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Effect of Wood Characteristics on Adhesive Bond Quality of Yellow-Poplar for Use in Cross-Laminated Timbers

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Effect of Wood Characteristics on Adhesive Bond Quality of Yellow-Poplar for Use in Cross-Laminated Timbers

Daniel Hovanec

**Thesis submitted
to the Davis College of Agriculture, Natural Resources and Design
at West Virginia University**

in partial fulfillment of the requirements for the degree of

**Master of Science in
Forestry with an emphasis in Wood Science and Technology**

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Division of Forestry and Natural Resources

**Morgantown, West Virginia
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Keywords: Cross-laminated timber, yellow-poplar, adhesion, bond quality

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ABSTRACT

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Daniel Hovanec

Cross-laminated timber (CLT) panels are gaining more interest in North America, though CLTs are currently only approved for manufacture under ANSI/APA PRG-320 using select softwood species. Much of the low-grade Appalachian hardwood lumber produced has potential for being used to produce CLT panels given that necessary research data is developed to show that hardwood CLTs meet the requirements of the standard. One particular issue with using hardwood lumber in CLT panels is that it is often more difficult to achieve a strong, durable adhesive bond.

Among the Appalachian hardwood species, yellow-poplar (*Liriodendron tulipifera*) is particularly abundant in West Virginia. The objective of this research was to identify which characteristics of yellow-poplar lumber have an effect on adhesive bond quality. Twelve treatments were applied to yellow-poplar lumber to examine the interactions and main effects of adherend thickness, lamination orientation, and orthotropic orientation (bonding surface plane). Bond strength and durability were determined using shear-block and cyclic delamination tests. Fluorescence microscopy was used to determine the level of adhesive penetration achieved on select samples that performed notably well or poorly.

The results of the research found that lamination orientation significantly affected bond strength in yellow-poplar, with parallel laminated samples yielding higher average shear strength and wood failure than perpendicular laminated samples. Furthermore, adherend thickness also appears to influence bond strength, as the samples with thinner adherends had significantly higher levels of wood failure in shear block specimens. None of the tested effects had a clear impact on bond durability. Lastly, in comparing the results of the yellow-poplar samples to a reference species (hard pine) that is accepted for CLT manufacture, no differences were noticed in percentage of wood failure or delamination (bond durability). Yellow-poplar had a significantly higher mean shear strength than the reference samples, but this may tell more about the wood itself than the adhesive bond strength. Based on the findings of this research, yellow-poplar could facilitate adhesive bonds of the necessary strength and durability to be used in CLT manufacture.

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Chapter 1: Introduction

1.1 Development of Hardwood CLTs

Research is currently being performed in an effort to demonstrate the feasibility of, and ultimately develop new markets for cross-laminated timber (CLT) panels made of low-grade hardwood, specifically yellow-poplar (*Liriodendron tulipifera*). This collaborative project has five specific research aims that have been assigned to five different universities. One of these research goals was completed at West Virginia University: to determine the most effective bonding parameters of yellow-poplar for its use in CLTs. This information will be delivered to other research facilities to aid in the determination of the mechanical properties of hardwood CLT panels and the development of mathematical models to predict strength and stiffness of hardwood CLTs.

The use of hardwoods in a bonding assembly can sometimes result in poor bond quality. A greater presence of extractives can interfere with available bonding sites on the wood surface, and higher density can negatively affect bond quality as the dimensional changes resultant of moisture absorption and loss can create stress on the bond line. Also, pressing hardwood bond assemblies in a way that results in closely-mating surfaces can be more difficult given the greater mechanical resistance of many hardwoods (Frihart and Hunt, 2010). However, yellow-poplar is listed in a category of wood species that “bond well” (Frihart and Hunt, 2010). If the factors that affect bond quality of yellow-poplar can be determined and controlled, then, from an adhesion perspective, satisfactory CLT panels made from yellow-poplar could be produced.

The goal of this research project was to determine the characteristics of yellow-poplar that affect bond quality. Testing evaluated the effect of factors such as bonding surface plane, adherend thickness, and lamination orientation.

1.2 Yellow-poplar in Engineered Wood Products

Yellow-poplar is currently used to produce a number of engineered wood products (Wiemann 2010). Plywood, Parallel Strand Lumber, Laminated Veneer Lumber, and Oriented Strand Board are just a few examples of wood composite products that are commonly manufactured, at least in part, with yellow-poplar. Because of the success of yellow-poplar in these products, which all involve bonding yellow-poplar wood elements to other yellow-poplar elements or other species, it seems that yellow-poplar might be considered as a material for CLTs. Yellow-poplar has been shown to be capable of producing strong, durable adhesive bonds in these products.

Chapter 2: Literature Review

2.1 Cross-Laminated Timber Production

The manufacturing process for CLTs begins with preparing the individual adherends that will ultimately form the panel. There are several requirements for the adherends that form the layers of a CLT, including minimum and maximum thicknesses, allowable thickness within a layer, width requirements, and qualification of lumber grade. Depending on the adhesive being used in a given process, it may also be necessary to insure that the moisture content of each adherend is within a certain range that allows for proper adhesive cure (Yeh et al., 2013).

With the individual pieces of lumber prepared, the appropriate adhesive is applied and the pieces are placed together to form the panel. The panel is pressed at a specific pressure and for a known length of time based on the adhesive formulation. When the adhesive is set, the panels undergo any cutting or shaping necessary relative to their end use (Yeh et al., 2013). An example of a CLT panel showing the cross-lamination of the individual adherends is shown in Figure 1.

Currently, three different types of adhesive are used in CLT production: Phenolic resins, emulsion polymer isocyanate resin, and one-component polyurethane resin. The adhesive used in production can be chosen for a number of reasons, including ease of use, set times, curing parameters, and appearance (Yeh et al., 2013). For this project, a resorcinol formaldehyde adhesive was used, as it has proven its effectiveness in bonding large wood composites. Also, no suitable polyurethane adhesives could be obtained.

Figure 0-1. Example of a CLT panel emphasizing cross-lamination. Source: Gagnon et al., 2013.

2.2 Adhesive Penetration

Adhesive penetration refers to the degree of which an adhesive can spread into the cellular network below the wood surface. However, penetration can occur at two levels: micrometer level penetration and nanometer level penetration. Micrometer level penetration, otherwise known as gross penetration, refers to the movement of adhesive throughout the structure of wood, including cell lumens and pits. Nanometer, or cell-wall level penetration, is a lesser understood phenomenon. Several theories attempt to explain the mechanism of cell-wall penetration, and while no single theory has been proven or unanimously accepted, it can be

assumed that a greater level of adhesive penetration will allow for more cell-wall penetration (Kamke and Lee, 2007).

The two wood characteristics that affect adhesive penetration are permeability and surface energy. The permeability of wood varies with respect to its orthotropic nature. While low permeability can restrict adhesive penetration, an overly permeable substrate can be subject to over-penetration, causing a starved glue joint (dry-out). Permeability also tends to be highly variable between earlywood and latewood, as well as between sapwood and heartwood. Due to the variable nature of permeability in wood, formulating an adhesive specific to the anticipated permeability of a species can be difficult (Kamke and Lee, 2007).

While it seems apparent that adhesive penetration directly impacts the strength of an adhesive bond, other factors may have an overlying effect on bond strength. Though greater penetration would facilitate a greater surface contact area for which the adhesive can bond to the wood, mechanisms such as cohesive strength and chemical bonding might be more important. Regardless, adhesive penetration is still accepted as an important factor in terms of adhesive bond strength (Kamke and Lee, 2007).

2.3 Wetting

Wood with a higher surface energy will exhibit greater wettability (Kamke and Lee, 2007). Wettability of wood refers to an adherend's ability to attract a liquid, such as an adhesive. Adequate wetting of the surfaces of adherends is necessary to achieve a strong adhesive bond. Wetting is aided by the polarity of the surface of the adherend, as the oppositely charged molecules in the adhesive actively spread to occupy open bond sites. Proper machining of an

adherend leaves a polar surface; however, these sites can be occupied by a number of substances, including extractives and water within the wood (Custódio et al., 2009). When wood is dried, water soluble extractives can be carried to the surface and essentially deposited there when the water evaporates (Hse and Kuo, 1988). Because of the propensity for extractives to occupy available bond sites, it is recommended that bonding of wood substrates be performed within twenty-four hours of surface preparation (Davis, 1997). Should more than twenty-four hours pass between initial surface preparation and bond assembly, an inactivated surface can be restored by planing (Custódio et al., 2009).

