by any method, but in manufacturing, adhesives are usually applied mechanically, such as by roll-spreader, extruder, curtain-coater, or spray. Instead of applying a uniform film, extruders apply continuous, uniformly spaced beads of specific diameter.

For composite manufacturing involving flakes, strands, particles, or fibers, the adhesive is applied as a slow stream or as droplets using a spray nozzle or spinning disc to the wood particles. Adhesive is further spread by allowing the wood particles to contact each other in a drum blender, kneader, or tube blender. These binder adhesives hold the product together by a series of joints similar to spot bonds rather than a continuous film typical of film adhesives. Microscopic analysis of droplet size and distribution in binder adhesives shows the importance of adhesive distribution on board properties.

Assembly and Pressing

Adhesive viscosity is important during application, open time, closed time, and pressing conditions. Keeping the viscosity at the correct level throughout this process requires

balancing a variety of factors. The general relationship between adhesive viscosity and bonding pressure is illustrated in Figure 10–5. Viscosity strongly affects wetting, flow, penetration, and, particularly, transfer of adhesive to opposing wood surfaces when pressure is applied to the assembly. After application, adhesive viscosity will often change due to evaporation, change in temperature, polymerization, or migration of adhesive components into the wood cell walls. When the adhesive-covered surfaces remain open before assembly (open assembly), the adhesive thickens by losing solvent to the air by evaporation and to the wood by absorption and can become too dry to form a useful bond. Bringing the adhesive-covered surfaces together (closed assembly) stops evaporation but not absorption. Cold-setting waterborne wood adhesives lose water by absorption and evaporation, so that viscosity steadily increases until the adhesives eventually set. Thermosetting waterborne adhesives also dry out, but they may continue to flow to some extent in the presence of heat, eventually hardening by chemical reaction.

Pressure during bond assembly serves several useful purposes by

- forcing the wood pieces into close contact with each other,
- forcing trapped air from the joint,
- bringing adhesive into molecular contact with the wood surfaces,
- forcing adhesive to penetrate into the wood structure for more contact area, as well as getting the adhesive to contact undamaged cells beneath the surface,
- squeezing the adhesive into a thin film, and
- holding the assembly in position while the adhesive cures.

If pressure is too high, however, the adhesive flows too deeply into the wood or in some cases out of the bond so that there is insufficient adhesive to fill the glue line. These conditions of overpenetration and excess squeeze-out result in a starved joint and produce inferior bond strength (Fig. 10–5). Overpenetration is especially common in low-density woods, whereas excess squeeze-out is common in high-density woods. The strongest joints are made with moderately high clamping pressure for the wood density, using adhesive with viscosity high enough to avoid overpenetration and excess squeeze-out at that pressure.

Low pressures near 0.7 MPa (100 lb in⁻²) are suitable for low-density wood because the surfaces easily conform to each other, thus ensuring intimate contact between adhesive and wood. High pressures up to 1.7 MPa (250 lb in⁻²) are required for the highest density woods, which are difficult to compress. Small areas of flat, well-planed surfaces can be bonded satisfactorily at lower pressures.

Because adhesives become thicker after they are applied to the wood and some start to cure immediately, assembly

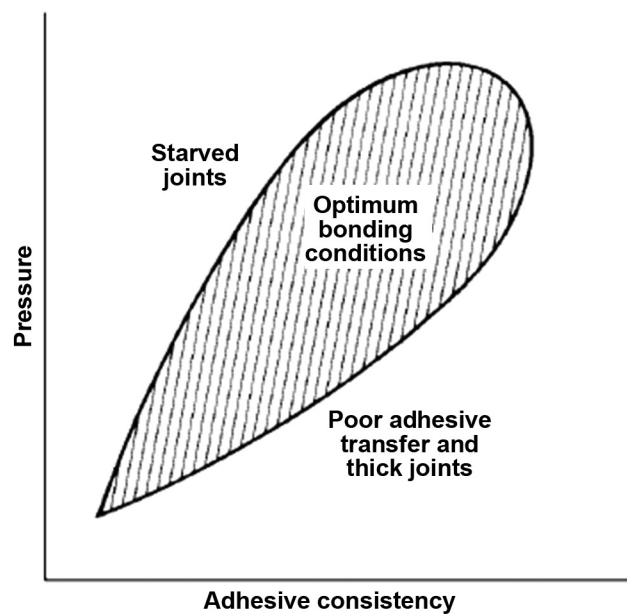


Figure 10–5. Relationship between adhesive consistency and bonding pressure during bond formation using thermosetting adhesive.

