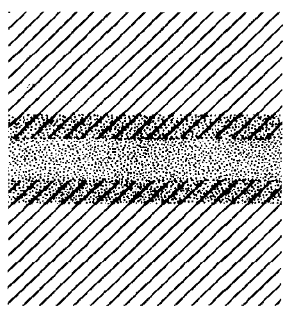
Glues and Gluing

Woodworking adhesives, used correctly, are stronger than wood

by R. Bruce Hoadley

The general term "adhesive" covers any substance that can hold two materials together by surface attachment. Those most commonly used for wood are called "glues," although materials described as "resins," "cements" and "mastics" are equally important in the assembly of wood products. Today's woodworkers use adhesives in a number of ways: to make pieces larger than available stock (such as carving blocks or laminated beams), to create combinations or composites for physical or esthetic improvement (such as plywood, overlays or marquetry) and to join parts to create a final product (as in furniture, sporting goods or structures). Certain basic considerations which may be overlooked or misunderstood are too often the cause of serious gluing problems and are worthy of systematic review.

A logical starting point is to wonder why glue sticks at all. It is sometimes assumed that adhesion results from the interlocking of minute tentacles of hardened adhesive into the fine porous cell structure of the wood surface. However scientific research has shown that such mechanical adhesion is insignificant compared to the chemical attachment due to molecular forces between the adhesive and the wood surface, or specific adhesion. The assembled joint, or bond, is often discussed in terms of five intergrading phases, each of which can be thought of as a link in a chain. The weakest phase determines the success of the joint. Phases 1 and 5 are the pieces of wood, or adherends, being joined. Phases 2 and 4 are the interpenetrating areas of wood and adhesive, where the glue must "wet" the wood to establish molecular closeness for specific adhesion. Phase 3 is the adhesive itself, which holds together by cohesion.



Fundamentally, then, gluing involves machining the two mating surfaces, applying an adhesive in a form which can flow onto and into the wood surface and wet the cell structure, and then applying pressure to spread the adhesive uniformly thin and hold the assembly undisturbed while the adhesive solidifies. The typical adhesive is obtained or mixed as a liquid but sets to form a strong glue layer, either by loss of solvent, which brings the adhesive molecules together and allows them to attach to one another, or by a chemical reaction that develops a rigid structure of more complex molecules.

A wide and sometimes confusing array of adhesive products confronts the woodworker. A common pitfall is the dangerous belief that some glues are "better" than others; the notion that simply acquiring "the best" will ensure success tempts disastrous carelessness in using it. With certain qualifications, it can generally be assumed that all commercially available adhesives will perform satisfactorily if chosen and used within their specified limitations. An important corollary is that no adhesive will perform satisfactorily if not used properly. Within the specified limitations, most woodworking adhesives are capable of developing a joint as strong as the weaker of the woods being joined; that is, the wood, rather than the glue or its bond, is the weak link in the chain.

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Wood

Wood is a complicated material. Due to the cellular arrangement within the wood and, in turn, the reactive cellulose within the cell, adhesive bonding is maximum at side-grain surfaces, and minimum at end-grain surfaces. This is especially important to realize in view of the large longitudinal-to-transverse strength ratio we are accustomed to in solid wood. Thus end-grain attachment should be considered only in conjunction with appropriate joints or mechanical fastenings. With side-to-side grain combinations, lamination of pieces with parallel grain arrangement is most successful. With cross-ply orientation, the relative thicknesses of adjacent layers must be considered in relation to the dimensional changes the composite will have to restrain.

Different woods have different gluing properties. In general, less dense, more permeable woods are easier to glue; for example, chestnut, poplar, alder, basswood, butternut, sweetgum and elm. Moderately dense woods such as ash, cherry, soft maple, oak, pecan and walnut glue well under good conditions. Hard and dense woods, including beech, birch, hickory, maple, osage orange and persimmon, require close control of glue and gluing conditions to obtain a satisfactory bond. Most softwoods glue well, although in uneven-grained species, earlywood bonds more easily than denser latewood. Extractives, resins or natural oils may introduce gluing problems by inhibiting bonding, as with teak and rosewood, or by causing stain with certain glues, as with oaks and mahogany.

Since most adhesives will not form satisfactory bonds with wood that is green or of high moisture content, wood should at least be well air-dried. Ideally wood should be conditioned to a moisture content slightly below that desired for the finished product, to allow for the adsorption of whatever moisture might come from the adhesive. For furniture, a moisture content of 5% to 7% is about right. For thin veneers, which take up a proportionately greater amount of moisture, an initial moisture content below 5% might be appropriate.