The degree of wetting that occurs can be evaluated in three ways: (1) by measuring the contact angle of the droplet of adhesive as it forms on the surface of the substrate, (2) by measuring how far the adhesive spreads over the substrate, and (3) by determining the extent to which the adhesive penetrates into the substrate (Shi and Gardner, 2000). Shi and Gardner (2000) developed a model to describe how wetting occurs with adhesives on wood. Their model uses a parameter (k-value) to describe the process of adhesive penetration and spreading in terms of wetting. A higher k-value indicates that an adhesive system (a given adhesive on a given substrate) exhibits greater spreading and deeper penetration than an adhesive with a lower k-value, and thus shows greater wetting.

In their research, Shi and Gardner (2000) examined the contact angle of adhesives as they occurred on wood in regard to several characteristics, one of which was the grain direction. The study considered the instantaneous contact angle of the adhesive, as well as the degree to which the angle changed over time. Their results showed that a lower contact angle and a higher k-value occurred with wetting along the direction of the grain as compared to wetting perpendicular to the direction of the grain. They concluded that wood has a greater wettability

along the direction of the grain, and that this was most likely a result of the structure of the softwoods used, which have longitudinal tracheids that are longer in the direction of the grain than they are wide.

Given the importance of proper wetting in achieving a strong adhesive bond, the surface preparation of all materials used in this research will be controlled to maximize the likelihood of achieving a strong bond. Also, because of the differential wetting that has been observed in adhesive parallel to the grain versus perpendicular to the grain, there may be a weakness in the bond lines of cross-laminated adherends.

2.4 Yellow-poplar Anatomy

Yellow-poplar is a diffuse-porous hardwood that falls into the *Magnoliaceae* family (Hoadley, 1990). Gross anatomic characteristics of yellow-poplar include green, yellow, or tan heartwood, light-colored sapwood, marginal parenchyma, small solitary pores, and rays that can be easily seen on a radial surface, but may require a magnification device to be seen on a transverse or tangential surface (Hoadley, 1990).

An understanding of wood anatomy is critical in understanding how gross adhesive penetration occurs. Gross penetration occurs in part due to hydrodynamic flow, which results from force being applied to wood surfaces onto which adhesive has been applied, typically in a press or clamping mechanism (Kamke and Lee, 2007). In hardwoods such as yellow-poplar, hydrodynamic flow occurs longitudinally throughout the vessel elements (Kamke and Lee, 2007). In yellow-poplar, the adhesive must flow through scalariform perforation plates, commonly seen to have several thick bars (Hoadley, 1990). Adhesive penetration can also occur

through intervessel pits, which lack a membrane (Kamke and Lee, 2007). Pits in yellow-poplar are ovalular or rectangular in shape, and present oppositely (Hoadley, 1990). Hardwoods with a higher proportion of vessels within the woody tissue may be susceptible to a greater degree of adhesive penetration, as wide cell lumens do not restrict the hydrodynamic flow of adhesive (Gavrilovic-Grmusa et al., 2012).

Microscopy techniques were employed in this project, so it is important to understand the path through which adhesives might penetrate the wood. This understanding will help in determining the extent to which adhesive penetration occurred in a particular sample.

2.5 Characteristics of Wood that Affect Adhesion

2.5.1 Density

The density of a wood substrate can affect the quality of an adhesive bond. As the density of wood increases to around 800 kilograms per cubic meter (kg/m^3), the strength of a bond to that substrate will typically increase. However, above 800 kg/m^3 , the maximum bond strength will decrease (Frihart and Hunt, 2010). This relationship in part is a result of the thicker cell walls that occur in denser wood. Because the cell walls are thicker, the cell lumens are smaller. Both of these characteristics negatively impact the ability of an adhesive to penetrate into the wood substrate. Furthermore, because more dense woods tend to be stronger, more dense substrates are generally harder to bring into contact with each other when assembling the glue joint. Poor assembly negatively impacts bond strength (Frihart and Hunt, 2010).

In a study performed by Widsten et al. (2006), nine species of Australian timber were tested to determine the impact of various factors on their ability to form adhesive bonds, with one of those factors being density. The effect of density on the bond strength was determined by analyzing the tensile strength of cross-lap joints. The median tensile strength (location of 50% of the specimen failures) was used to analyze the results. The results showed that of the nine species tested, with the exception of *Eucalyptus marginata*, all species with a density above 740 kg/m³ yielded a lower median tensile strength than the species of lower density. The study concluded that density was an important factor in the gluability of the species tested, and higher densities tended to result in poorer adhesive bonds.

Using equation 4-12 in chapter four of the Wood Handbook, at 12% moisture content, the density of yellow-poplar is expected to be approximately 470.4 kg/m³ (Glass and Zelinka, 2010). Furthermore, Frihart and Hunt (2010) and Widsten et al. (2006) indicate that the density of yellow-poplar is low enough that there would not be any density-related bonding deficiencies. The lower relative density of yellow-poplar should allow for good surface-to-surface contact between adherends during bond assembly and should be low enough as to not cause any other density-related issues.

2.5.2 Method of Surface Preparation

The method of surface preparation can also impact the quality of an adhesive joint. Surface preparation through planing or jointing, which is the most industrially common method, must be achieved with the use of sharp blades, as planing or jointing with dull blades can essentially crush the wood cells and limit the ability of an adhesive to penetrate that cell

(Custódio et al., 2009). Also, planing with dull blades or an insufficient feed rate can cause excessive heating of the wood surface and essentially impart a localized heat treatment which can affect the surface properties of the wood (Hernandez and Naderi, 1999).

Jokerst and Stewart (1976) examined the strength of adhesive bonds in materials prepared with a knife planer compared to an abrasive planer. Their research found that material that was abrasive-planed had damaged cells at the surface, whereas knife-planed material had a cleanly cut surface. While there was no significant difference in the dry shear strength of samples knife-planed versus those that were abrasive-planed, there was a higher degree of separation of lamina as a result of an accelerated aging cycle among abrasive-planed samples. Abrasive-planed samples also exhibited excess checking near their surfaces after the accelerated aging cycle. This was assumed to be a product of the increased swelling of the damaged subsurface cells, which were not nearly as present in knife-planed samples. Murmanis et al. (1983) conducted a similar study in which they also used fluorescence microscopy (FM) and scanning electron microscopy (SEM) to evaluate the surface of materials before and after soak-dry treatments. Their results were consistent with those achieved by Jokerst and Stewart (1976) with knife-planed and abrasive-planed specimens possessing similar dry shear strengths and significantly lower shear strengths occurring from soak-dry cycled abrasive-planed specimens. SEM on Douglas-fir samples showed damage had occurred in the S2 layer of the cell wall, as well as separations between the S1 and S2 layers. Such damage was infrequent on knife-planed soak-dry cycled specimens.

Davis (1997) also identified two conditions observed in abrasive-planed wood that negatively impact adhesion. First, the surface achieved from abrasive planing tends to be comprised of several layers of damaged fibers. Second, the fine particles resultant of abrasive

planing can obstruct the cell lumens on the surface, which can negatively impact adhesive penetration.

Given that surface preparation can potentially affect the wettability, and ultimately the gluability of wood, all wood materials used in this research were prepared in a manner that attempted to achieve the best possible surface for bonding as a result of mechanical preparation (i.e., no chemicals were used for surface preparation).

2.6 Bonding Parameters

The parameters under which the adhesive bond is set may have an impact on the adhesive penetration that occurs in the wood adherends. Moisture content, pressure, press time, and temperature can all effect adhesive penetration, and the impact of these factors is likely interrelated (Brady and Kamke, 1988, and Kamke and Lee, 2007). To prevent any unnecessary introduction of variability, all bonding parameters were carefully controlled throughout the project.

2.6.1 Consolidation Pressure

Rabiej and Behm (1992) determined that an appropriate consolidation (clamping) pressure for sugar maple could be expressed as a coefficient of the compressive strength of the adherend. They determined the compressive strength for tangentially and radially oriented specimens (as opposed to using accepted values for general compressive strength), and then determined the shear strength of the orthotropically oriented samples resultant from a range of clamping pressures. The ratio of clamp pressure to compression strength at the proportional

limit, expressed at the CP/CS ratio, was then determined based on the data. They found that for both radially and tangentially oriented samples of sugar maple, the maximum shear strength occurred from a CP/CS ratio of 0.5 to 0.6. However, the gains in shear strength as a result of clamping pressure were most quickly realized up to a CP/CS ratio of 0.3. Above this level, the additional shear strength gained by increased clamping pressure occurred more gradually and represented a small portion of shear strength.