times can be very important. Some adhesives require time before pressing to allow solvents to evaporate or adsorb into the wood, so that the adhesive is thick enough to avoid overpenetration when pressure is applied. This is true for contact adhesives where the adhesive is applied to both surfaces and the solvent evaporates until both sides become tacky and then the bond is formed. On the other hand, adhesives that dry or cure too much before pressing often do not transfer, or wet the opposite surface, resulting in thick, weak bondlines. Generally, in manufacturing, adhesives are applied to one surface for ease of manufacture, even though applying to both surfaces eliminates the transfer issue.

Bonded material should be kept under pressure until the adhesive is strong enough to resist any forces that may cause parts to shift or open gaps in the glue line. When cold-pressing lumber under normal conditions, this stage can be reached in as little as a few minutes or as long as 24 h, depending on adhesive temperature and curing characteristics and the absorptive characteristics of the wood. During hot pressing, the time under pressure varies with temperature of platens, thickness of the assembly, species of wood, and adhesive formulation. The limiting factor is typically the time at temperature in the core for composites. Typical hot-pressing times are 2 to 15 min, and up to 30 min for very thick laminates because of slow heat transfer to the middle. High-frequency heating, steam injection, pre-heating wood, or anything that gets the core up to temperature more quickly can reduce press time. Press factor, or the number of seconds under pressure per unit of thickness of panel, is a way to discuss press times more generally across different panel thicknesses. Press factors as low as 3 s mm⁻¹ of board thickness, or 18 s for a 6-mm-thick panel, are known for some particleboard lines where

the wood is heated before entering the press. The press factor for hardwood plywood is typically around 16 s mm^{-1} , or 4 min for a 15-mm- (5/8-in.-) thick panel.

With stiff structural adhesives (phenol-, resorcinol-, melamine-formaldehyde), the strongest bonds generally have gluelines between 0.08 and 0.15 mm (0.003 and 0.006 in.) thick. Thinner gluelines may not effectively transfer stresses, particularly stresses from moisture-induced dimensional changes. As these gluelines become thicker, they become weaker and fracture more easily. Many adhesives also contain solvents, including water, which cause the adhesive to shrink upon curing and may even leave voids. Thick gluelines result from inadequate pressure or incorrect adhesive consistency. When rough, warped, or poorly mated surfaces are joined, pressure will be uneven along the glueline. As a result, the adhesive flow from the areas of very high pressure to those of little to no pressure will result in very thick gluelines. Both the starved and thick areas of the glueline lead to weak bonds.

For composites, the adhesive needs to have enough strength to withstand the steam pressure inside the panel as the applied press pressure is released. If the adhesive is not sufficiently strong, the internal steam pressure will cause a large delamination (blow) within the product when the press pressure is released. As the size of the composite increases, there is less relative area for steam escape and the chance of delamination increases. Drier wood, high-solids adhesives, less adhesive with better distribution, and faster curing adhesives can decrease the problem of delamination.

Post-Cure Conditioning

In the process of bonding edge-grain joints with waterborne adhesives, the wood in the joint swells upon absorbing water from the adhesive. If the bonded assembly is surfaced before this excess moisture has evaporated or adsorbed uniformly, more wood is removed along the swollen joint than elsewhere. As the added moisture evaporates, the wood in the joint shrinks beneath the surface. These sunken bondlines become very conspicuous under a high-gloss finish. This is particularly important when using adhesives containing large amounts of water. Moisture can be well distributed by conditioning the bonded assembly for 24 h at 70 °C (158 °F), 4 days at 50 °C (122 °F), or 7 days at room temperature before surfacing. In each case, the relative humidity must be adjusted to prevent drying the wood below the target moisture content.