Machining is especially critical. In some cases, especially for multiple laminations, uniform thickness is necessary for uniform pressure. Flatness is required to allow surfaces to be brought into close proximity. The surfaces to be glued should have cleanly severed cells, free of loose fibers. Accurate hand planing is excellent if the entire surface, such as board edges, can be surfaced in one pass. On wide surfaces, peripheral milling (planing, jointing) routinely produces adequate surfaces. Twelve to twenty-five knife marks per inch produce an optimum surface. Fewer may give an irregular or chipped surface; too many may glaze the surface excessively.

Dull knives that pound, heat and glaze the surfaces can render the wood physically and chemically unsuited for proper adhesion even though it is smooth and flat. Planing saws are capable of producing gluable surfaces, but in general (with exceptions, like epoxies) sawn surfaces are not as good as planed or jointed ones.

Surface cleanliness must not be overlooked. Oil, grease, dirt, dust and even polluted air can contaminate wood surface and prevent proper adhesion. Industry production standards usually call for "same-day" machining and gluing. Freshly machining surfaces just before gluing is especially important for species high in resinous or oily extractives. Where this is not possible, washing surfaces with acetone or carbon tetrachloride is sometimes recommended. One should not expect a board machined months or years ago to have surfaces of suitable chemical purity. If lumber is flat and smooth, but obviously dirty, a careful light sanding with 240-grit or finer abrasive backed with a flat block, followed by thorough dusting, can restore a chemically reactive surface without seriously changing flatness. Coarse sanding, sometimes thought to be helpful by "roughening" the surface, is actually harmful because it leaves loose bits. In summary, wood should be surfaced immediately prior to gluing, for cleanliness and to minimize warp, and should be kept free of contamination to ensure a gluable surface.

Time

Shelf life is the period of time an adhesive remains usable after distribution by the manufacturer. Unlike photographic films, adhesives are not expiration dated. Beware the container which has been on the dealer's shelf too long. Outdated package styles are an obvious tip-off. It is wise to mark a bottle or can with your date of purchase. It is amazing how fast time can pass while glue sits idle in your workshop.

The adage, "when all else fails, read the instructions," all too often applies to glue. It is unfortunate that instructions are so incomplete on retail glue containers. Manufacturers usually have fairly elaborate technical specification sheets but supply them only to quantity consumers. Too often, many critical factors are left to the user's guesswork or judgment. Mixing proportions and sequence are usually given clearly; obviously they should be carefully followed.

Glues with a pH above 7 (alkaline), notably casein resins, will absorb iron from a container and react with certain woods such as oak, walnut, cherry, and mahogany to form a dark stain. Coffee cans or other ferrous containers can contribute to this contamination. Nonmetallic mixing containers such as plastic cups or the bottoms of clean plastic bleach jugs work out nicely.

Once glue is mixed, the pot life, or working life, must be regarded. Most adhesives have ample working life to handle routine jobs. The period between the beginning of spreading the glue and placing the surfaces together is called open assembly time; closed assembly time indicates the interval between joint closure and the development of full clamping pressure. Allowable closed assembly time is usually two or three times open assembly time. With many ready-to-use adhesives, there is no minimum open assembly time; spreading and closure as soon as possible is recommended, especially in single spreading, to ensure transfer and wetting of the other surface. If the joint is open too long, the glue may precure before adequate pressure is applied. The result is called a dried joint. In general, assembly time must be shorter if the wood is porous, the mixture viscous, the wood at a low moisture content, or the temperature above normal. With some adhesives, such as resorcinol, a minimum open assembly may be specified for dense woods and surfaces of low porosity, to allow thickening of the adhesive and prevent excessive squeeze-out.

Whereas commercial operations usually have routine procedures for clamping, the nemesis of the amateur is not having his clamps and cauls ready. In the scramble to adjust screws or find extra clamps, parts may be shifted and assembly time exceeded. It is worthwhile to clamp up an assembly dry to make sure everything is ready before spreading the glue.

Spreading

Glue should be spread as evenly as possible, even though some degree of self-distribution will of course result when pressure is applied. Brush application works well with thinner formulations. A spatula, painter's palette knife or even a flat stick can be used as a spreader. A small rubber roller for inking print blocks does a great job in spreading glue quickly and evenly. Paint rollers and paint trays can be used with some adhesives.