2.6.2 Moisture Content

A moisture content of approximately 10% is generally appropriate for structural adhesive bonds in wood (Davis, 1997). However, certain adhesives perform best on wood substrates of a specific moisture content, and this information is typically provided by the adhesive manufacturer. Generally speaking, water-borne adhesives that are both cold-setting and set through a chemical reaction perform better on wood with a moisture content between 8% and 12%. However, adhesives that set when water is lost exhibit better bonding with substrates of a moisture content in the range of 6-8% (Davis, 1997). Kamke and Lee (2007) noted that as water-borne adhesives are drawn into wood, the wood tends to absorb the water into the cell wall more rapidly than the adhesive as a whole. In wood with a low moisture content, the viscosity of the adhesive can increase near the surface of the adherend and negatively impact bonding.

Polyurethane adhesives are a type of moisture-curing adhesive. Some formulations of polyurethane adhesives recommend a substrate moisture content of up to 19%, while others suggest misting the surface with water before gluing. This ensures that there is sufficient moisture available to allow the adhesive to cure properly. Because polyurethane adhesives are so

popular in CLT manufacture, if future work is done on this project, it may be advantageous to perform it using an appropriate polyurethane adhesive. If this occurs, care must be taken to condition the adherends to a suitable moisture content.

2.7 Effect of wood characteristics on adhesive bond quality

2.7.1 Orthotropic Structure and Saw Pattern

Rabiej and Behm (1992) evaluated the effect of the orthotropic structure of wood on adhesive bond quality. They used one hardwood and one softwood species in their research. The adherends were either quartersawn or flatsawn, and two different adhesives were used. The bonds were evaluated by their shear strength and the amount of wood failure that occurred during testing. Specific gravity was also a factor considered in the experiment. Their results showed that for sugar maple, bonds made on the tangential surfaces were significantly stronger than those made on radial faces. Also, higher specific gravity correlated with higher bond strengths for both radially and tangentially glued blocks. For wood failure, radially bonded samples had a wood failure of 98%, which was not impacted by varying specific gravities. On the tangentially glued samples, specific gravity did seem to have an effect on wood failure, as samples with a specific gravity of 0.65 yielded 100% wood failure, while samples with a specific gravity of 0.81 produced only 25% wood failure. They concluded that the orthotropic nature of wood, as well as its specific gravity, do affect adhesion and should be considered when bonding wood.

Results from the research of Okkonen and River (1988) agreed with the results of Rabiej and Behm (1992) with regard to the effect of grain orientation on the shear strength of glue bonds. Results showed that white oak (*Quercus alba*) and hard maple (*Acer saccharum*) both yielded higher shear strengths from specimens that were tangentially oriented rather than radially oriented. This observation held true for every comparison in the experiment between white oak and maple. This phenomenon was explained in part by the abundance of rays in oak and maple acting to help resist the shear forces in the tangential plane (Okkonen and River, 1988).

Using epi-fluorescence microscopy on samples of beech (*Fagus sylvatica*) bonded with a liquid urea-formaldehyde adhesive, Sernek et al., (1999) observed greater adhesive penetration in the tangential face than in the radial face. The researchers attributed the greater penetration to the fact that beech has thin latewood bands which contain fewer and smaller vessels through which the adhesive can flow, as well as the vessels containing more pits on the radial surfaces, allowing for greater penetration tangentially.

As research has shown that hardwoods tend to have a greater adhesive strength from bonds made on the tangential surface, this project included bonding surface plane as one of the tested effects in the experimental design. However, because the rays in yellow-poplar (1-5 seriate) are smaller than those found in sugar maple (7-8 seriate), beech (15-25 seriate), and white oak (characteristically large rays) (Hoadley, 1990), this effect may not be as great.

2.7.2 Lamellae Thickness

Past research suggests that lamella thickness affected the delamination resistance of European Beech glulam beams (Ohnosorge et al., 2009). The beams with the smallest lamellae

thickness (29 mm, ~1.14 in) showed only 1.3% average delamination, whereas the beams with the thickest lamellae (38 mm, ~ 1.50 in) showed an average of 13.2% delamination in laboratory tests. This effect is believed to be caused by increased internal stresses that occur within bigger lamellae, given the greater amount of wood present to absorb or release moisture and cause swelling or shrinkage.

CLTs are commonly manufactured using 0.75 inch thick adherends. However, it is not uncommon to produce CLT panels with 1.5 inch thick adherends. According to Ohnosorge et al. (2009), this could cause a decrease in bond durability. In this research, testing was performed to determine if yellow-poplar suffers a decrease in bond durability as a result of lamellae thickness by testing two adherend thicknesses.

2.8 Objective and Hypotheses

The objective of this research was to examine which characteristics of yellow-poplar lumber affect adhesive bond quality. Three hypotheses were tested in order to examine the effect of and interactions between the lumber characteristics: bonding surface plane, lamination orientation, and adherend thickness.

Hypothesis 1: Yellow-poplar with tangential bonding surfaces will possess a higher bond strength and bond durability than yellow-poplar with radial bonding surfaces.

Hypothesis 2: Yellow-poplar that is bonded with the longitudinal axis of each lamella parallel to the that of the adjacent lamella will exhibit a stronger and more durable bond than perpendicular laminated yellow-poplar.

Hypothesis 3: Adhesively-bonded yellow-poplar with a greater thickness will yield lower bond durability than thinner lamellae.

Chapter 3: Methods

3.1 Material Preparation

To evaluate the effect of various factors on adhesive bond quality, locally-obtained yellow-poplar (*Liriodendron tulipifera*) provided by Allegheny Wood Products in Hazelton, West Virginia was used as the primary material. A subset of samples of construction lumber were used as the reference specimens, as traditional S-P-F construction lumber is used in current CLT production. Upon the procurement of the S-P-F construction lumber, the boards were further identified as fitting into the hard pine category based on the presence of resin canals, pinoid pits in the ray parenchyma cells, and dentate ray tracheids. Identification to a specific species within the hard pine group was unfeasible.

Upon obtaining the yellow-poplar, all pieces were planed to a thickness greater than their final target thickness (i.e., 1.000 and 1.375 inches) by one-eighth of an inch using a large Oliver thickness planer. The boards were then ripped to a width of 5.5 inches before being placed in a conditioning chamber for fourteen weeks at an average temperature of 68.7° F and an average relative humidity of 65.2%. A long conditioning period was required for the yellow-poplar adherends, as the lumber was between approximately 5% and 6% moisture content when it was obtained. The hard pine adherends used were close to the appropriate moisture content upon purchase, so a shorter two-week conditioning period was sufficient to allow them to reach equilibrium at the same average temperature and relative humidity conditions as the yellow-poplar adherends. Given the conditions in the chamber, the final moisture content of the adherends was believed to be approximately 12.0%, based on table 4-2 in chapter four of the

Wood Handbook (Glass and Zelinka, 2010). Data collected measuring the actual temperature and relative humidity of the conditioning chamber through the period of yellow-poplar conditioning can be found in Appendix A.

Within four hours prior to bonding, the adherends were planed again to a final thickness (1.000 or 1.375 inches, depending on the treatment parameters of the sample) to expose a fresh surface for bonding. The final dimensioning was achieved using a DeWalt thickness planer with a three-knife cutterhead with carbide-tipped knives. Care was taken to reduce the instance of planer snipe, which could have affected the bonding assembly, by feeding all adherends into the planer directly behind each other and by starting and ending each line with sacrificial wood blocks on which snipe could occur with no consequence.

After the final planing was completed for each adherend, images of the surface to which adhesive would be applied, as well as both end grain surfaces were captured. These images were taken so that further examination of the influence of grain angle on bond strength may be investigated through future research.

To determine the density of each adherend, thickness, width, and length were measured at two different points on each adherend using a digital caliper, and mass was recorded using a digital balance. The averages of the measurements for thickness, width, and length were used in the calculation of density. Density information for each adherend is available in Appendix A.

Because half of the samples for this research were bonded with one adherend in the assembly oriented perpendicular to the other adherend, one adherend per perpendicular laminated assembly was crosscut in half after it was planed. Figure 2 shows how the

perpendicular laminated samples were assembled.

Figure 0-2. Example of perpendicular lamination applied to certain samples.

3.2 Adherend Randomization

To minimize the effect of the variability of wood, the two adherends that were bonded together to form one sample were chosen at random. However, there were several considerations that were made in the randomization of the adherends. First, two different thicknesses were present amongst the adherends as part of the experimental design of this research. Thus, the randomization occurred in two settings: once for the 1.000 inch thick adherends, and once for the 1.375 inch thick adherends. Second, it was not possible to randomize the bonding surface plane present on an individual adherend; rather, this was an intrinsic characteristic of each piece (Figure 3). Each adherend was assigned an identification number, and in an Excel spreadsheet, it was noted whether that adherend possessed a radial or tangential surface on its widest face.

