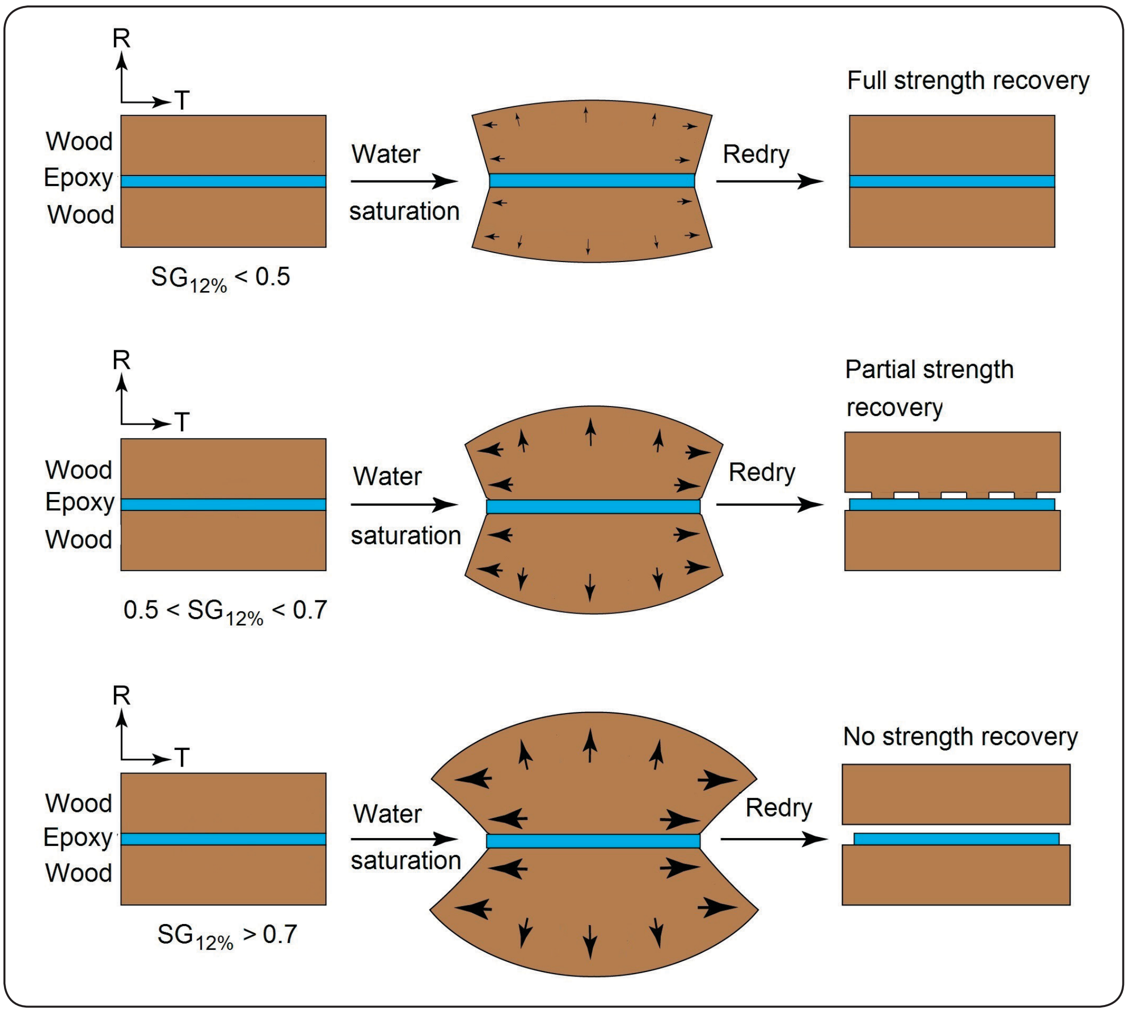
United States Department of Agriculture

Influence of Anatomical, Physical, and Mechanical Properties of Diffuse-Porous Hardwoods on Moisture Durability of Bonded Assemblies

Daniel J. Yelle
Ashley M. Stirgus



Forest Service
Forest Products Laboratory
General Technical Report FPL–GTR–244
September 2016

Abstract

Studying wood adhesive bond durability is challenging because wood is highly variable and heterogeneous at all length scales. In this study, three North American diffuse-porous hardwoods (hard maple, soft maple, and basswood) and their adhesively bonded assemblies were exposed to wet and dry cyclic tests. Then, their density differences were related to bond durability. Physical and mechanical properties (compression-shear) of the solid wood were measured along with mechanical properties of epoxy-bonded assemblies. Specific gravity tests gave the expected result (hard maple > soft maple > basswood), but volumetric swelling–shrinkage values for basswood were as high as those for hard maple. Tangential swelling–shrinkage values for basswood were approximately equal, suggesting that basswood can withstand swelling stresses with minute deformation. The compression-shear test showed that solid wood lost half its strength after vacuum-pressure soaking but recovered well after redrying. The epoxy-bonded assemblies also lost substantial strength after vacuum-pressure soaking, but soft maple and basswood assemblies completely recovered their strength after redrying. The goal of this study was to further the understanding of how density affects wood adhesive bond durability under a single wet–dry cycle in which swelling and shrinkage stresses are greatest. This study found that epoxy bond durability begins to deteriorate from the swelling–shrinkage stress in the range of densities between that of hard maple and soft maple. For species that have low density and high volumetric swelling–shrinkage (such as basswood), density is a controlling factor for moisture durability of bonded assemblies.