Proper spread is difficult to control. Too little glue results in a starved joint and a poor bond. A little overage can be tolerated, but too much results in wasteful and messy squeeze-out. With experience the spread can be eyeballed, and it is useful to obtain some commercial specifications and conduct an experiment to see just what they mean. Spreads are usually given in terms of pounds of glue per thousand square feet of single glue line, or MSGL. A cabinetmaker will find it more convenient to convert to grams per square foot, by dividing lbs./MSGL by 2.2. Thus a recommended spread of 50 lbs./MSGL, typical of a resorcinol glue, is about 23 grams per square foot. Spread it evenly onto a square foot of veneer for a fair visual estimate of the minimum that should be used. Usually, the recommended spread appears rather meager.

Double spreading, or applying adhesive to each of the mating surfaces, is recommended where feasible. This ensures full wetting of both surfaces, without relying on pressure and flatness to transfer the glue and wet the opposite surface. With double spreading, a greater amount of glue per glue line is necessary, perhaps a third more.

Clamping

The object of clamping a joint is to press the glue line into a continuous, uniformly thin film, and to bring the wood surfaces into intimate contact with the glue and hold them undisturbed until setting or cure is complete. Since loss of solvent causes some glue shrinkage, an internal stress often develops in the glue line during setting. This stress becomes intolerably high if glue lines are too thick. Glue lines should be not more than a few thousandths of an inch thick.

If mating surfaces were perfect in terms of machining and spread, pressure wouldn't be necessary. The "rubbed joint," skillfully done, attests to this. But unevenness of spread and irregularity of surface usually require considerable external force to press properly. The novice commonly blunders on pressure, both in magnitude and uniformity.

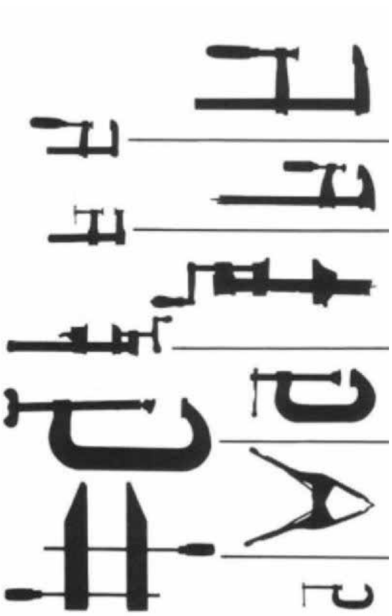
Clamping pressure should be adjusted according to the density of the wood. For domestic species with a specific gravity of 0.3 to 0.7, pressures should range from 100 psi to 250 psi. Denser tropical species may require up to 300 psi. In bonding composites, the required pressure should be determined by the lowest-density layer. In gluing woods with a specific gravity of about 0.6, such as maple or birch, 200 psi is appropriate. Thus gluing up one square foot of maple requires pressure of (12 in. x 12 in. x 200 psi) 28,800 pounds. Over 14 tons! This would require, for an optimal glue line, 15 or 20 cee-clamps, or about 50 quick-set clamps. Conversely, the most powerful cee-clamp can press only 10 or 11 square inches of glue line in maple. Jackscrews and hydraulic presses can apply loads measured in tons. But since clamping pressure in the small shop is commonly on the low side, one can see the importance of good machining and uniform spread.

But pressure can be overdone, too. Especially with low-viscosity adhesives and porous woods, too much pressure may force too much adhesive into the cell structure of the wood or out at the edges, resulting in an insufficient amount remaining at the glue line, a condition termed a starved joint. Some squeeze-out is normal at the edges of an assembly. However, if spread is well controlled, excessive squeeze-out indicates too much pressure; if pressure is well controlled, undue squeeze-out suggests too much glue. Successful glue joints depend on the right correlation of glue consistency and clamping pressure. Excessive pressure is no substitute for good machining. Panels pressed at lower pressures have less tendency to warp than those pressed at higher pressures. Additionally, excessive gluing pressure will cause extreme compression of the wood structure. When pressure is released, the cells spring back and add an extra component of stress to the glue line.