Conditioning to the moisture content of service is especially important for plywood, veneers, and other composites made of thin layers. During room-temperature bonding, water often needs to be removed, which can be done by controlling humidity on a time schedule. If room-temperature-bonded products are dried too much, warping, checking, and debonding increase markedly. Softwood plywood is often very dry after hot pressing; this can be corrected by spraying the hot panels and stacking them

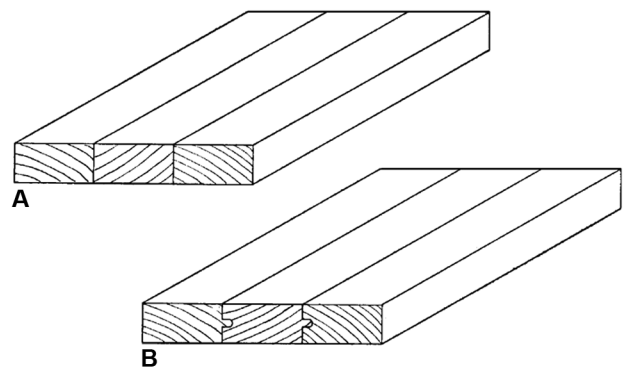


Figure 10–6. Edge-grain joints: A, plain; B, tongue-and-groove.

tightly to allow the moisture to diffuse uniformly. This process also restores some of the panel thickness lost by compression during hot pressing and helps minimize warping in service. Many composite panels need time after pressing for the adhesive to cure completely and for the moisture to equilibrate throughout the panel.

Bonded Joints

Edge-Grain Joints

Edge-grain joints (Fig. 10–6A) can be as strong as the wood in shear parallel to the grain, tension across the grain, and cleavage. The tongue-and-groove joint (Fig. 10–6B) and other shaped edge-grain joints have a theoretical strength advantage because of greater surface area than the straight edge-grain joints, but they typically do not produce higher strength. The theoretical advantage is lost, wholly or partly, because the shaped sides of the two mating surfaces cannot be machined precisely enough to produce the perfect fit that will distribute pressure uniformly over the entire joint area. Because of poor contact, the effective bonding area and strength can actually be less in a shaped joint than on a flat surface. Tongue-and-groove and other shaped joints have the advantage that the parts can be quickly aligned in clamps or presses. A shallow-cut tongue-and-groove is just as useful in this respect as a deeper cut, and less wood is wasted.

End-Grain Joints

It is practically impossible to make end-grain butt joints (Fig. 10–7A) strong enough to meet the requirements of ordinary service with conventional bonding techniques. Even with special techniques, butt joints reach only about 25% of the tensile strength of the wood parallel-to-grain. To approximate the tensile strength of clear solid wood, a scarf joint or finger joint (Fig. 10–7B to E) should have a surface area at least 10 times greater than the cross-sectional area of the piece, because wood is approximately 10 times stronger in tension than in shear. Joints cut with a slope of 1 in 12 or flatter (12 times the cross-sectional area) produce the highest strength. Scarf joints work because they essentially

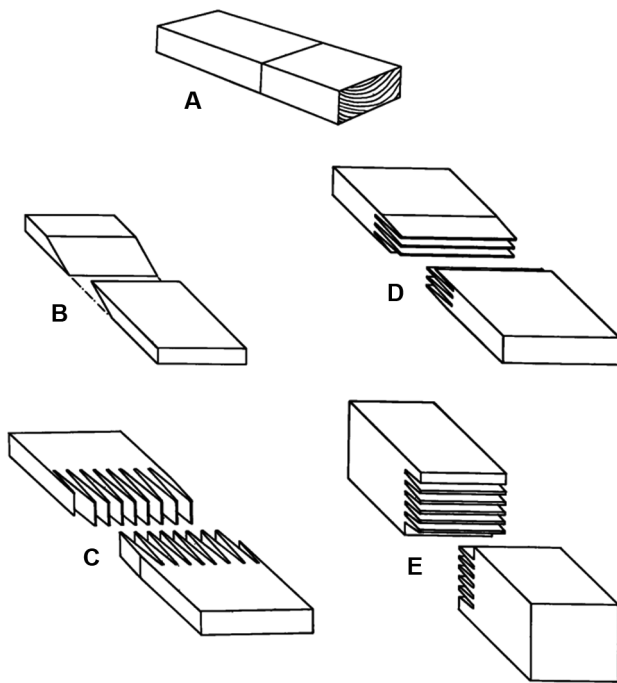


Figure 10-7. End-to-end-grain joints: A, butt; B, plain scarf; C, vertical structural finger joint; D, horizontal structural finger joint; E, nonstructural finger joint.

convert an end grain joint into an edge grain joint. Finger joints can be thought of as scarf joints folded over to reduce waste. In plywood scarf and finger joints, a slope of 1 in 8 (8 times the cross-sectional area) is typical for structural products. For nonstructural, low-strength joints, these requirements may be relaxed.