Keywords: bond durability, diffuse-porous, physical properties, compression-shear, epoxy

September 2016

Yelle, Daniel J.; Stirgus, Ashley M. 2016. Influence of anatomical, physical, and mechanical properties of diffuse-porous hardwoods on moisture durability of bonded assemblies. General Technical Report FPL-GTR-244. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 8 p.

A limited number of free copies of this publication are available to the public from the Forest Products Laboratory, One Gifford Pinchot Drive, Madison, WI 53726-2398. This publication is also available online at www.fpl.fs.fed.us. Laboratory publications are sent to hundreds of libraries in the United States and elsewhere.

The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

Contents

Conversion Table

English unit	Conversion factor	SI unit
inch (in.)	25.4	millimeter (mm)
pound per square inch (lb/in^2)	6894.7	pascal (Pa)
temperature (°C) = [temperature (°F) − 32]/1.8		

Influence of Anatomical, Physical, and Mechanical Properties of Diffuse-Porous Hardwoods on Moisture Durability of Bonded Assemblies

Daniel J. Yelle, Research Forest Products Technologist
Ashley M. Stirgus, Physical Science Technician Intern
Forest Products Laboratory, Madison, Wisconsin

Introduction

Durability of wood adhesive bonds exposed to moisture is an important topic in the wood products industry. When kiln-dried wood is used for adhesive bonding, the hygroscopic and anisotropic nature of wood can lead to swelling and shrinking stresses upon exposure to moisture content (MC) above or below the equilibrium moisture content (EMC) used during bonding. The stresses are produced by dimensional changes that occur from the swelling or shrinking of the wood cell wall in all three orthogonal directions (tangential (T), radial (R), and longitudinal (L)) both externally and internally to the wood, thus creating strain-induced stresses (Peck 1957, Stamm 1935). Most adhesives do not absorb stresses as well as the bulk wood because they do not swell and shrink like wood. Thus, a large strain can develop between the adhesive and the wood, leading to internal stress on the bondline in addition to any applied loads. These stresses that occur in bonded wood products must be absorbed by the bondline, allowing the forces to be distributed and the energy to be dissipated. If stresses are concentrated, bond failure is likely to occur under wet conditions.

Not all adhesives create durable bonds with wood, especially when exposed to wet conditions. Certain adhesives, such as phenol-formaldehyde (PF) and resorcinol-formaldehyde (RF), have been shown to bond tremendously well to most wood species and provide highly durable bonds. Other adhesives, such as epoxies, do not bond as well to wood (AITC 1992) but do provide sufficient dry strength for certain applications (such as wood beam repair). When failures do occur under severe moisture tests, they typically occur within the epoxy interphase region closest to the wood surface (Frihart 2003). This region displays substantial interfacial stress upon exposure to wet conditions because the wood swells and shrinks, while the epoxy does not to any significant degree (Frihart 2006b). Therefore, studying adhesives such as epoxies that do not bond well to wood gives results that allow for a better understanding of why bonds fail. For example, if PF or RF is used to study bond durability, it would take several wet–dry cycles to achieve bond failure; this type of failure is normally within the bulk wood. Thus, one learns little from these studies because these adhesive bonds are just as durable as the bulk wood itself. When epoxies are used, bond failure will typically occur within one or two wet–dry cycles. Because epoxies are known to have poor tensile elongation, bond failure caused by tensile strain between wood and epoxies is inevitable. This allows us to analyze the bond failures and develop hypotheses on their failure mechanisms.

Further study is necessary for understanding bond durability of epoxy-bonded assemblies with different wood species. The degree of wood swelling under wet conditions is hypothesized to proportionally affect internal stress on the bondline. In a previous study, compression-shear strength (ASTM D 905 (1994a)) and percentage delamination (ASTM D 2559 (2004)) of epoxy-bonded assemblies for white oak, hard maple, aspen, Sitka spruce, and southern yellow pine were evaluated (Frihart 2006a). The less dense and lower strength aspen and Sitka spruce formed more durable bonds in both ASTM D 905 and D 2559 type tests compared with white oak, hard maple, and southern yellow pine. These results suggested that density of wood must play a substantial role in bond durability. However, missing from this previous study are measured physical properties of the wood and how the intrinsic swelling and strength of the wood affect bond durability. The following unanswered questions still remain: (1) What are the density and swelling–shrinkage properties of the solid wood species? (2) What are the shear strengths of solid wood at 12% EMC, at full water saturation (FWS) and at 12% EMC after drying from FWS to 12% MC? (3) What effect does the intrinsic strength of these wood species have on the bond durability of epoxy-bonded assemblies? (FWS is defined here as the maximum amount of water that the wood specimens were able to forcibly absorb into the wood lumens and cell wall based on the pressure and time in this test. This is not the same as fiber saturation point as the specimens may not be at a point of maximum swelling.) The purpose of this study was to investigate the bond durability of three uniformly grained diffuse-porous hardwoods with respect to density and swelling–shrinkage properties. We determined the physical and mechanical properties of solid wood and their bonded assemblies. The bonded assemblies were further evaluated using fluorescence microscopy. The results of this study may shed more light on the mechanisms of bond durability as a function of wood density and its close correlation to dimensional changes.