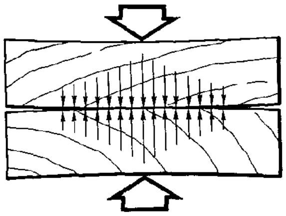
The second troublesome aspect of clamping is uniformity, usually a version of what I call "the sponge effect." Lay a sponge on a table and press it down in the center; note how the edges lift up. Similarly, the force of one clamp located in

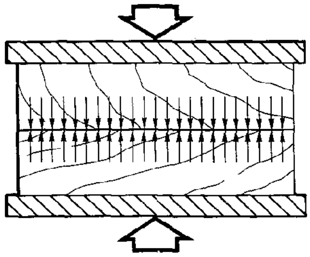
To find out just how much pressure typical woodworking clamps could apply, Hoadley attached open steel frames to the crossheads of a universal timber-testing machine. With a clamp positioned to draw the frames together, the load applied was indicated directly.

The clamps are described in the table, with the last column giving the average of three trials by average-sized Hoadley, tightening as if he were trying to get maximum pressure in a gluing job. The quick-set clamp listed first in the table was used to calibrate the setup: A secretary squeezed 330 lbs., a hockey player squeezed 640 lbs., and Hoadley squeezed 550 lbs. Repeated trials by each person yielded readings that agreed to within 10%. An asterisk indicates that the clamp began to bend and the test was stopped at the value listed.



Brand, size, handle style	Screw dia., thread type	Load, pounds
Lust, 5-in. jaw, straight handle	.645 in., square	550
Hartford, 4-in. jaw, straight handle	.370 in., square	400
Jorgenson, 4-in. jaw, straight handle	.375 in., V	420
Stanley, 6 in., T-bar handle	.375 in., V	355*
S.H. Co. bar, crank handle	.625 in., square	2060
Sears 3/4-in. pipe, butterfly crank	.625 in., square	1120*
Jorgenson, 4 in., T-bar handle	.610 in., square	2110
Jorgenson 8 in., butterfly handle	.750 in., square	1100
Pony, 8 in.	spring	25
Craftsman, 10 in., straight handle	.435 in., square	920
Unknown C-clamp 2-in. jaw, T-bar	.310 in., V	560



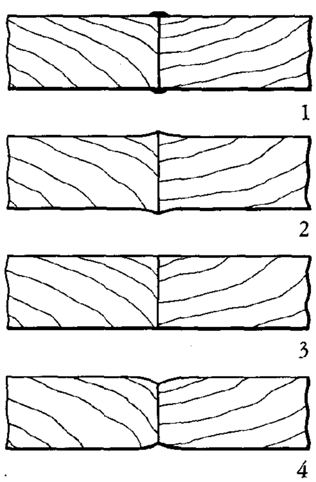


the middle of a flat board will not be evenly transmitted to its edges. It is therefore essential to use heavy wooden cover boards or rigid metal cauls to ensure proper distribution of pressure.

Clamp time must be long enough to allow the glue to set well enough so that the joint will not be disturbed by clamp removal. Full cure time, that is, for development of full bond strength, is considerably longer. If the joint will be under immediate stress, the clamp time should be extended. Manufacturer's specified clamp times are established for optimum or recommended shelf life, temperature, wood moisture content, etc. If any of these factors is less than optimum, cure rate may be prolonged. It's best to leave assemblies overnight.

Most glue specifications are based on "room temperature" (70° F). Shelf life is shortened by storage at above-normal temperature, but may be extended by cold storage. Normal working life of three to four hours at 70° F may be reduced to less than one hour at 90° F. Closed assembly at 90° F is 20 minutes, against 50 minutes at 70° F. A curing period of 10 hours at 70° F can be accelerated to 3-1/2 hours by heating to 90° F.

Finally, cured joints need conditioning periods to allow moisture added at the glue line to be distributed evenly through the wood. Ignoring this can result in sunken joints. When edge-gluing pieces to make panels, moisture is added to the glue lines (1), especially at the panel surfaces where squeeze-out contributes extra moisture. If the panel is surfaced while the glue line is still swollen (2, 3), when the moisture is finally distributed the glue line will shrink (4), leaving the sunken joint effect.



Adhesives

No truly all-purpose adhesive has yet been manufactured and probably never will be. A general-purpose adhesive cannot hope to attain all the individual capabilities and attributes of closely designed ones. Although any of the standard commercial glues will do a satisfactory job if the moisture content of the wood is below 15% and the temperature remains within the human comfort range, there is an increasing trend toward development of special adhesives. Adhesive selection must therefore take into account factors such as species, type of joint, working properties as required by anticipated gluing conditions, performance and strength, and, of course, cost.