Figure 0-3. Example of tangential and radial surfaces of wood. Source: <http://www.aaes.auburn.edu/comm/pubs/bulletins/figureinwood/figure2.html>

The adherends were assigned to a sample based on their order in the list after the list was randomized. For example, the first twenty adherends that were 1.375 inches thick and had a tangential wide face were assigned to samples A1 through A10. The next ten of these adherends were assigned as the tangential adherend in samples C1 through C10 (as samples in treatment C consisted of one adherend with a radial wide face and one adherend with a tangential wide face),

because treatment group B required adherends with a radial wide face. The adherends were assigned in order until all 120 samples were configured.

3.3 Sample Bonding

For this research, a resorcinol formaldehyde adhesive produced by Momentive (Cascophen LT-5210J resin with Cascoset FM-6310LS hardener) was used. Adhesive rate, consolidation pressure, and clamping time were held constant (Table 1) throughout the entire experiment. These bonding parameters were determined based on the adhesive manufacturer's recommendation.

Table 1. Parameters for sample bonding.

Adhesive Rate	70 pounds/ 1000 square feet
Adhesive Mixture Ratio (Resin : Hardener)	2.3 : 1
Consolidation Pressure	150 psi
Clamping Time	5 hours
Press Platen Temperature	70 °F

Samples were pressed using an automated Carver Press capable of adjusting to hold a consistent pressure. The press had a capacity of twelve inches by twelve inches that allowed for two samples to be placed side-by-side in the press. To reduce the time needed to complete the bonding of all samples, two stacks of two samples were placed in the press for each cycle, resulting in the bonding of four samples per press cycle (Figure 4). Upon completion of the press

cycle, samples were returned to the conditioning chamber.

Figure 0-4. Four samples in the press.

Once all of the samples were prepared and prior to testing, the samples were edge trimmed to a width of 4.125 inches using a table saw. This piece was then ripped in half, leaving two separate two inch wide samples (assuming 1/8th inch saw kerf). From these two samples of the same bond line, one was machined to form specimens for shear block tests, while the other was used to form specimens for the cyclic delamination tests (Figure 5). A table saw with a straight-tooth blade was used to produce specimens of necessary size, depending on the test to be performed. After machining, all test specimens were returned to the conditioning chamber which was set to maintain conditions of 73°F and 53% relative humidity (approximately 9.7% EMC), as prescribed in ASTM D905. The specimens remained in the chamber until no difference in weight was observed over a twenty-four hour period, which took approximately ten days.

Figure 0-5. Sample layout for obtaining test specimens. Sections A and B represent the two inch wide bond line samples from which the cyclic delamination or shear block specimens were cut. Which section (A or B) was used to produce which type of test specimen was not controlled nor randomized.

3.4 Experimental Design

A 2 x 2 x 3 factorial design was used to test the main effects of and interactions between three factors: adherend thickness (2), lamination orientation (2), and bonding surface plane (3). The design tested twelve different treatments (Figure 6), and each treatment was tested in two ways: for bond strength through a shear block test, and for bond durability through a cyclic delamination test. For both tests, thirty specimens representing ten different bond lines were tested for each treatment. In addition to the yellow-poplar samples, ten samples of hard pine

were bonded together and tested as the reference species for the experiment. The hard pine was subjected to a treatment of the experimental design under which the yellow-poplar samples exhibited the best bond line performance.

Figure 0-6. Factorial design of experiment. The treatments shown were subjected to each adhesive test.

For this experimental design, 360 yellow-poplar specimens were tested for each adhesive test. An additional thirty samples (representing ten bond lines) of the treatment option that yielded the highest bond strength and durability were evaluated using both adhesive tests on the hard pine reference. Ultimately, this experimental design required the testing of 780 individual specimens (Table 2).

In statistical evaluation, each treatment was evaluated based on the average results for each bond line, rather than for each specimen. Statistically, the experimental unit of each treatment is one bond line, and not one specimen from a given bond line. By testing three specimens per bond line and using three data points to calculate an average for that bond line, the inherent variability of a given specimen will have less of an effect in the analysis of results.

Table 2. Outline of performed testing.

Species	Adhesive Test	Purpose of Test	Number of Specimens
Yellow-poplar	Cyclic Delamination	Experimental Design	360
Yellow-poplar	Shear Block	Experimental Design	360
Hard Pine	Cyclic Delamination	Reference	30
Hard Pine	Shear Block	Reference	30
Total:			780

3.5 Test Methods

All samples used to test the hypotheses of this research were subjected to the same means of evaluation. All samples were evaluated under the shear block test or the cyclic delamination test. Upon the completion of the shear block tests, wood failure percentage was estimated as well.

3.5.1 Shear Block

The strength of the adhesive bond was tested using the shear block test method described in ASTM D 905: *Standard Test Method for Strength Properties of Adhesive Bonds in Shear by Compression Loading* (ASTM 2010). The specimens were cut from bond line samples in a

manner such as that described in Figure 8. Each specimen was machined from a two inch wide strip from a bond line sample to fit into the shearing tool fixture. To shape the samples, a paper template was adhered to the side of the sample (Figure 7). A table saw sled was used to send the samples over a straight-tooth table saw blade capable of making square saw kerfs. Four shear block samples were cut from each bond line sample, the first three of which were tested. The fourth was kept as a backup, if needed.

Figure 0-7. Shear block specimens being cut from sample using paper template and table saw with crosscut sled.

Specimens remained in the conditioning chamber until immediately prior to testing. To determine the shear area of each specimen, the length and width of the bond line were both measured in two locations (approximately 0.5 inches inward from the edge of the bond line on each side) using a digital caliper. These measurements, recorded to the nearest thousandth of an inch, were averaged together to determine a mean bond line length and width, and from these

measurements, the bond line shear area was calculated. Each specimen was tested in the shearing fixture at a loading rate of 0.20 inches per minute until failure occurred. The shear strength was reported as the shear stress at failure divided by the area of the bond line (pounds-force per square inch). An example of a shear block specimen is shown below in Figure 9.

Figure 0-8. Method for producing five shear block samples from one bond line. Source: ASTM 2010.

Figure 0-9. Single shear block specimen. Source: ASTM 2010.

3.5.2 Cyclic Delamination

The durability of the adhesive bond was tested using ASTM D 1101-97a: *Standard Test Methods for Integrity of Adhesive Joints in Structural Laminated Wood Products for Exterior Use* (ASTM 2013). This test method closely replicates AITC T110-2007: *Cyclic Delamination Test*, which is the cyclic delamination test that is used for testing cross-laminated timber members (AITC 2007). Specimens were cut to two inches wide by 2.5 inches in length. Prior to testing, the length of each section of the bond line on end-grain surfaces was measured and the weight of each specimen was recorded. Using a plastic container inside of a steel chamber, samples were submersed in water (65 to 85° F) and subjected to a vacuum of 25 inches of

Mercury for a total of 30 minutes. Then, 75 pounds per square inch (psi) of air was released into the chamber and held for two hours. The samples were placed in a Cincinatti Sub-Zero, CSZ C32PLUS (Cincinatti, OH) temperature/humidity chamber at a temperature of 155°F and relative humidity of 12% while circulating air at a rate of 500 feet per minute throughout the chamber. When the samples returned to within 15% of their original weight (which took on average 16 hours), the delamination along each section of the bond line of end-grain surfaces for each specimen was measured using a digital caliper and recorded to the nearest thousandth of an inch. A 0.003 inch feeler gage was used to determine if minor delaminations were large enough to be

recorded. The total delamination of a sample was expressed as a percentage of the total length of the bond line of that sample. Figure 10 shows an example of a partially delaminated bond line.

Figure 0-10. Example of partial bond line delamination.

3.5.3 Estimation of Wood Failure

Wood failure of shear block specimens was determined using the techniques described in ASTM D 5266: *Standard Practice for Estimating the Percentage of Wood Failure in Adhesive Bonded Joints* (ASTM 2013). Joint failure surfaces were categorized as either adhesive failure or wood failure (including both shallow and deep wood failure). Adhesive failure was considered

any failure occurring within the bulk adhesive layer, or failure along the adhesive interface with the adherend in which no wood fiber remained bonded to the adhesive. Shallow wood failure is any wood failure occurring within the first one or two layers of wood cells below the adhesive interface, “in which the fracture path is not influenced by the wood-grain angle or growth-ring structure” (ASTM 2013). Deep wood failure is viewed as any failure occurring within the bulk wood material, as influenced by the wood structure.