Experimental

In this study, we used three different kiln-dried wood species obtained from Wisconsin-based lumber companies, *Tilia americana* (basswood, low specific gravity (SG)), *Acer rubrum* (soft maple, medium SG), and *Acer saccharum* (hard maple, high SG), all with straight grain, little or no heartwood, and minor defects. These diffuse-porous hardwoods were chosen for consistent vessel distribution throughout the growing season, straight grain, and fairly low extractive contents. All lumber was stored at 80 °F/65% relative humidity (RH) (12% MC) for approximately 3 months before experiments began. To test that EMC was reached for each wood species, we measured mass changes of pre-cut blocks from the lumber on a weekly basis. After the weight change levelled out to approximately 0%, the wood was considered ready for experiments. All mass measurements were made on a Mettler–Toledo (Columbus, OH) balance (±0.001-g accuracy). All length, width, and thickness measurements were made using a Mitutoyo (Kanagawa, Japan) digital caliper (±0.0001-in. accuracy).

Physical Properties of Solid Wood

In total, 90 specimens for physical property measurements were prepared with dimensions of 0.75 × 0.75 × 0.75 in. For each species, 30 specimens were labelled with either B (basswood), SM (soft maple), or HM (hard maple). On the label, a dash with SG, V, or RT for SG, volumetric shrinkage, and radial–tangential shrinkage was added. For example, B-SG-1 is the first basswood specimen for SG measurements. For physical property measurements, the procedures subsequently outlined detail the modifications of ASTM D 2395 (2007) for SG, ASTM D 143 (1994b) (section 19) for volumetric swelling–shrinkage, and ASTM D 143 (section 20) for radial and tangential swelling–shrinkage.

Growth Rings

The wood selected for physical property tests was initially separated by similarity in growth ring properties. For example, each of the 90 cubed specimens designated for SG, V, and RT was measured for number of growth rings per inch and growth ring width. This was performed to minimize differences associated with growth rings and potentially help in explaining any differences related to growth rate.

Specific Gravity

For SG measurements, ASTM D 2395 method A procedure was followed. With the 30 specimens equilibrated to 12% EMC, we measured length (L), width (R), and thickness (T) for the specimens and put L, R, or T on the spots the measurements were taken. Weight (I) of each specimen was taken at 12% EMC. After all specimens were measured in dimensions and mass, they were placed into an oven maintained at 100 °C for 48 h, removed, and placed into a desiccator (W.A. Hammond Drierite Co., Ltd., Xenia, OH) and weighed. With the following equation, SG was calculated at 12% EMC and at FWS:

$$SG = K \cdot W/[1 + (M/100)] \cdot L \cdot R \cdot T$$

where

K = 0.061 (when weight is in grams and volume is in cubic inches),

W is either I for initial weight of specimen at 12% EMC or S for swollen weight at FWS,

M is sample moisture content at time of measurement (%),

L is length at 12% EMC or FWS,

R is radial dimension at 12% EMC or FWS, and

T is tangential dimension at 12% EMC or FWS.

Volumetric Swelling and Shrinkage

For the volumetric swelling–shrinkage (V) measurements, ASTM D 143 (section 19) procedure was followed. With the 30 specimens equilibrated at 12% EMC, L, R, and T for each of the specimens were measured and labelled with L, R, or T on the spots the measurements were taken. Weight (I) was taken for each specimen at 12% EMC. We placed the 30 specimens (plus 1 dummy specimen per species) into a vacuum-pressure soak (VPS) tank, filled up the tank, and pulled a vacuum at 14 lb/in^2 (gauge pressure). The vacuum was held for 15 min, and water pressure was slowly added at 65 lb/in^2 (gauge pressure) and held for 1 h. This cycle was performed three times in total. The tank was then opened, and the dummy specimen for each species was split open to observe a full saturation gradient. The water-saturated specimens were then weighed (S), and the wet dimensions (L, R, and T) were taken in the same spot as at 12% EMC. Volumetric swelling (from 12% EMC to FWS), volumetric shrinkage (from FWS to 12% EMC), and SG (at FWS) were calculated. For example, swelling was the difference between swollen volume and volume at 12% EMC, divided by volume at 12% EMC. Likewise, shrinkage was the difference between swollen volume and volume at 12% EMC, divided by swollen volume.

Radial and Tangential Swelling and Shrinkage

For the radial and tangential swelling–shrinkage measure ments, ASTM D 143 (section 20) was followed. With the 30 specimens equilibrated at 12% EMC, we measured R and T and labelled them with R or T on the spots the measurements were taken. Weight (I) was taken of each specimen at

12% EMC. We placed the 30 specimens into a VPS tank, filled up the tank, and pulled a vacuum at 14 lb/in^2 (gauge pressure). The vacuum was held for 15 min, and water pressure was slowly added at 65 lb/in^2 (gauge pressure) and held for 1 h. This cycle was performed three times in total. After this cyclic soaking, we measured the weight (*S*) of the saturated specimens and the wet dimensions (*R*, *T*). The specimens were placed into a humidity room at 65% RH and 80 °F to return to 12% EMC. The specimens were allowed to equilibrate for 1 week. Measurements were taken again of weight and dimensions for each specimen (*R*, *T*) at 12% EMC. The percentage swelling to FWS and percentage shrinkage back to 12% EMC were calculated similarly to that previously described for volumetric swelling and shrinkage.