When finger joints are cut with a high slope, such as 1 in 12, the tip thickness must be no greater than 0.8 mm (1/32 in.). A thickness of 0.4 to 0.8 mm (1/64 to 1/32 in.) is about the practical minimum for machined tips. Sharper tips are possible using dies that are forced into the end grain of the board.

Finger joints can be cut with the profile showing either on the wide face (vertical joint) or on the edge (horizontal joint) (Fig. 10-7). Vertical joints have greater area for designing shapes of fingers but require a longer cutting head with more knives. Vertical joints cure faster than horizontal joints in high frequency heating. A nonstructural finger joint, with fingers much shorter than in the two structural finger joints, is shown in Figure 10-7E.

A well-manufactured scarf, finger, or lap joint in end grain can have up to 90% of the tensile strength of clear wood and exhibit behavior much like that of clear wood. However, the cycles-to-failure for a well-manufactured end joint are often lower than for clear wood.

End-to-Edge-Grain Joints

It is difficult to design a plain end-to-edge-grain joint (Fig. 10-8A) capable of carrying appreciable loading. As a

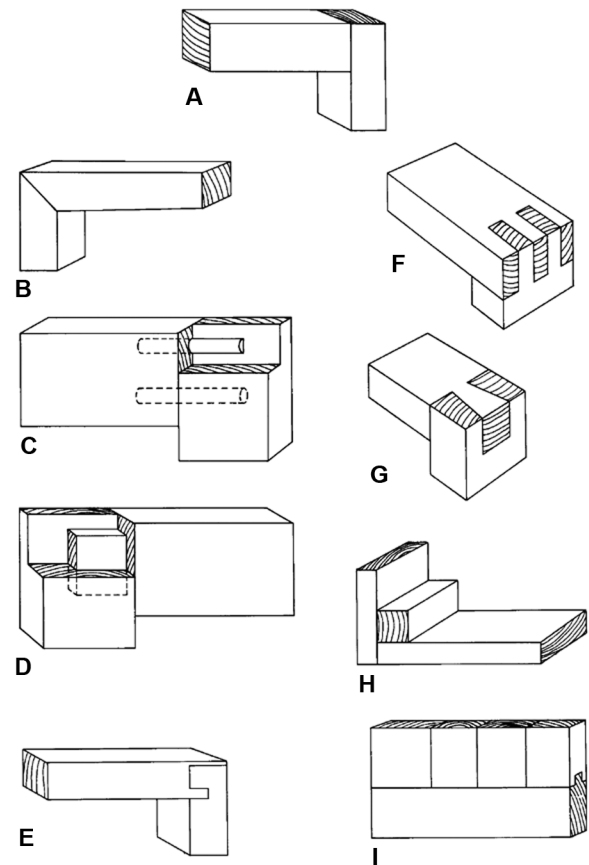


Figure 10-8. End-to-edge-grain joints: A, plain; B, miter; C, dowel; D, mortise and tenon; E, dado tongue and rabbet; F, slip or lock corner; G, dovetail; H, blocked; I, tongue-and-groove.

result, it is necessary to design these joints with interlocking surfaces so that edge grain of the interlocking piece bonds to the edge grain of the adjoining piece. Increasing the joint surface area also helps by providing more bondline to transfer load. Some examples of strong connections are dowels, mortise and tenons, and rabbets (Fig. 10-8). Because wood swells so much more across the grain than along the grain, moisture changes in these joints produce large internal stresses. All end-to-edge-grain joints should be protected from changes in moisture content in service.

Construction Joints

Elastomeric construction adhesives are commonly used in the light-frame construction industry for field assembly of panelized floor and wall systems. Structural panels are bonded to floor joists and wall studs with these adhesives, which have the unique capability of bridging gaps up to 6.5 mm (1/4 in.) between rough and poorly fitting surfaces (Fig. 10-9). Without any premixing, the adhesive is extruded in a bead along framing members with a hand-held caulk gun or a pressurized dispenser. Nails or screws provide the only pressure for bonding to hold materials in position while the adhesive sets. Elastomerics are also uniquely tolerant of temperature and moisture content

