# DURABLE WOOD BONDING WITH EPOXY ADHESIVES

*Charles R. Frihart*
*USDA Forest Service, Forest Products Laboratory*
*Madison, Wisconsin, U.S.A*
*cfrihart@fs.fed.us*

## Introduction

Although wood was one of the earliest materials to be adhesively bonded, the factors that contribute to strong wood bonds are still not well understood. Wood is a very complex substrate in that it is non-uniform in most aspects. On the macro scale, it is a porous structure with different sized and shaped voids for fluid flow. The structural cells contain four different wall layers, and there is a middle lamella region between the cells. Each cell wall layer is made up of different amounts of three structural components: cellulose, mostly present as a crystalline and rigid polymer; hemicellulose, a mixture of branched carbohydrate polymers; and a matrix of lignin, a crosslinked aromatic polymer.

Wood is easy to bond, probably because of its porosity and polar surface. However, few adhesives make a bond that can withstand exterior conditions. With wood, generally the most severe condition involves either stress under wet conditions or cycles of water soaking followed by rapid drying. During a wetting and drying cycle, the wood expands and contracts, whereas most adhesives do not change significantly in volume. Thus, there is a large stress-strain gradient at the wood/adhesive interphase region.

Most books and review articles on wood adhesion cover the normal fundamentals of adhesion, but not bond strength. The emphasis is on what takes place at the interface, with discussion of the typical list of chemical interactions that can take place between adhesive and substrate. For bond strength, the interphase regions are also important. Emphasis has been on the preparation of wood surfaces for bonding (1), because it is easy to damage the wood surface so that the surface cells are weak (2). For example, sanding a surface makes it smooth, but pressure from mechanical sanders crushes the surface cells. Planing and knife cutting were found to be the most effective for producing a good surface, with blade angle and sharpness being important factors.

Although some adhesives give very durable bonds to wood, epoxy adhesives surprisingly do not. The epoxies are known normally for their good durability. They bond well to plastics, which are less polar than wood, and to metals, which are more polar than wood. The reason that epoxies do not form excellent bonds to wood for exterior applications is not clear. This study provides better insight to factors important to wood bonding and evaluates several models for explaining failure mechanisms of wood bonds.

## Experimental

One of the most severe tests for wood adhesion is ASTM D 2559 (1), which involves vacuum application to deaerate the wood, water soaking, then oven drying. Three of the vacuum/soak cycles are repeated, with steaming added in the second cycle. To make the test specimens, six blocks of 3- by 12-inch southern yellow pine were bonded together under light pressure after adhesive was applied on each side of the wood. For bonding of the epoxies, enough pressure was applied to get a slight squeeze out, and after curing for 24 hours, the glued blocks were heated in an oven at 80°C and 67% relative humidity. After trimming the edges, the blocks were cut into 2¾- by 3-inch specimens.

Two epoxies were used. One was FPL 1A that uses an amine type of cure (3), while the other uses a commercial polyamide hardener. These were chosen because the FPL 1A is a very rigid and low-viscosity formulation. The polyamide is more flexible because it has much longer segments between the epoxy groups and is less polar than the amine-cured epoxy.

After the adhesives were tested using the treatment cycles of ASTM D 2559, the failed bondline was exposed by making cuts into the wood blocks. The samples were examined using optical microscopy (10× to 70×) and scanning electron microscopy (SEM). A p-dimethylaminocinnamaldehyde stain was used to detect the nitrogen compounds in the amine curative (4). Specimens were examined by SEM after gold plating.

## Bond Failure Models

The focus in wood adhesion discussions has been on the adhesive/wood interface. This becomes difficult to assess with wood because there are many types of surfaces. Cleavage of the wood can occur in the middle lamella, giving an amorphous surface made of mainly lignin. Cleavage through the central cell void would give surfaces involving mainly the warty layer inside the lumen along with the primary cell wall and the three secondary layers.