One interesting adhesive is water. It is easily spread, wets wood well and solidifies to form a remarkably strong joint. It is delightfully inexpensive. However, it is thermoplastic and its critical maximum working temperature is 32° F. At temperatures at which it will set it has a very short assembly time. But due to its temperature limits water will never capture a very important position among woodworking adhesives.

Glues made from natural materials have been used from earliest times. Although synthetic materials have emerged to the forefront, traditional natural adhesives are still in use.

Hide glue (LePage's Original Glue, Franklin's Liquid Hide Glue) is made from hides, tendons, and/or hoofs of horses, cattle and sheep. It is available in granules which must be soaked in water, but more commonly in ready-to-use form. Hide glue sets by evaporation and absorption of solvent. It has a moderate assembly time and sets in a matter of hours at room temperature. It develops high strength but is low in moisture resistance. Hide glue is used mainly for furniture. Its popularity in recent years has declined drastically with the development of synthetic glues.

Casein glue is primarily a milk derivative although it contains lime and other chemicals in various formulations. It is purchased as a powder that is mixed with water; after mixing, it must be allowed to set for about 15 minutes. Casein glue has the advantage of fairly long assembly time (15 to 20 minutes) but cures rather slowly (8 to 12 hours at room temperature). The glue line is neutral in color but may stain many woods and is somewhat abrasive to cutting tools. The claim of being a good gap-filling adhesive seems somewhat doubtful. Casein has moderately good heat resistance and bonds show significant short-term moisture resistance, but it is not recommended for exterior use. Casein is used extensively for laminating and large carpentry jobs.

Polyvinyl resin emulsions are probably the most versatile and widely used wood adhesives. These are the white glues (Elmer's Glue-All, Franklin's Evertite white glue, Sears' white glue), also called PVA because of their principal constituent, polyvinyl acetate. White glues have a long shelf life and can be used as long as the resin remains emulsified. Setting is by water absorption and quite rapid at room temperature; clamping time of less than one hour may suffice if the joints are not to be stressed immediately. The white glues are non-staining and dry clear. The glue does not dull tools but excess squeeze-out may clog or foul sandpaper under frictional heating because the adhesive is thermoplastic. These glues develop high strength but have low resistance to moisture and heat. An important characteristic is their "cold flow," or creep under sustained loading. This is an asset where dimensional conflict is involved, as in mortise and tenon joints. However, in edge gluing and lamination, "shifting" of adjacent pieces may in time produce visible unevenness at joints. In chair seats, joints may open along end grain due to drastic moisture change.

Numerous modified PVA glues give greater rigidity and improved heat resistance. The so-called aliphatic resin glues, commonly called yellow glue (Franklin's Titebond, Elmer's Carpenter's Wood Glue) fall into this group. The low viscosity of the white glues was always troublesome in furniture assembly, since any dribble of glue from joints caused difficulty in later finishing. The aliphatic glues are much more viscous and greatly reduce this problem. Some consider these glues as representing an intermediate position between the white glues and the urea-formaldehyde glues. However, yellow glues are not sufficiently weather-resistant to replace urea resins in carpentry.

The development of modern plywood and laminated products that have outstanding durability under extremes of outdoor exposure was possible only with the thermosetting resin adhesives. Several of these types are available to the woodworker.

Resotcinol-formaldehyde (Franklin or U.S. Plywood Resorcinol Waterproof Glue, Elmer's Waterproof Glue) are the woodworker's mainstay because of their high strength and resistance to heat and moisture. The most common form is a dark reddish liquid resin with a tan powdered hardener, paraformaldehyde. The mixed resin has four or more hours of working life at room temperature and its ample assembly time allows for complicated clamping operations. With high-density woods, double spreading with open assembly of 10 or 15 minutes is recommended to prevent starved joints. The adhesive will set at room temperature; cure periods are 8 to 12 hours, but can be drastically shortened by elevating temperature, which also ensures maximum durability. Use of the adhesive below 70° F is not recommended. Resorcinols are invaluable for room-temperature bonding of laminated timber and of assembly joints that must withstand severe conditions, such as marine and outdoor use. Phenol-formaldehyde adhesives have the superior durability of resorcinols but require heat for curing and are thus not readily suited to the average cabinet shop. They are used mainly for commercial production of plywood and particleboard.