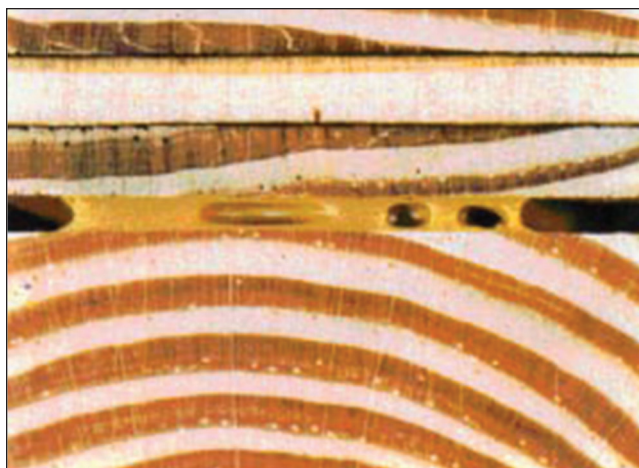


Figure 10–9. Gap-filling construction adhesive in field-assembled floor system. The adhesive minimizes problems arising from imperfect assembly.

variations at field construction sites. Although they do not deliver the strength and durability of conventional structural adhesives, elastomerics are strong and flexible enough to give long-term performance under most conditions of installation and service.

Construction adhesives enable a nailed or screwed floor system to act to some degree as a composite assembly with increased stiffness. Floors are less bouncy with fewer squeaks and nail pops or screw pulls. However, structural design of the composite assembly is based only on the stiffness of nailed or screwed panel and framing materials. The strength contributed by the adhesive cannot be factored into the engineering design but provides increased value.

Testing and Performance

Testing is necessary to ensure that adhesively bonded materials hold together within a given service environment for the life of the structure. Many methods are available to test bonding performance, particularly for bonded assemblies. Generally, these testing methods attempt to predict how bonded joints are likely to perform in a specific loading mode (shear, tensile, creep) in an assembly at specific temperature and moisture conditions for a specific time.

Most performance tests are short term. They are based on chemical, mechanical, and rheological laboratory tests of adhesive polymers, adhesives, and bonds. Intermediate-term tests of products that are conducted in pilot operations and field experiments are integrated with short-term laboratory tests in an effort to extrapolate these data into long-term performance. Long-term tests of bonded assemblies under actual environmental exposures are rarely conducted, because this information may not be available for 10 to 30 years. Therefore, short-term tests are used extensively to predict long-term performance. As we learn more about the relationships between chemical structure and mechanical

performance, and as companies are under continued pressure to launch new products, reliance on short-term testing is increasing.

Analytical, Chemical, and Mechanical Testing of Polymers

Although many methods of characterizing adhesives are available, this section only briefly mentions some of the most important and common methods. Nuclear magnetic resonance (NMR) spectroscopy and other spectroscopic techniques help characterize the molecular structures of adhesive polymers. Molecular-size distribution is commonly measured by gel permeation chromatography (GPC), also known as size exclusion chromatography (SEC). Differential scanning calorimetry (DSC) and gel times provide information on rates of chemical curing reactions. The rheological properties of curing and cured adhesives are characterized by rheometers, dynamic mechanical analysis (DMA), and torsional-braid analysis (TBA). Sophisticated fracture mechanics techniques are used to measure toughness of adhesive bonds as they fail in a cleavage mode. High-magnification microscopes, including scanning electron microscope, transmission electron microscope, and atomic force microscope, enable scientists to see wood and adhesive surfaces in minute detail before, during, and after fracture. Fluorescent and confocal microscopies provide excellent information on adhesive distribution, adhesive penetration, and bond fracture surfaces because of their ability to distinguish between wood and adhesive.

Although much can be learned from measurements of chemical, mechanical, and rheological properties of polymers and adhesives before their application to wood, the correlation between laboratory test and product performance is never perfect. There is no substitute for testing performance in bonded assemblies prepared with specific adhesives and materials and tested under specific loading modes, environmental conditions, and duration of loading. Although adhesives are formulated through a blend of scientific analysis and art of formulation, they are tested for strength and durability in the laboratory and field, usually by industry-accepted standard test methods and product specifications.

Mechanical Testing of Bonded Assemblies

To promote communication and understanding, many standardized test methods have been developed for evaluating and comparing the performance of different materials. Most test methods, specifications, and practices for adhesives and bonded assemblies are consensus standards. ASTM International publishes a book of standard methods each year. European jurisdictions tend to specify ISO standards developed by the International Standards Organization or their own national standards. Several trade associations have their own specifications and performance standards that apply to their specific wood products.