Wood failure was visually measured and categorized on each half of the failed specimen, and a total percentage was recorded to represent the amount of wood failure for each specimen. Wood failure was estimated to the nearest 5%. The estimation of wood failure for all specimens in this research was performed by TECO (Eugene, OR), an accredited third-party testing and inspection agency. Figure 11 shows all of the shear block samples from Treatment B displayed for evaluation of wood failure. Figure 12 shows a specimen with 100% wood failure.

Figure 0-11. Treatment B shear block samples displayed to show wood failure.

Figure 0-12. Specimen with 100% wood failure (Z4-1).

Chapter 4: Results and Discussion

The following chapter includes the presentation and discussion of all test results. In all statistical analyses, the alpha level was 0.05.

4.1 Yellow-poplar: Shear Strength

Figure 13 shows a box and whisker plot of the mean shear strength test results for the yellow-poplar samples. Results of the reference (hard pine) comparison are discussed in sections 4.6 – 4.9. Based on the test results, the perpendicular laminated samples had an apparently lower mean shear strength as compared to samples that were parallel laminated. Table 3 shows the mean shear strength test results with standard deviation, coefficient of variation, as well as minimum and maximum values.

Figure 0-1. Box and whisker plot of mean shear strength test results for yellow-poplar samples.

Table 3. Summary statistics of shear strength test results for yellow-poplar.

Treatment	Shear Strength (psi)	Standard Deviation (psi)	Coefficient of Variation (%)	Min. Strength (psi)	Max. Strength (psi)
A (1.375,0°,Tan)	1,595	125	8	1,357	1,768
B (1.375,0°,Rad)	1,546	161	10	1,267	1,771
C (1.375,0°,Combo)	1,658	191	12	1,400	1,913
D (1.375,90°,Tan)	721	69	10	636	868
E (1.375,90°,Rad)	814	140	17	636	1,039
F (1.375,0°,Combo)	802	137	17	540	1,039
G (1.000,0°,Tan)	1,776	183	10	1,537	2,137
H (1.000,0°,Rad)	1,566	184	12	1,312	1,935
I (1.000,0°,Combo)	1,558	153	10	1,402	1,786
J (1.000,90°,Tan)	758	220	29	518	1,326
K (1.000,90°,Rad)	821	257	31	541	1,232
L (1.000,0°,Combo)	819	180	22	568	1,112

Results of the analysis of variance (ANOVA) (Table 4) indicated that there was a statistically significant difference in the mean shear strengths of samples that were perpendicular laminated and the samples that were parallel laminated. The same ANOVA analysis also indicated that there was a statistically significant interaction between bonding surface plane and lamination orientation (Figure 14).

Table 4. ANOVA Effect Tests of mean shear strength test results for yellow-poplar.

Source	Prob > F
Thickness	0.3941
Bonding Surface Place	0.7680
Lamination Orientation	<0.0001
Thickness * Bonding Surface Plane	0.1504
Thickness * Lamination Orientation	0.8349
Bonding Surface Plane * Lamination Orientation	0.0245
Thickness * Bonding Surface Plane * Lamination Orientation	0.2451

Figure 0-2. Plot of mean shear strength interaction between surface bonding plane and lamination orientation.

As seen in Figure 14, there is a significant interaction between bonding surface plane and lamination orientation. The mean shear strengths of parallel laminated samples tend to, at least in principle, mirror the mean shear strengths of their perpendicular laminated counterparts. Tangential surfaces bonded together yielded the highest shear strength mean for parallel laminated samples, while tangential surfaces yielded the lowest shear strength mean for

perpendicular laminated samples. Radial surfaces bonded together yielded the lowest shear strength mean for parallel laminated samples, while radial surfaces yielded the highest shear strength mean for perpendicular laminated samples. For both parallel and perpendicular laminated samples, samples with a combination of surface bonding planes produced an intermediary mean.

A Tukey HSD test on the interaction between bonding surface plane and lamination orientation revealed that, regardless of bonding surface plane, samples that were perpendicular laminated had a significantly lower average shear strength than samples that were parallel laminated. However, no samples of a given lamination orientation (i.e., perpendicular or parallel laminated) had a significantly different shear strength than samples of the same lamination orientation based on bonding surface plane alone.

4.2 Yellow-poplar: Wood Failure

Figure 15 shows a box and whisker plot of the mean wood failure results for the yellow-poplar samples. As determined by a Poisson regression analysis, all three effects were statistically significant in influencing wood failure percentage (Table 5). Furthermore, the interaction between lamination orientation and bonding surface plane (Figure 16) was also

statistically significant as determined by the Tukey-Kramer test (Littell et al., 2006). Table 7 provides summary statistics of the mean wood failure results for yellow-poplar.

Figure 0-3. Box and whisker plot of mean wood failure results for yellow-poplar samples.

Table 5. Poisson Regression Analysis: Type III Tests of Fixed Effects of mean wood failure results for yellow-poplar.

Source	Prob > F
Thickness	0.0076
Bonding Surface Place	<0.0001
Lamination Orientation	<0.0001
Thickness * Bonding Surface Plane	0.1152
Thickness * Lamination Orientation	0.9104
Bonding Surface Plane * Lamination Orientation	0.0063
Thickness * Bonding Surface Plane * Lamination Orientation	0.2895

Figure 0-4. Plot of mean wood failure interaction between surface bonding plane and lamination orientation.

The interaction between lamination orientation and bonding surface plane was significant ($p=0.0063$). The mean wood failure observed followed a similar trend for parallel laminated versus perpendicular laminated samples: radially bonded surfaces showed the highest amount of mean wood failure, followed by combined surfaces and tangentially bonded surfaces, respectively. However, for perpendicular laminated samples, the trend was considerably more pronounced. For perpendicular laminated samples, radial surfaces averaged 88.5% wood failure while tangential surfaces averaged 72.7% wood failure, a difference of 15.8%. For parallel laminated samples, radial surfaces averaged 95.9% wood failure while tangential surfaces averaged 92.2% wood failure, a difference of only 3.7%. Statistically significant comparisons within this interaction are shown in Table 6 below.

Table 6. Select comparisons of bonding surface plane and lamination orientation interactions of wood failure results for yellow-poplar. Tukey-Kramer, adjusted for multiple comparisons.

<i>Treatment 1</i>		<i>Treatment 2</i>		
Bonding Surface Plane	Lamination Orientation	Bonding Surface Plane	Lamination Orientation	Adj. P
Radial	Parallel	Combo	Perpendicular	<0.0001
Radial	Parallel	Tangential	Perpendicular	<0.0001
Combo	Parallel	Combo	Perpendicular	<i>0.0004</i>
Combo	Parallel	Tangential	Perpendicular	<0.0001
Tangential	Parallel	Combo	Perpendicular	.00011
Tangential	Parallel	Tangential	Perpendicular	<i><0.0001</i>
Radial	Perpendicular	Tangential	Perpendicular	<i><0.0001</i>

Comparisons were evaluated using the Tukey-Kramer test adjusted for multiple comparisons, although not all comparisons were of interest. For this interaction, comparisons that share a common effect parameter were considered to be of interest, and the adjusted p-values of those comparisons are shown in bold italics in Table 6. As shown above in Figure 16, radial

surfaces that were perpendicular laminated yielded significantly higher mean wood failure than tangential surfaces that were perpendicular laminated. For tangential surfaces bonded together, parallel laminated samples had an average wood failure of 92.2%, while perpendicular laminated samples had an average wood failure of 72.7%. Lastly, for samples with a combination of bonding surfaces, parallel laminated samples had an average wood failure of 93.1%, compared to perpendicular laminated samples which averaged 80.3% wood failure. The complete comparison matrix for the interaction between bonding surface plane and lamination orientation for mean wood failure can be found in Appendix C.

Table 7. Summary statistics of mean wood failure results for yellow-poplar.