However, the process of preparing the wood surface damages the wood surface cells; this damage could cause the wood interphase to serve as a failure zone. Of the wood surface preparations of cutting, planing, or sanding, the use of a planer or jointer does the least damage to the wood. However, a planed surface is one generated by a localized fracturing of the wood; this fracture surface varies considerably depending upon conditions. Planing of the wood not only splits open the surface cells but also creates debris on the surface. Thus, penetration of the cell lumens and cell wall should be important to adhesion. For bonding wood, it is important to also consider the weak boundary layer (WBL) that can be divided into chemical and mechanical components (5). The chemical component relates to extractives blocking the surface, while the mechanical one is due to damaged cells. The chemical component is more nano level, whereas the mechanical is more micro- and macroscopic. The mechanical component is due to fractures in the surface cell or compression of the cellular interphase region.

The adhesive can also have a weak interface. This can be generally caused by incomplete cure. For some adhesives, the pH of the wood can alter the pH of the adhesive at the interface and disrupt the cure, especially for heat-cured adhesives. For two-component systems, one component may be preferentially absorbed into and adsorbed onto the wood. The altered ratio of components would reduce the strength of the adhesive at the surface.

## Results and Discussion

Specimens using the two epoxies (amine cured and polyamide cured) were made up and tested using the cyclical soaking/drying process. In Table 1, the data show that amine-cured epoxy was much more water resistant than the polyamide-cured epoxy. This ranking of failure was independent of whether the wood was flat-sawn (cut on the tangential plane) or quartersawn (cut on the radial plane). The bonds are made with the wood at approximately 10% moisture content. However, for this test the wood becomes completely saturated, which causes the wood to expand greatly in the tangential and radial planes but not in the longitudinal plane. After swelling, the samples are dried rapidly in a 65°C oven. This rapid drying causes uneven shrinkage and cracking in the wood. More gradual drying of the wood allows the wood to relax so the internal stresses are not as large. This process can give mode I, II, and III types of failures in the adhesive. Although there was extensive wood failure, we are concerned only about understanding the failure along the bondline (Figure A). With delamination along 20% to 100% of the bondline, the question of the manner of failure arises. By cutting the test specimens along the vertical axis, we can expose the failed surface. This surface presented very little evidence of an adhesive failure. From visual observations, the failure appeared to be more in the epoxy portion than in the wood. Some of it was cohesive, some bulk epoxy failure, but most was in the interphase regions. Use of the p-dimethylaminocinnamaldehyde stain showed that even where the epoxy film pulled away there was an even distribution of amine groups on the surface of the failed wood. In the presence of amines, the stain develops a reddish color, compared with gray for bare wood (Figure B). The SEM data showed only small fragments of the wood cell surface on the epoxy failure side and adhesive coating on the wood side of the failure (Figure C). The combined data show that failure is mainly along the interphase regions of the epoxy and the wood.

Table 1. Delamination of Epoxies in Southern Yellow Pine Assemblies

| Orientation of wood | FPL 1A (amine) | Commercial (polyamide) |
|---|---|---|
| Radial | 31.8% | 100% |
| Tangential | 20.9% | 100% |

Given the desire to use epoxies for repair of wood surfaces, but poor adhesion of epoxy to wood, it is desirable to have a way to improve the bond strength. The use of hydroxymethylated resorcinol improves the bond strength of the epoxy to the wood by reducing the delamination to less than 5% of the bondline (6).

## Conclusions

The emphasis on wood bond strength has been on interface interaction between the wood and the adhesive, with some discussion on the chemical weak boundary layer of the wood due to extractives. Alternative failure mechanisms, other than interfacial and cohesive failure in the bulk wood and adhesive, need to be considered. These alternative failure modes include mechanical failure of the adhesive and wood interphase regions.

Epoxies are normally durable adhesives, except in the case of wood bonding. The cause for this weakness has not been previously investigated but has been attributed to poor interfacial adhesion. Specimens from the cyclic water soak, heat-drying method were cut open to look at the delaminated surfaces. Microscopy has determined that some bulk cohesive failure of the epoxy occurs, along with a little interfacial failure. The main failure mechanism is in the wood and epoxy interphase regions.