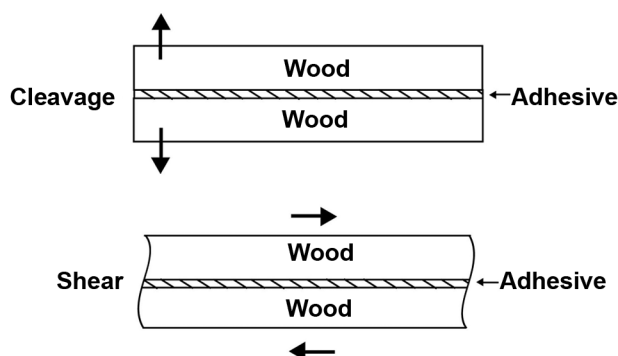


Figure 10–10. Failure modes of cleavage and shear in adhesive bonds.

Customers may also have their own tests. Standard tests attempt to specify all the relevant variables: materials, conditions of materials and testing, testing procedures, etc. to ensure repeatability and enable valid comparisons of data.

Two basic failure modes, cleavage and shear, are commonly used to test adhesive bonds to determine strength levels during impact, flexure, fatigue, and creep under long-term stress (Fig. 10–10). The following describes the basic stress modes in adhesive-bonded joints:

- Cleavage, or mode I, failure results from forces applied perpendicular to the bondline. These forces may be applied by a wedge or other crack-opening device, by pulling on a double cantilever beam, or by pulling two faces apart, such as in a section of particleboard. Tensile loads often result in cleavage failures.
- Shear, or mode II, failure results from forces applied parallel to the bondline, either in compression or tension, but care needs to be taken so to minimize the cleavage mode from the shear test due to substrate deflection.

As the names imply, impact, fatigue, and creep are tests that pertain to the rate at which loads are applied. Standard testing is done so that load continues to increase until failure, typically occurring between 1 and 5 min. Impact loads are sudden; for example, hitting a specimen with a swinging arm. Fatigue is the loss in strength from repeated loading and unloading to reflect bond deterioration from mechanical stresses. Sometimes, environmental stresses such as moisture and temperature, are added as well. Creep loads are static loads applied for long times, from a few days to years, usually under extreme environmental conditions.

The common measures used to estimate potential performance of bonded wood joints are strength and wood failure from mechanical tests and delamination after exposure to water. The highest performance level after exposure to severe environmental conditions is bond strength being greater than wood strength, wood failure in more than 85% of the bonded area, and less than 5% or 8% delamination of the joint, for softwoods and hardwoods, respectively. These performance values reflect how wood,

adhesive, and environmental exposure interact in response to loading.

Exceeding the strength of wood is a desired performance criterion, and especially in the North American market, can be more important than measured shear strength. Percentage of wood failure is the amount of wood that fails as a percentage of the area of the bonded joint. In general, strong and durable bonds give high wood failure and fracture deep into the grain of the wood. If wood failure is shallow with only wood fibers remaining attached to the adhesive film, bond strength and durability may be lacking. Thus, a consistently high level of wood failure, above 75% in some standards and above 85% in others, means that the shear strength associated with these bonds is a good estimate of the load-carrying capability of the joint. High levels of wood failure in a wet and hot environment suggest that the adhesive bond is as strong as or stronger than the wood. Wood failure is considered a valid measure of bond strength only to solid wood, not in reconstituted products made of bonded wood particles.

Bonds in structural assemblies are expected to exceed the strength of the wood, so in traditional design of joints, adhesive strength has been ignored. Traditionally, adhesives that are not as strong as the wood simply have not been used in structural applications.

Short- and Long-Term Performance

Virtually all bonded wood products, even for interior applications, have some kind of moisture durability test. Even interior, nonstructural products will occasionally get wet, and the swelling forces during wetting can be very high. In addition to the added swelling stress, mechanical properties of wood, adhesives, and bonded products typically decrease with moisture and heat. Therefore, cyclic wetting–drying, sometimes with additional heat, are challenging for many wood adhesives.

Delamination testing is one way to evaluate how well the bonded joint withstands severe moisture-induced swelling and shrinking stresses. Delamination is the separation between laminates because of adhesive failure, either in the adhesive or at the interface between adhesive and wood. If adhesives are able to resist delaminating forces, any wood failure will occur adjacent to the bondline, not within it. For example, after exposure to three cycles of saturation followed by oven drying in ASTM D2559–12a, glulam beams cannot exceed 5% delamination in softwoods and 8% in hardwoods.