Treatment	Wood Failure (%)	Standard Deviation (%)	Coefficient of Variation (%)	Min. Wood Failure (%)	Max. Wood Failure (%)
A (1.375,0°,Tan)	89	17	19	43	98
B (1.375,0°,Rad)	95	4	4	85	98
C (1.375,0°,Combo)	90	9	10	75	98
D (1.375,90°,Tan)	73	27	37	8	95
E (1.375,90°,Rad)	88	14	16	52	97
F (1.375,0°,Combo)	74	22	29	30	93
G (1.000,0°,Tan)	95	3	3	90	98
H (1.000,0°,Rad)	97	2	2	95	100
I (1.000,0°,Combo)	96	3	3	93	100
J (1.000,90°,Tan)	72	24	33	20	95
K (1.000,90°,Rad)	90	12	13	60	100
L (1.000,0°,Combo)	87	10	12	68	97

4.3 Yellow-poplar Shear Block Failure Patterns

To help understand and explain the lower average shear strength and wood failure percentage of samples that were perpendicular laminated, all shear block specimens were evaluated based on failure patterns. Unlike other analyses in this project, calculated statistics were based on readings from individual specimens as opposed to averaging the specimen results to analyze trends based on sample averages. No statistical analysis was performed in evaluating the failure patterns; rather, the goal was to determine if any telling trends were present for the shear block wood failure patterns.

Shear block failure patterns were characterized based on three criteria: depth of wood failure, if wood failure occurred on one or both sides of the specimen bond line, and if the direction of the failure was parallel or perpendicular to the direction of loading during the initial shear test. In characterizing shear block failure patterns, only wood failure was considered (i.e., if a specimen had 50% wood failure, then only that 50% of the specimen was viewed in characterizing the failure pattern). Table 8 shows the criteria for failure characterization.

Table 8. System for characterizing shear block failure patterns.

Category	Characterization	Criteria
Depth of failure	Deep	>75% of wood failure deep into wood tissue
	Shallow	>75% of wood failure shallow; adhesive visible behind failure
	Mixed	Both deep and shallow wood failure present between 25% and 75%
Location of failure	One-Sided	>75% of wood failure on one side of adhesive bond line
	Both Sides	<75% of wood failure on one side of adhesive bond line
Direction of failure	Parallel	>75% of wood failure parallel to direction of loading
	Perpendicular	>75% of wood failure perpendicular to direction of loading
	Both Directions	Wood failure in both directions of loading present between 25% and 75%

Table 9 shows the results of shear block failure characterization for parallel laminated samples as compared to perpendicular laminated samples in terms of the direction of failure. None of the parallel laminated specimens exhibited any failure in the perpendicular direction, which was expected. With both adherends in the specimens having been loading with the longitudinal direction of the wood parallel to the applied shear force, the failure naturally travelled through the grain of the wood longitudinally. Failure occurred parallel to the plane of shear force for 100% of the parallel laminated specimens.

Table 9. Shear block failure characterization based on direction of failure.

	Parallel Laminated (no. of specimens)	Parallel Laminated (%)	Perpendicular Laminated (no. of specimens)	Perpendicular Laminated (%)
Perpendicular Failure	0	0.0	119	66.1
Parallel Failure	180	100.0	18	10.0
Failure in Both Directions	0	0.0	43	23.9

For specimens that were perpendicular laminated, failure most often occurred in the direction perpendicular to the applied shear force during the test. Furthermore, during the shear block tests, it was noted the perpendicular laminated specimens often failed differently than the parallel laminated specimens. Instead of the specimen reaching a maximum stress and then rapidly failing, resulting in a drastic drop in the measured applied load (as was the case for parallel laminated specimens), the specimens most often reached a maximum stress and then began to slowly yield as the adherend within the specimen oriented perpendicular to the applied shear force essentially peeled away from the other adherend. Given the difference in shear strength between solid yellow-poplar parallel to the grain versus perpendicular to the grain (see section 5.5), this is not surprising as the failure followed the weaker section of the specimen.

Table 10 shows the characterization of shear block failure patterns based on the depth of wood failure. There were no major differences for parallel versus perpendicular laminated samples based on depth of failure. Shallow failure occurred slightly more often in perpendicular laminated samples.

Table 10. Shear block failure characterization based on depth of wood failure.

	Parallel Laminated (no. of specimens)	Parallel Laminated (%)	Perpendicular Laminated (no. of specimens)	Perpendicular Laminated (%)
Shallow Failure	26	14.4	34	18.9
Deep Failure	72	40.0	68	37.8
Failure at Both Levels	82	45.6	78	43.3

Table 11 shows the characterization of shear block failure patterns based on the location of wood failure. There appear to be no major differences between perpendicular laminated and parallel laminated specimens based on location of wood failure. Perpendicular laminated specimens more often failed on only one side, but the difference was slight (73.3% for perpendicular laminated specimens compared to 66.7% for parallel laminated specimens).

Table 11. Shear block failure characterization based on location of wood failure.

	Parallel Laminated (no. of specimens)	Parallel Laminated (%)	Perpendicular Laminated (no. of specimens)	Perpendicular Laminated (%)
Failure On One Side	120	66.7	132	73.3
Failure On Both Sides	60	33.3	48	26.7

More specific comparisons can also be made regarding shear block failure patterns. In terms of shear strength and wood failure, for perpendicular laminated yellow-poplar, samples with radial bonding surfaces performed well compared to samples with tangential or combined bonding surfaces. By looking at the failure patterns in these comparisons (Table 12), it can be seen that specimens with radial bonding surfaces only displayed parallel failure direction in 1.7% of specimens (1 occurrence). Samples with tangential bonding surfaces and combined bonding surfaces had 13.3% and 15.0% parallel failure, respectively. Large disparities were not found between specimens based on bonding surface plane in terms of depth of wood failure or location of wood failure.

In perpendicular laminated specimens with radial bonding surfaces that displayed any shallow wood failure, it with not uncommon to observe entire rays adhered to the specimen bond line (Figure 17). Because radial faces of hardwoods expose the wide surface of wood rays (i.e., ray fleck), it could be that the adhesive used in the project was proficient at bonding to the rays. It could also be that the connection of the wood rays to the rest of the wood structure is perhaps stronger than certain connections achieved by adhering tangential surfaces (with only ray ends exposed to bonding) to other tangential surfaces or radial surfaces. This could explain why, at least in the case of perpendicular laminated yellow poplar, samples with either radial bonding surfaces or combined bonding surfaces outperformed samples with tangential bonding surfaces both in shear strength and wood failure percentage. Furthermore, compared to counterpart samples in terms of adherend thickness and lamination orientation, samples with radial bonding

surfaces always averaged higher levels of wood failure.

Figure 0-5. Example of specimen showing shallow, perpendicular wood failure on one side of the bond line. Close inspection shows wood rays adhered to the bond line (left adherend). Specimen K7-1.

Table 12. Shear block failure characterization for all perpendicular laminated samples, compared by bonding surface plane.

Category	Tangential Bonding Surfaces (no. of specimens)	Tangential Bonding Surfaces (%)	Radial Bonding Surfaces (no. of specimens)	Radial Bonding Surfaces (%)	Combined Bonding Surfaces (no. of specimens)	Combined Bonding Surfaces (%)
Perpendicular Failure	32	53.3	44	73.3	43	71.7
Parallel Failure	8	13.3	1	1.7	9	15.0
Failure Both Directions	20	33.3	15	25.0	8	13.3
Shallow Failure	11	18.3	13	21.7	10	16.7
Deep Failure	25	41.7	22	36.7	21	35.0
Failure at Both Levels	24	40.0	25	41.7	29	48.3
Failure On One Side	38	63.3	43	71.7	51	85.0
Failure On Both Sides	22	36.7	17	28.3	9	15.0

4.4 Yellow-poplar: Cyclic Delamination

Figure 18 shows a box and whisker plot of the results of the mean cyclic delamination tests on yellow-poplar samples. The results of these tests tended to be quite variable, with samples within the same treatment group ranging from 0.0% delamination to 16.9% delamination. However, the greatest observed delamination in terms of treatment average was only 3.7% (treatment C). Treatment G had no observable delamination on any single specimen,

and thus the treatment average was 0.0%. A Poisson regression analysis (Table 13) revealed that none of the treatment main effects were statistically significant in affecting delamination, nor were any of the two-way effect interactions. The only significant interaction was the three-way effect interaction, which is shown in Figure 19. Table 14 provides summary statistics for the mean cyclic delamination test results for yellow-poplar.

Figure 0-6. Box and whisker plot of mean cyclic delamination results for yellow-poplar samples.

Table 13. Poisson Regression Analysis: Type III Tests of Fixed Effects of mean cyclic delamination results for yellow-poplar.

Source	Prob > F
Thickness	0.9693
Bonding Surface Place	0.9143
Lamination Orientation	0.9799
Thickness * Bonding Surface Plane	0.8424
Thickness * Lamination Orientation	0.9737
Bonding Surface Plane * Lamination Orientation	0.9961
Thickness * Bonding Surface Plane * Lamination Orientation	0.0016

Table 14. Summary statistics of mean cyclic delamination test results for yellow-poplar samples.