Mechanical Properties from Compression-Shear Parallel-to-Grain Test

Solid Wood

For compression-shear parallel to the grain of solid wood (ASTM D 143, section 14), we made 12 assemblies for each species, totalling 36 assemblies. From each assembly, we cut out four block-shear specimens with the dimensions as shown in Figure 1. From each assembly, one specimen was tested in compression-shear under ambient conditions (80 °F/65% RH) and a second specimen was tested in compression-shear after a VPS cycle.

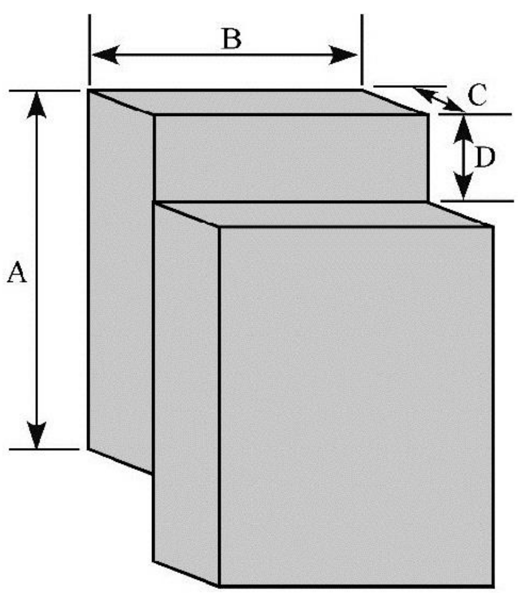


Figure 1. Dimensions of the ASTM D 143 (section 14) and reduced size D 905 specimen, where A = 1.25 in., B = 1.0 in., C = 0.25 in., and D = 0.25 in.

A third specimen was tested in compression-shear using ASTM D 905 fixture (no offset) after the VPS cycle and conditioning back to EMC of 12%. The total number of specimens tested was 3 species × 12 assemblies × 3 conditions = 108 compression-shear specimens. Additionally, we measured width and thickness of each specimen at 12% EMC and after VPS to determine tangential and radial swelling after VPS, and we weighed specimens at 12% EMC and after VPS to determine percentage moisture gain.

Epoxy-Bonded Assemblies

For the compression-shear parallel-to-grain tests of epoxy-bonded assemblies (ASTM D 905, reduced specimen size), we made eight assemblies for each species, totalling 40 assemblies. FPL-1A epoxy resin was prepared and applied as previously described (Vick and Okkonen 1997). A fluorescent pigment (0.1% w/w, L-212, Beaver Luminescers, Newton, MA) was added to the epoxy resin mixture before application. From each assembly, four block-shear specimens were cut with the dimensions shown in Figure 1. From each assembly, one specimen was tested in compression-shear under ambient conditions (80 °F/65% RH) and a second specimen was tested in compression-shear after a VPS cycle. A third specimen was tested in compression-shear after the VPS cycle and conditioning back to EMC of 12%. The assembly material left over was used for light and fluorescence microscopy sections for determining adhesive penetration into lumens. The total number of specimens tested was 3 species × 12 assemblies × 3 conditions = 108 compression-shear specimens. Additionally, we measured width and thickness of each specimen at 12% EMC and after VPS to determine tangential and radial swelling after VPS and we weighed specimens at 12% EMC and after VPS to determine percentage moisture gain.

Results and Discussion

A major contributing factor in wood that controls how much dimensional change will occur is its density (or SG). There are many other factors that come into play as well, such as extractives, juvenile wood, reaction wood, and slope of grain just to name a few. However, density has undoubtedly the largest effect on dimensional change. Density may seem like a simple factor to control when using substrates that are homogeneous and have a predictable, repeatable structure at all length scales. However, wood is a challenging material in that it has a highly heterogeneous structure at all length scales. Therefore, controlling the density factor is not so simple. One way to narrow down the variability of wood species to study with respect to density is to use species known for uniformity in pore distribution. Such species include the diffuse-porous hardwoods, which compared with ring-porous hardwoods, typically have more predictability when it comes to anatomical structure in that the vessel pore diameters are uniformly distributed throughout the growth ring. As density increases in diffuse-porous species, the fiber cell content will increase but the vessel distribution will remain quite uniform. Figure 2 shows light micrographs of the three North American diffuse-porous hardwoods used in this study, which vary in density. Each of these images shows an earlywood-to-latewood transition (that is, one growth ring) as indicated by the horizontal band of dense fiber cells.