## Acknowledgments

I thank Tom Kuster for his excellent analytical work and Dan Yelle for his excellent laboratory work.

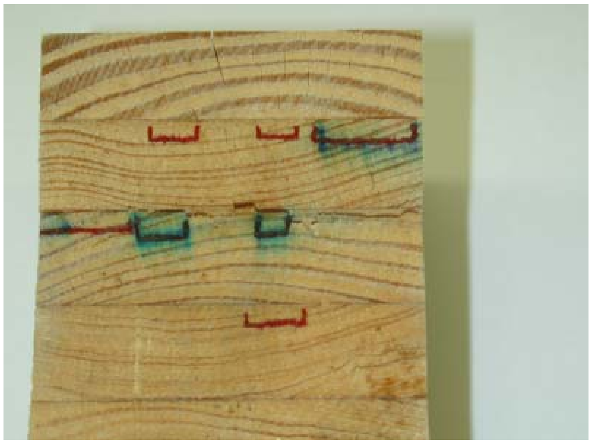

Figure A. Failure in ASTM D 2559 Specimen Bonded with Epoxy

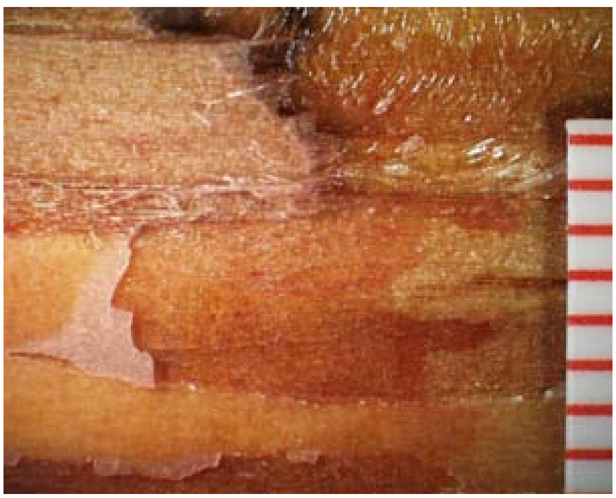

Figure B. Failure Surface with Stain from ASTM D 2559 Specimen

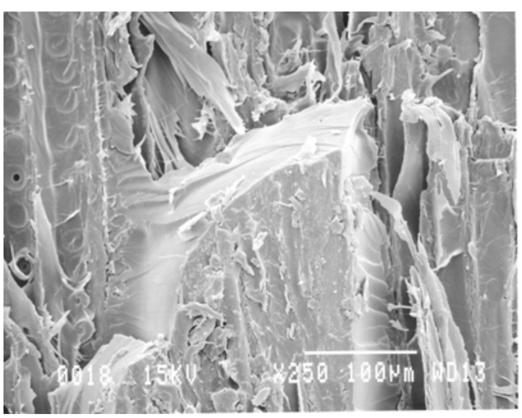


Figure C. SEM of Failure Surface from ASTM D-2559 Specimen

## References

1. D 2559-00, Annual Book of ASTM Standards, 2000, Vol. 15.06 ASTM International, West Conshohocken, PA.
2. W. Z. Olsen and R. F. Bloomquist, Forest Products Journal, 1962, 7, pp 74-80.
3. B. H. River, C. B. Vick, and R. H. Gillespie, in Treatise on Adhesion and Adhesives, J. D. Minford, ed., Marcel Dekker, New York, 1991, chapter 1 from Volume 7.
4. E. Schriever, Holz als Ror- und Werkstoff, 1981, 39, pp 227-229.
5. M. Stehr and I Johansson, J. Adhesion Science and Technology, 2000, 14, pp 1211-1224.
6. W. Christiansen, C. B. Vick, and E. A. Okkonen, Wood Adhesives 2000, Forest Products Society, Madison, WI, 2002, pp 245-250.

Frihart, C. R., “Durable Wood Bonding with Epoxy Adhesives,” Proceedings 26th Annual Meeting of the Adhesion Society, The Adhesion Society, Blacksburg, VA, 2003, pp. 476–478.