Treatment	Delamination (%)	Standard Deviation (%)	Coefficient of Variation (%)	Min. Delamination (%)	Max. Delamination (%)
A (1.375,0°,Tan)	2.9	5.2	177.6	0.0	13.1
B (1.375,0°,Rad)	2.1	3.1	142.9	0.0	9.1
C (1.375,0°,Combo)	3.7	6.9	188.0	0.0	16.9
D (1.375,90°,Tan)	1.4	2.8	204.0	0.0	9.1
E (1.375,90°,Rad)	2.6	3.7	145.9	0.0	8.7
F (1.375,0°,Combo)	1.0	1.2	124.6	0.0	3.2
G (1.000,0°,Tan)	0.0	0.0	0.0	0.0	0.0
H (1.000,0°,Rad)	1.7	3.6	210.8	0.0	8.6
I (1.000,0°,Combo)	0.8	2.5	316.2	0.0	8.0
J (1.000,90°,Tan)	1.6	2.8	175.0	0.0	8.1
K (1.000,90°,Rad)	0.5	1.3	258.1	0.0	4.0
L (1.000,0°,Combo)	1.1	2.5	222.7	0.0	7.3

Figure 0-7. Three-way interaction of effects on mean cyclic delamination results for yellow-poplar samples.

Figure 19 does not reveal any apparent interaction that might influence delamination test results. While the three-way effect interaction was itself statistically significant ($p=0.0016$), many of the included comparisons were either not statistically significant or were not of particular interest/use. The entire comparison matrix for the three-way effect interaction for the mean cyclic delamination results can be found in Appendix C. Table 15 below shows all of the

statistically significant comparisons as determined by the Tukey-Kramer test (adjusted for multiple comparisons) (Littell et al., 2006).

Table 15. Select comparisons of three-way effect interactions of mean cyclic delamination test results for yellow-poplar. Tukey-Kramer, adjusted for multiple comparisons.

<i>Treatment 1</i>			<i>Treatment 2</i>			Adj. P
Bonding Surface Plane	Thickness	Lamination Orientation	Bonding Surface Plane	Thickness	Lamination Orientation	
Combo	1.375	Parallel	Combo	1.0000	Parallel	<i>0.0082</i>
Combo	1.375	Parallel	Radial	1.0000	Perpendicular	0.0032
Combo	1.375	Parallel	Combo	1.375	Perpendicular	<i>0.0179</i>
Combo	1.375	Parallel	Combo	1.000	Perpendicular	0.0327
Tangential	1.375	Parallel	Radial	1.000	Perpendicular	0.0195
Radial	1.375	Perpendicular	Radial	1.000	Perpendicular	<i>0.0479</i>

Several of the comparisons above, though statistically significant, do not appear to be of any use: for example, little insight is gained by comparing samples that were 1.375 inches thick, had tangential bonding surfaces, and were parallel laminated to samples that were 1.000 inch thick, had radial bonding surfaces, and were perpendicular laminated. The three comparisons in Table 15 that are in bold italics were deemed to be of interest.

Treatment C (combined bonding surfaces, 1.375 inches thick, parallel laminated) appeared in four out of the six statistically significant comparisons, two of which were actually of interest. Treatment C had an average delamination of 3.7%, which is the greatest of all treatments. Thus, it could be expected to have significant comparisons to other treatments.

4.5 Yellow-poplar Summary

Twelve different treatments were applied to yellow-poplar lumber to test for the main effects and interactions between three factors: adherend thickness, bonding surface plane, and lamination orientation. ANOVA and Poisson regression analysis were used to detect statistically significant differences of the effects.

Parallel laminated samples showed a greater mean shear strength than did perpendicular laminated samples. This difference alone, however, is not a very useful finding: when testing perpendicular laminated samples in shear, the orthotropic nature of wood becomes a large factor. According to Table 5-3b in Chapter 5 of the Wood Handbook, at 12% moisture content, the shear strength of yellow-poplar parallel to the grain is 1,190 psi, while the shear strength is only 540 psi perpendicular to the grain (Kretschmann 2010). ANSI/APA PRG 320-2012 recognizes this difference in shear strengths and its relevance to testing the bond strength of cross-laminated timber samples. Section 6.4.3: Edge and face joints in laminations reads as follows:

*“The wood failure and durability of the face and edge (when required for structural performance) joints shall be qualified in accordance with Sections 4.5.4.1, 4.5.4.3, and 5.5.2 if ANSI/AITC A190.1 and meet all requirements, **except for shear strength**, specified in Sections 4.5.4.1 and 4.5.4.3 of that standard in the U.S., or shall be qualified in accordance with Sections 9.2 and 9.3 of CSA O177 and meet all requirements, **except for shear strength**, specified therein in Canada.”*

Due to the inherently lower shear strength of perpendicular laminated samples, shear strength alone is not valid for evaluation: wood failure must be considered. In doing so, for this research it was found that for yellow-poplar, a decrease in bond strength when samples are perpendicular laminated versus parallel laminated still exists. This could be a potential shortcoming of yellow-poplar CLTs in terms of bond strength. However, simply having a lower bond strength does not disqualify perpendicular laminated yellow-poplar. If samples are still able to meet product standard specifications for wood failure, the difference might not be limiting.

Face joints in laminations for CLTs must meet the requirements of ANSI/AITC A190.1 for wood failure. ANSI/AITC A190.1 requires that, for process qualification and adhesive lot testing, the average wood failure of shear specimens shall equal or exceed 80% for softwoods and “non-dense hardwoods,” which would include yellow-poplar. Of the twelve yellow-poplar treatments tested, all six of the parallel laminated treatment groups had an average wood failure of greater than 80%. However, this result is not as important for CLTs, as any tested face joints in CLTs would typically be perpendicular laminated. Of the six perpendicular laminated treatment groups, three did not meet the 80% minimum average wood failure requirement: Treatments D (1.375 inches, tangential bonding surfaces), F (1.375 inches, combined bonding surfaces), and J (1.000 inch, tangential bonding surfaces). Therefore, in terms of achieving the required bond strength based on wood failure to meet the relevant CLT production standards, perpendicular laminated yellow-poplar with radial bonding surfaces, either 1.000 or 1.375 inches thick have been shown to be most appropriate. If 1.000 inch thick adherends are being used to produce panels, then alternating lamellae with radial and tangential bonding surfaces would also be capable of meeting the required bond strength based on the average wood failure results of this research.

Lamination orientation had a limited effect on bond durability, as evaluated by the cyclic delamination tests. Lamination orientation alone was not found to have a statistically significant effect on delamination, although it did appear to have a significant influence in one particular comparison. For samples that were 1.375 inches thick and had a combination of bonding surfaces, the perpendicular laminated samples had a lower average delamination than did the parallel laminated samples.

Adherend thickness was found to have some influence on bond strength. In evaluating wood failure, the 1.000 inch samples had a significantly greater average wood failure than the 1.375 inch samples (89.4% and 84.8% respectively). This difference, however, was not found in shear strength. Therefore, in terms of bond strength, 1.000 inch yellow-poplar has an advantage over 1.375 inch stock.

Bond durability was not as directly affected by adherend thickness, although some specific comparisons did appear to be affected by thickness. Samples that had 1.000 inch adherends with radial faces that were perpendicular laminated showed a lower average delamination than their 1.375 inch counterparts. Similarly, samples that had 1.000 inch adherends with a combination of bonding surfaces that were parallel laminated also showed a lower average delamination than their 1.375 inch counterparts. Given the findings of this study on the effect of adherend thickness on bond strength and its limited effect on bond durability, the use of 1.000 inch thick yellow-poplar would be preferential over the use of 1.375 inch thick yellow-poplar to achieve a high quality adhesive bond.

Bonding surface plane had no statistically significant effect on bond durability, though it did have a significant impact on wood failure. Samples with radial faces had higher average wood failure than samples with combined surfaces, which had a higher average wood failure

than samples with tangential faces. The interaction between bonding surface plane and lamination orientation also had a significant effect on wood failure, and one specific comparison appeared to be relevant: for perpendicular laminated samples, those with radial faces had higher average delamination than those with tangential faces. This result is consistent with the overall effect of bonding surface plane on wood failure.

ANSI 190.1-2012 requires for bond durability that face joints in laminations in hardwoods yield no more than 8% delamination (5% for softwoods). The standard is ambiguous in describing how exactly delamination is analyzed: whether as an average of all tested specimens, or if all individual test samples within a round of testing must show less than the required level of delamination. Given this lack of detail, both analytical approaches were considered in the discussion of yellow-poplar's ability to meet the product standard requirements based on the results of this project.