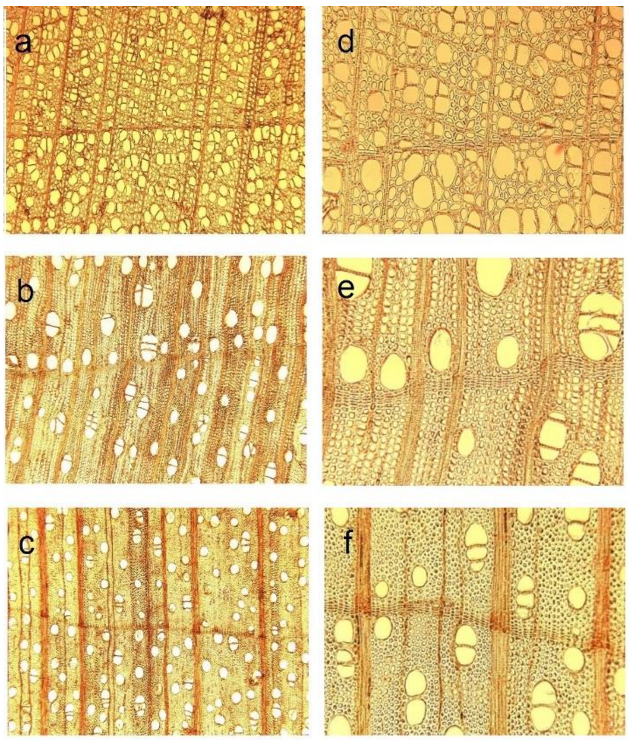


Figure 2. Transmission light microscopy images of solid wood cross sections (30-µm thickness) of (a) basswood, (b) soft maple, and (c) hard maple taken at 10× and (d) basswood, (e) soft maple, and (f) hard maple taken at 16×

Physical Properties of Solid Wood

A summary of all measured physical properties is shown in Table 1. The following section attempts to describe differences between the wood species tested.

Growth Rings

Major differences are seen between hard maple and soft maple. Hard maple has almost twice as many rings per inch than soft maple, thus giving ring widths in hard maple approximately half those of soft maple. Basswood showed rings per inch and ring widths close to those of hard maple. One might expect that a slower annual growth rate may lead to greater density. This is not always true and is more species dependent. Therefore, growth rate does not appear to influence wood density in the case of the diffuse-porous hardwood specimens examined in this study.

Table 1. Measured physical properties of wood species using ASTM standard methods[a]

Property	Hard maple	Soft maple	Basswood
Growth rings per inch[b]	10.2 (2.0)	5.6 (0.5)	8.3 (0.3)
Growth ring width (in.)[b]	0.09 (0.02)	0.16 (0.03)	0.11 (0.02)
SG at 12% EMC [c]	0.67 (0.01)	0.48 (0.01)	0.38 (0.01)
SG at FWS[c]	0.61 (0.00)	0.45 (0.01)	0.35 (0.00)
Volumetric swelling (%)[c]	14.1 (0.8)	9.9 (1.0)	13.6 (1.3)
Radial swelling (%)[c]	4.4 (0.8)	2.9 (0.8)	2.4 (0.5)
Tangential swelling (%)[c]	9.1 (0.9)	6.5 (0.5)	8.4 (0.7)
Volumetric shrinkage (%)[c]	12.3 (0.6)	9.0 (0.8)	12.0 (1.0)
Radial shrinkage (%)[c]	1.9 (0.7)	0.7 (0.7)	1.8 (0.4)
Tangential shrinkage (%)	7.6 (0.9)	5.2 (1.1)	8.2 (0.7)

[a]Standard deviation is shown in parentheses; SG, specific gravity; EMC, equilibrium moisture content; FWS, full water saturation.
[b]$n = 30$.
[c]$n = 10$.

Specific Gravity

The SG of the wood used in this study was measured at both 12% EMC and FWS after the volumetric swelling test. The density differences were clear: hard maple > soft maple > basswood. As expected, when the wood was in a swollen state, density decreased for all wood species. In this case, hard maple had the most dramatic SG change from 12% EMC to FWS with a 9% decrease. Under the same MC change, soft maple had a 6% decrease and basswood had an 8% decrease.

Volumetric Swelling and Shrinkage

In this study, the change in volume going from 12% EMC to FWS is considered volumetric swelling. The change in volume going from FWS back to 12% EMC is called volu metric shrinkage. Not surprisingly, hard maple showed the greatest volumetric swelling and shrinkage of all three species tested. However, basswood also displayed high volumetric swelling and shrinkage, close to that of the higher density hard maple, despite its much lower density. One factor that may be influencing this is that basswood is known for having considerably more tension wood than most hardwood species. Tension wood, made up of a gelatinous (G) layer formed toward the lumen, has nearly pure cellulose and can form in place of the S2 or S3 layers (Côte and Day 1965, Daniel et al. 2006). This G-layer makes tension wood much more susceptible to moisture absorption leading to more dramatic dimensional changes (Panshin and de Zeeuw 1980, Skaar 1972).

Radial and Tangential Swelling and Shrinkage

The two orthogonal dimensions that change the most with moisture are radial and tangential, with tangential swelling–shrinkage being typically twice that of radial (Panshin and de Zeeuw 1980). Therefore, these dimensions were measured for swelling and shrinkage. As for radial swelling and shrinkage, hard maple showed the highest values. The radial swelling was similar for soft maple and basswood, but radial shrinkage was slightly higher for basswood. For tangential shrinkage and swelling, hard maple and basswood showed high values, similar to what was shown for volumetric swelling and shrinkage. Interestingly, basswood tangential swelling and shrinkage values were almost equivalent. Of course, these values come from a single wet–dry cycle, but because after swelling and shrinkage, basswood returned to the initial sample dimensions at 12% EMC, basswood displayed more of an elastic response compared with hard maple or soft maple. This result suggests that basswood is more effective at restoring initial swelling stresses than is hard maple or soft maple, possibly because of its lower density. Another possibility for these results is that soft maple and hard maple, being higher density species than basswood, were not fully equilibrated to 12% MC after 1 week of storage at 80 °F/65% RH. If this were the case, the maple specimens may not have fully shrunk to their equilibrium dimension.