If the adhesive and wood are not deformed beyond their yield points during the exposure, they may return to their original size after drying and cooling, and so wetting–drying may not actually degrade the product. When considering bond degradation with exposure, wood properties generally decrease faster under heat and moisture than do rigid thermosetting adhesives like resorcinol-,

phenol-, and melamine-formaldehyde, but this is not true for urea-formaldehyde. Therefore, evaluating short-term performance of products made with these adhesives is simply not a matter of testing bonds at room temperature in dry and wet conditions. With increased moisture and/or heat, thermoplastic adhesives such as poly(vinyl acetate), elastomerics, hot-melts and pressure-sensitive adhesives tend to lose stiffness and strength more rapidly than does wood. These adhesives must be tested dry, dry after water soaking, and after prolonged exposure to high humidity environments. High wood failure in shear of water-saturated bonds is also a strong indicator of moisture durability. In addition, some specifications require testing bonded structural and nonstructural products at elevated temperatures similar to what might be encountered in roofs or enclosed shipping containers. A short-term dead-load test at elevated temperatures may also be required. Adhesive specifications for structural products such as laminated beams and plywood require high minimum strength and wood failure values after several different water exposure tests.

Long-term deterioration of wood, adhesives, and bonded products is determined by the levels of temperature, moisture, and stress, and in some instances by concentrations of chemicals and presence of microorganisms. Long-term performance is the ability of a product to resist loss of a measured mechanical property over the time of exposure. A durable bonded product is one that shows no greater loss of properties during its life in service than does solid wood of the same species and quality. Many adhesives in bonded products have decades of documented performance in many environments. Thus, it is possible to predict with a high degree of certainty the long-term performance of similar products. Well-designed and well-made joints with any of the commonly used woodworking adhesives will retain their strength indefinitely if the moisture content of the wood does not exceed approximately 15% and if the temperature remains within the range of human comfort. However, some adhesives deteriorate when exposed either intermittently or continuously to temperatures greater than 38 °C (100 °F) for long periods. Low temperatures seem to have no significant effect on strength of bonded joints, but test data are sparse for very cold conditions.

Products made with phenol-formaldehyde, resorcinol-formaldehyde, and phenol-resorcinol-formaldehyde adhesives have proven to be more durable than wood when exposed to warm and humid environments, water, alternate wetting and drying, and even temperatures high enough to char wood. These adhesives are adequate for use in products that are exposed to the weather indefinitely (Fig. 10–11).

Well-made products with melamine-, melamine-urea-, and urea-formaldehyde resin adhesives have proven to be less durable than wood. Melamine-formaldehyde is only slightly

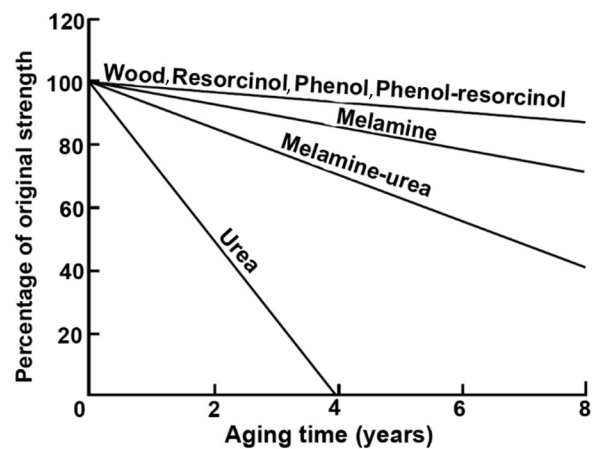


Figure 10–11. Relative rates of deterioration of bond strength of small specimens exposed directly to weather.

less durable than phenol-formaldehyde or resorcinol-formaldehyde and is considered acceptable for structural products. Although considered less durable, melamine-urea-formaldehyde is also accepted in structural products at a melamine-to-urea ratio of 60:40 or larger. Urea-formaldehyde resin is susceptible to deterioration by heat and moisture (Fig. 10–11).

Products bonded with poly(vinyl acetate) and protein-based adhesives without cross-linkers often fail after exposure to wet–dry cycling. However, if properly formulated with appropriate cross-linkers, these adhesives are durable in normal interior environments.