Urea-formaldehyde glues (Weldwood or Craftsman Plastic Resin Glue), often marketed as "plastic resin adhesive," have become extremely important for the woodworker. The ureas represent perhaps the most versatile resin type, capable of bonding at room or elevated temperatures and curable with electronic gluing equipment. They are widely used in cabinetmaking, veneer work, plywood, interior particleboard and furniture. They can be modified with filler to form excellent gap-fillers. They commonly come as a tan powder consisting of both resin and hardener, activated by mixing with water. Liquid ureas are also available. Working life of mixtures is 3 to 5 hours at *70°* F. Use with wood at moisture contents below 6% is not recommended, because of the rapid rate of water absorption from the glue. Assembly time of 15 minutes is allowed and the inconspicious white-to-tan glue lines cure in 6-8 hours at room temperature. Glue bonds are highly water-resistant but lack durability at temperatures above 120° F.

Melamine adhesives are similar in appearance and mixing properties to ureas. They are very strong and resistant to water and heat. They are especially useful where the dark glue line of phenolic or resorcinol resins is undesirable. However, they require heat for curing, and find greatest use as a fortifier for urea in industrial applications and for high-frequency edge gluing.

Hot melts (Sears Glue Gun, Franklin's hot melt) are thermoplastic synthetics marketed as solid sticks that are softened in an electrically heated gun. These glues are applied hot, the assembly quickly closed, and rapid setting effected as cooling takes place. Hot melts are not a new concept, for great-grandfather's double boiler glue-pot used hot animal glue in just this way. Modern hot melts are new chemically, however, and include polyvinyl esters, acetals, cellulose esters or polyamides. Their principal advantage is the rapid development of initial strength upon cooling; a disadvantage is the very brief open assembly time. Hot melts are convenient for applying edge banding, furniture reinforcement, blocking, toy parts, and the like. They are easier to use if the wood is heated to extend assembly time.

Epoxy glues (Elmer's epoxy, Devcon clear epoxy) are among the modern "miracle" adhesives. There are several chemically different types, but all involve two liquids, a resin and hardener, which are mixed in equal amounts to initiate curing. The rate of cure varies widely. In the rapid-set types (Devcon 5-minute epoxy) open assembly is limited to a couple of minutes, but stiffening takes place quickly and a high percentage of full-bond strength is developed in less than ten minutes. Other formulations have up to an hour of working life but take up to 24 hours or more to cure. Epoxy resins will bond to glass, ceramics, tile, brick and many plastics (but not polyethylene, polypropylene and Teflon). They cure by chemical reaction rather than loss of solvent, and are excellent gap fillers. It has been reported that epoxy bonds better on clean, sanded surfaces or even sawn surfaces than on smoothly planed wood. Most glue lines are clear or nearly clear and waterproof. The major disadvantages of epoxy are relatively high cost and rather short pot life.

Contact cements (Goodyear Pliobond, Weldwood Plus-10, Elmer's Acrylic Latex Cabinetmaker's Contact Cement) are thermoplastics applied by double spreading and allowed to dry until no longer tacky. When the adhesive layers are touched together, cohesive bonding forms up to two-thirds of the ultimate strength immediately, hence the term contact cement. They will bond to many materials in addition to wood. Although contact cements have lower strength than conventional adhesives they are suited to many applications where clamping pressure would be difficult to apply and sustain and where high strength is not a requirement. Contact cements are perhaps best known for applying plastic laminates to counter tops. They are liable to fail about 120° F. Water-soluble formulations are available but have relatively low moisture resistance. A major disadvantage is the zero closed assembly time: surfaces bond immediately and cannot be repositioned once contact is made.

Mastics include a variety of thick, pasty cements. They are commonly marketed in caulking cartridges and many are termed "construction adhesives," intended for use in bonding subflooring to joists or plywood wall paneling to studs. They vary widely in rate of cure, usually developing slowly and retaining some flexibility in the adhesive layer. Their gap-filling capability is an additional advantage.

Acrylic adhesives (Franklin's Rexite) are used by applying the thick resin to one adherend, the activator to the other. Within minutes after bringing the surfaces together, amazingly high strength develops. I bonded together two maple dowels 1 in. in diameter and 4 in. long, end-to-end. After allowing a full half-hour for curing, no one was able to break the joint apart by hand. Another outstanding feature of the adhesive is that it cures by polymerization, and so it is a great gap filler. On the other hand, this adhesive so far has only about a six-month shelf life and has therefore not been made available for retail distribution.