Mechanical Properties from Compression-Shear Parallel-to-Grain Test

Okkonen and River (1988) studied several factors that affect the apparent strength of solid wood and adhesive-bonded joints under compression-shear. They found that, using ASTM D 905 and D 143 test methods, the presence or absence of an offset in the shear plane was the most consistent and powerful factor. Also, specimen double-notching consistently gave strengths equal to or greater than the single-notched shape. The underlying conclusion was that the D 905 test (no-offset) and the D 143 test (offset) are not comparable. Thus, if comparison between solid wood and adhesive-bonded specimens is necessary (as is the case for this study), all specimens (solid and adhesive-bonded) should be tested in the D 905 double-notched configuration with no-offset, have equal slopes of grain, have T bonding surfaces, and have similar rings per inch and ring width for compression-shear tests. Figure 1 shows the specimen dimensions used for this study. Both ASTM tests performed in this study gave results that represent testing to failure.

Solid Wood

In comparing the compression-shear stress of the solid wood specimens under dry, wet, and wet–dry, there are some similarities and differences. Figure 3 shows a bar graph of the results. With all species tested, the wood displayed a 50% decrease in shear strength going from dry to wet condition. However, when these species went from wet, then back to dry condition, the basswood was the only species to completely regain its original dry shear strength. Hard maple and soft maple did recover most of their initial strength but not completely. As was previously mentioned, this result could be because basswood has good elasticity and recovers well

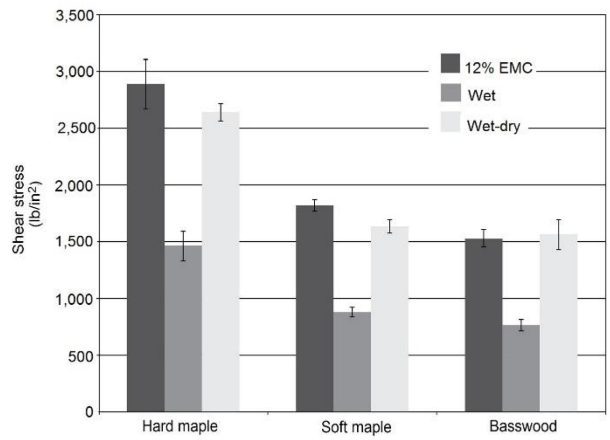


Figure 3. Compression-shear stress parallel to the grain of solid wood species (*n* = 12) (EMC, equilibrium moisture content).

from initial swelling stresses. However, it also could mean that the maple specimens did not completely reach 12% MC before testing, thus giving slightly lower strength values compared with initial values. Another plausible cause is that the hard maple and soft maple showed some loss in strength after swelling and shrinking because of cleavage of bonds between cells or within cell walls during the wet–dry cycle.

Epoxy-Bonded Assemblies

After the three species were bonded with epoxy, the compression-shear stress of the assemblies was tested in an identical fashion (Fig. 4). A major difference in these results compared with solid wood was that the epoxy-bonded hard maple lost more than 70% of its initial dry shear strength when exposed to wet conditions. In contrast, the epoxy-bonded soft maple and basswood lost 50% of its initial dry shear strength, thus behaving similarly to the solid wood. When the epoxy-bonded assemblies went from wet and then

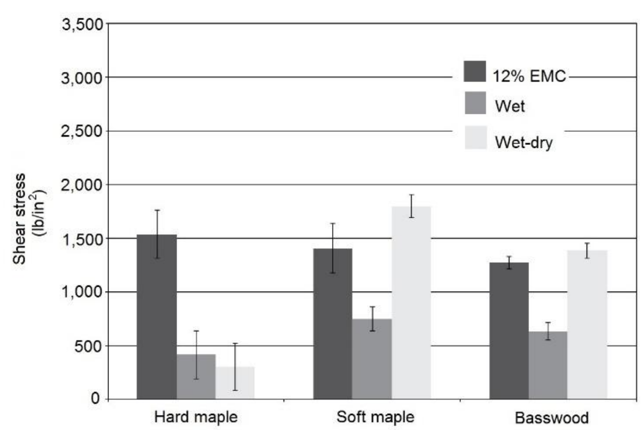


Figure 4. Compression-shear stress parallel to the grain of epoxy-bonded assemblies (*n* = 12) (EMC, equilibrium moisture content).

back to dry condition, the hard maple lost even more strength compared with the wet condition. This result is different from that observed in Frihart (2006a) in which conditions were 70 °F/50% RH instead of the 80 °F/65% RH in this study, which may have affected the strength recovery mechanism. That is, a drier ambient condition (10% MC instead of 12% MC) may have allowed the epoxy-bonded hard maple to recover more of its initial strength. In contrast to the hard maple, shear strength of the soft maple and basswood assemblies actually increased 28% and 9%, respectively (beyond their initial dry strength) after the wet–dry cycle. This result is interesting because the lower density species appear to be completely unaffected by the wet–dry cycle. Although this is only one wet/dry cycle, the result suggests that there is probably some density (or range of densities) between that of soft maple and hard maple at which below this density, a wet–dry cycle will not affect the epoxy–wood bond and above this density, catastrophic failure of the epoxy–wood bond may occur. Tarkow and Turner (1958) demonstrated that an increasing density of wood, when exposed to a range of low to high RH, will exponentially increase the swelling pressure of the wood. Therefore, it is probable that the low-density basswood used in this study did not produce as much swelling pressure, and stress, as did the high density hard maple.