Some isocyanate, epoxy, polyurethane, and cross-linked poly(vinyl acetate) adhesives are durable enough to use on lower density species even in exterior conditions, but for most of these adhesives, exterior exposure should be limited. Some elastomer-based adhesives may be durable enough for limited exposure to moisture with lower density species in nonstructural applications or in structural applications when used in conjunction with approved nailing schedules. Some polyurethane, emulsion polymer isocyanates (EPI), and polymer emulsion polyurethane (PEP) adhesives that chemically cure and remain flexible are among the durable structural adhesives.

New adhesives do not have a history of long-term performance in service environments, so accelerated laboratory exposures that include cycles of heat, moisture, and stress are used to estimate long-term performance. However, laboratory exposures cannot duplicate the actual conditions of a service environment. Estimates of long-term performance can be obtained by exposing specimens outdoors for up to 30 years. Outdoor exposures may be intensified by facing specimens toward the sun to maximize solar heating and by establishing exposure sites in regions with the most extreme service environments, for example, southern coastal and arid southwestern regions. To date, only four long-term laboratory-aging methods have been

standardized for adhesives approval, but the bonded product is the item that must meet code standards. Therefore, performance of any new adhesive or bonded product must be compared with performance of established adhesives or products tested in the same laboratory exposure.

Product Quality Assurance

After the short- and long-term performance of a product has been established, maintenance of the manufacturing process to ensure that the product will be made and perform at that level is the major concern of a quality-assurance program, which consists of three parts:

1. Establishing limits on adhesive properties and bonding process factors that will ensure acceptable joints and product
2. Monitoring production processes and bond quality in joints and product
3. Detecting unacceptable joints and product, determining the cause, and correcting the problem

Structural panel, laminated-beam, particleboard, plywood, millwork, and other industrial trade associations have established quality-assurance programs that effectively monitor the joint and product performance at the time of manufacture for compliance with voluntary product standards. Product performance is usually evaluated immediately after manufacture by subjecting specimens from the product to a series of swell–shrink cycles. The treatments are more rigorous for products intended for exterior exposure. For example, exterior softwood plywood is subjected to two boil–dry cycles, whereas interior plywood is subjected to three cycles of soak–dry steps at room temperature. After exposure, specimens are evaluated for delamination, percentage wood failure, or both. Test results are compared with the minimum requirement in the trade association’s standards. Lengthy experience and correlations between exterior performance and accelerated laboratory tests have shown that products with at least the minimum values will likely perform satisfactorily in service. If the product meets the requirement, it is certified by the association as meeting the standard for satisfactory performance.

Heat Resistance of Adhesives

In the early 2000s, there was a surge of interest in the fire performance of structural adhesives. North America responded by creating the “Heat Resistant Adhesive” classification, for adhesives shown to be extremely stable in full-scale assemblies tested under load while exposed to fire. Europe’s approach was to recognize the insulating value of wood and demand that there be enough material left in the protected core of a structural member to carry the design load after the surface had charred. The fire performance of adhesives in cross-laminated timber (CLT) construction has been a focus of CLT development for tall wooden buildings.

No-Added-Formaldehyde and Bio-Based Adhesives

Environmental factors have played an increasing role in recent years. The emphasis in many developed countries to decrease formaldehyde emissions from wood products has had a big impact on the urea-formaldehyde adhesives. The trend towards no-added-formaldehyde adhesives to replace UF adhesives seem to be continuing, although these products still represent a small portion of the market.

In addition, a trend towards bio-based adhesives to replace those that come from petrochemicals is occurring. Given the low cost of wood adhesives, lignins from various sources are being widely investigated. Soy proteins have largely replaced UF in interior plywood in North America. Research and market demand continue to drive new product development.

Acknowledgment

Much of the information in this article is taken from “Adhesives with Wood Materials—Bond Formation and Performance,” chapter 10 of *Wood Handbook*, FPL–GTR–190, authored by Charles R. Frihart and Christopher G. Hunt.

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Wood Handbook

Wood as an Engineering Material

Abstract

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

Keywords: wood structure, physical properties (wood), mechanical properties (wood), lumber, wood-based composites, plywood, panel products, design, fastenings, wood moisture, drying, gluing, fire resistance, finishing, decay, preservation, wood-based products, heat sterilization, sustainable use

March 2021

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