Bondline thickness may also play a role in epoxy-bonded assembly durability. To visualize how density of the wood affected bondline thickness, cross sections of the bonded assemblies were observed using fluorescence microscopy (Fig. 5). When bonding any wood adhesive assembly, a balance is required for proper adhesive flow and surface spread. The pressure should not be too high as to push out the entire adhesive from the bondline (i.e., starving the joint), but not too low so that little adhesive exudes from the bondline (i.e., poor spread). If this balance is met correctly, some clear differences between species density can be observed. The basswood assembly showed the thickest epoxy bondline, followed by soft maple, and then hard maple with the thinnest epoxy bondline (Fig. 5). These images also show that the basswood anatomy allowed the epoxy to penetrate the farthest into the wood. Thus, a more dense wood makes adhesive penetrability a challenge as is the case with hard maple.

To better understand what the mechanical property data might mean with regards to durability, the differences between the compression-shear stress results in solid wood and epoxy-bonded assemblies can be shown as fractions. For example, the epoxy-bonded shear stress divided by the solid wood shear stress will give an idea of how the intrinsic strength of wood compares with strength of its bonded assembly, giving a bonded/solid ratio. Table 2 shows a summary of the compression-shear results along with the bonded/solid ratios. From these ratios, it becomes clearer

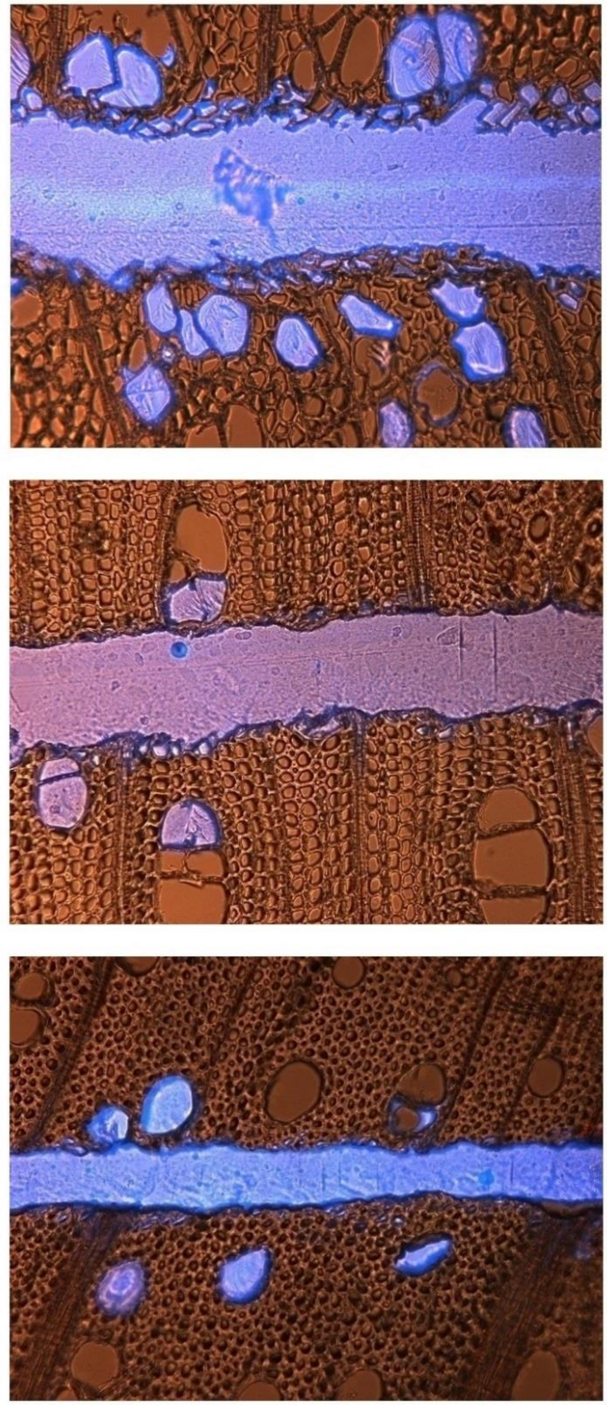


Figure 5. Fluorescence microscopy images of wood-epoxy bondline cross sections at 16× (30-µm thickness): basswood (top); soft maple (middle); hard maple (bottom).

that basswood is the most durable species when it comes to epoxy bonding because its stress ratios when wet, dry, and wet–dry were closest to each other. Soft maple also displayed ratios fairly close to each other. Hard maple displayed the most dramatically different ratios and thus would be considered the least durable epoxy-bonded species used in this study.

Table 2. Summary of compression-shear stress for solid wood and bonded assemblies

	Hard maple			Soft maple			Basswood		
	Dry	Wet	Wet–dry	Dry	Wet	Wet–dry	Dry	Wet	Wet–dry
Solid (lb/in^2)	2,885	1,458	2,638	1,814	876	1,631	1,524	764	1,559
Bonded (lb/in^2)	1,532	412	300	1,402	748	1,795	1,271	631	1,382
Bonded/solid	0.53	0.28	0.11	0.77	0.85	1.10	0.83	0.83	0.89

Conclusions

Understanding the factors involved in wood adhesive bond durability has been a challenge considering the tremendous variability of wood from the macroscale down to even the nanoscale. This study focused on relating density differences to bond durability when the sample was exposed to sequential wet and dry cycling conditions. The species were common North American diffuse-porous hardwoods (hard maple, soft maple, and basswood) with clear density differences but with fairly similar and uniform anatomical features. The physical properties of the solid wood were measured, followed by mechanical property measurements (compression-shear) on both solid wood and epoxy-bonded assemblies.

The two major findings pertaining to the physical properties of the solid wood were the following. First, although SG gave the expected result (hard maple > soft maple > basswood), the volumetric swelling–shrinkage values for basswood were as high as those for hard maple, potentially because of tension wood typically found in basswood. Second, the tangential swelling and shrinkage values for basswood were almost equivalent, suggesting that this species has good elasticity and can withstand swelling stress with minimal deformation.

The two major findings pertaining to the mechanical properties were the following. First, solid wood showed a 50% decrease in compression-shear strength after VPS, but recovered well after redrying to 12% EMC. Basswood showed a complete recovery of shear strength after redrying. Second, the epoxy-bonded assemblies also showed dramatic strength loss after VPS, but only the soft maple and basswood assemblies completely recovered this strength after redrying to 12% EMC.

This study demonstrated that density does indeed play a significant role in how wood adhesive bonds perform under wet–dry cycle durability tests. There seems to be a density or range of densities between that of hard maple and soft maple where epoxy bond durability begins to deteriorate from the swelling–shrinkage stress. This study also demonstrated that with species such as basswood with low density and high volumetric swelling–shrinkage, density is more of a controlling factor for bond durability. Future studies should explore more low-density species with a wide range of volumetric swelling–shrinkage values to better understand the reasons behind their good bond durability. Is it just because of their low density or are there other factors at play, such as pore size distribution and uniformity, type and frequency of cells, type and frequency of pits, reaction wood, juvenile wood, magnitude of the stresses at the bondline, etc.?

References

AITC. 1992. American national standard for wood products. Structural glued laminated timber. ANSI/AITC A190.1-92. Vancouver, WA: American Institute of Timber Construction.

ASTM. 1994a. Standard test method for strength properties of adhesive bonds in shear by compression loading. ASTM D 905. Philadelphia, PA: American Society for Testing and Materials.

ASTM. 1994b. Standard test methods for small clear specimens of timber. ASTM D 143. Philadelphia, PA: American Society for Testing and Materials.

ASTM. 2004. Standard specification for adhesives for structural laminated wood products for use under exterior (wet use) exposure conditions. ASTM D 2559. Philadelphia, PA: American Society for Testing and Materials.

ASTM. 2007. Standard test methods for specific gravity of wood and wood-based materials. ASTM D 2395. Philadelphia, PA: American Society for Testing and Materials.

Côte, W.A.; Day, A.C. 1965. Anatomy and ultrastructure of reaction wood. In: Côte, W.A., ed. Cellular ultrastructure of woody plants. New York: Syracuse University Press: 391-418.

Daniel, G.; Filonova, L.; Kallas, A.M.; Teeri, T.T. 2006. Morphological and chemical characterization of the G-layer in tension wood fibres of *Populus tremula* and *Betula verrucosa*: Labelling with cellulose-binding module CBM1HjCel7A and fluorescence and FE-SEM microscopy. Holzforschung. 60: 618-624.

Frihart, C.R. 2003. Durable wood bonding with epoxy adhesives. In: Proceedings, 26th annual meeting of the adhesion society. Blacksburg, VA: The Adhesion Society: 476-478.

Frihart, C.R. 2006a. Are epoxy-wood bonds durable enough? In: Frihart, C.R., ed. Wood adhesives 2005. November 2-5, 2005, San Diego, CA. Madison, WI: Forest Products Society: 241-246.

Frihart, C.R. 2006b. Wood structure and adhesive bond strength. In: Stokke, D.D.; Groom, L.H., eds. Characterization of the cellulosic cell wall. Proceedings, workshop cosponsored by USDA Forest Service-Southern Research Station, Society of Wood Science and Technology, and Iowa State University. August 25-27, 2003, Grand Lake, CO. Ames, IA: Blackwell Publishing: 241-253.

Okkonen, A.E.; River, B.H. 1988. Factors affecting the strength of block-shear specimens. Forest Products Journal. 39(1): 43-50.

Panshin, A.J.; de Zeeuw, C.H. 1980. Textbook of wood technology, 4th ed. New York: McGraw-Hill.

Peck, E.C. 1957. How wood shrinks and swells. Forest Products Journal. 7(7): 235-244.

Skaar, C. 1972. Water in wood. Côte, W.A., ed. New York: Syracuse University Press. 73-125.

Stamm, A.J. 1935. Shrinking and swelling of wood. Industrial and Engineering Chemistry. 27(4): 401-406.

Tarkow, H.; Turner, H.D. 1958. The swelling pressure of wood. Forest Products Journal. 8(7): 193-197.

Vick, C.B.; Okkonen, E.A. 1997. Structurally durable epoxy bonds to aircraft woods. Forest Products Journal. 47(3): 71-77.