Assuming that to pass the requirements of bond durability for ANSI 190.1-2012, the average of all tested samples is the criteria under which durability is evaluated, then all twelve treatments applied to yellow-poplar in the project met the required durability (less than 8% delamination). The greatest average delamination for any single treatment was only 3.7%, which occurred from treatment C. If the standard allows for this type of analysis, then yellow-poplar appears to be perfectly capable of meeting the required bond durability for use in CLTs.

However, if no individual sample can show greater than 8% delamination per round of testing, then several of the treatments tested in this project did not meet the standard requirements. Only treatments F, G, I, K, and L had no samples with more than 8% delamination. Of those five treatments, three of them were perpendicular laminated (F, K, and L). Thus, for this method of analyzing the results of the delamination tests, perpendicular

samples with a combined bonding surfaces, whether 1.000 inch thick or 1.375 inches thick, are capable of meeting the requirements of the standard. Additionally, perpendicular bonded samples with radial bonding surfaces and 1.000 inch thick adherends also met the requirements.

Considering the various findings of this study, certain assertions can be made regarding the use of yellow-poplar in CLTs in terms of adhesion. Bonding yellow-poplar perpendicularly appears to cause a decrease in bond quality based on shear strength and wood failure, but this may not exclude their use in CLTs if samples still meet applicable standard specifications. The use of 1.000 inch thick yellow-poplar results in a higher bond quality than 1.375 inch thick yellow-poplar, and may also have a limited advantage in achieving a more durable adhesive bond. Lastly, assuming the use of 1.000 inch thick yellow-poplar in a perpendicular laminated scenario (which would be certain in CLT manufacture), boards with radial bonding surfaces would result in a higher bond strength. This is not true for a situation in which yellow-poplar is parallel laminated.

4.6 Hypotheses and Results

Three hypotheses were made regarding the expected outcomes of this project. Because of the circumstantial results of the cyclic delamination tests, none of the three can be regarded as being confirmed or denied. However, certain elements of each hypothesis were found to be consistent with the findings of this research on bond strength of adhesively-bonded yellow-poplar.

The first hypothesis stated that tangentially bonded samples would exhibit a greater bond strength and durability than radially bonded samples. In terms of shear strength, this appeared to

be the case in certain instances: when the samples were parallel laminated, tangential adherend surfaces resulted in higher average shear strength values. However, in perpendicular laminated samples, radial adherend surfaces resulted in greater average shear strengths.

As this research aims to supplement knowledge regarding the feasibility of yellow-poplar for use in CLTs, a product in which each lamella is perpendicular laminated to each adjacent lamella, the samples that were perpendicular laminated are perhaps more interesting. Perpendicular laminated samples showed the greatest bond strength when bonded with radial faces. Furthermore, for both lamination orientations, samples with radial bonding surfaces exhibited greater average wood failure.

It may be the case that adhesive penetration greatly affected the shear strength and wood failure of the shear block samples. If this is indeed the case, and the samples with radial bonding surfaces experienced greater adhesive penetration, then this contradicts what past research has found regarding adhesive penetration in hardwoods. Gavrilovic-Grmusa (2012) observed greater adhesive penetration through tangential faces of poplar than through radial faces of poplar using three different adhesives at three different viscosities. Additionally, Sernek (1999) also observed greater adhesive penetration through tangential faces of beech than through radial faces of beech.

Results from the research of Okkonen and River (1988) found that for white oak and maple, shear block samples with tangential bonding faces yielded higher average shear strength than samples with radial bonding faces. However, this was not true for Douglas-fir, in which case samples with radial bonding surfaces most often produced higher shear strengths than samples with tangential bonding faces. These findings by Okkonen and River (1988) are, in some ways, consistent with the results of this research: In parallel laminated samples (similar to

those tested by Okkonen and River), those with tangential bonding surfaces showed a higher average shear strength than those with radial bonding surfaces. However, in perpendicular laminated samples (not tested by Okkonen and River), radial bonding surfaces offered higher average shear strengths than tangential bonding surfaces. It appears that lamination orientation influences adhesive bond strength, and previous assumptions made about the effect of bonding surface plane on parallel laminated samples cannot be applied to wood that is perpendicular laminated.

The second hypothesis was that parallel laminated samples would possess a higher bond strength and durability than perpendicular laminated samples. For shear strength and wood failure, the results of the experiment were as predicted by the second hypothesis. Parallel laminated samples had a significantly higher average shear strength than perpendicular laminated samples, and higher average wood failure was observed on parallel laminated samples than on perpendicular laminated samples.

The third and final hypothesis asserted that the thicker (1.375 inch) samples would result in a lower bond durability than the thinner (1.000 inch) samples. Statistical analysis did not find adherend thickness itself to significantly influence delamination. However, as discussed in section 5.4, adherend thickness did appear to have an effect in two statistically significant comparisons made within the three-way factor interaction: in both comparisons, with two factor levels being the same, samples with 1.000 inch thick adherends showed significantly lower delamination than samples with 1.375 inch thick adherends.

4.7 Reference Comparison: Shear Strength

To make comparisons to the reference samples, only Treatment G (Figure 6) of the yellow-poplar samples was considered, as Treatment G and the reference samples were subject to the same effect parameters: 1.000 inch thick adherends, tangential bonding surfaces, and parallel laminated. Treatment G was chosen to make the references comparisons based on it possessing the highest mean shear strength and lowest mean delamination of all the yellow-poplar treatments. Treatment G also performed well in terms of mean wood failure.

Figure 20 is a box and whisker plot of the two sample groups for the reference comparison for mean shear strength, and Table 16 shows summary statistics for the comparison. A t-test (Appendix C) detected a significant difference in the mean shear strength of the yellow-poplar samples compared to the hard pine samples ($p=0.0002$). The yellow-poplar group had an

average shear strength of 1,776 psi, and the hard pine group had an average shear strength of 1,433 psi.

Figure 0-8. Box and whisker plot of mean shear strength of reference comparison samples.

Table 16. Summary statistics of mean shear strength of reference comparison samples.

Treatment	Shear Strength (psi)	Standard Deviation (psi)	Coefficient of Variation (%)	Minimum Strength (psi)	Maximum Strength (psi)
G	1,776	183	10	1537	2137
Z (reference)	1,433	133	9	1254	1713

4.8 Reference Comparison: Wood Failure

Figure 21 shows a box and whisker plot of the mean wood failure data for the reference comparison. A t-test (Appendix C) determined that there was no statistically significant difference in the average wood failure between the yellow-poplar group and the hard pine group ($p=0.2367$). Table 17 provides summary statistics for the mean wood failure results of the reference comparison.

Figure 0-9. Box and whisker plot of mean wood failure results for reference comparison.

Table 17. Summary statistics of mean wood failure for yellow-poplar and hard pine groups for reference comparison.

Treatment	Wood Failure (%)	Standard Deviation (%)	Coefficient of Variation (%)	Minimum Wood Failure (%)	Maximum Wood Failure (%)
G	95	3	3	90	98
Z (reference)	94	2	3	88	97

4.9 Reference Comparison: Cyclic Delamination

The results for the cyclic delamination tests on the reference hard pine samples resulted in no measureable delamination in any of the samples (i.e., 0% delamination). Given these results and similar results of the yellow-poplar samples in Treatment G, the comparison of the cyclic delamination results is straightforward, as neither group included any single specimen that displayed any measureable delamination. Since the average delamination for both groups was 0%, no t-test was performed and both groups were considered to perform equally under cyclic delamination conditions.

4.10 Reference Comparison: Summary

Two sample groups were compared as a controlled trial: one yellow-poplar group, and one hard pine group. The effect parameters of both groups were identical. T-tests were used to determine if significant differences existed between the groups in terms of shear strength and wood failure.

A statistically significant difference was found to exist between the shear strength of the yellow-poplar group and the hard pine group ($p=0.0002$), which could possibly indicate a higher bond quality in yellow-poplar. However, this could also be due the inherent shear strength of the wood itself, rather than a difference in bond strength. Furthermore, the lower shear strength of the hard pine samples might have been affected by the disparity in latewood and earlywood zones intrinsic in hard pine species: if a large proportion of earlywood was present at the bond interface, the joint failure would likely be somewhat weaker and with a high percentage of wood failure. If the samples were assembled in such a way that a greater proportion of latewood was present at the bond interface, the results for shear strength could have been different (Okkonen and River, 1988).

Because there was no significant difference in wood failure between the yellow-poplar and hard pine groups ($p=0.2367$), it cannot be said with certainty that yellow-poplar has a higher bond strength. However, it appears that it has at least an equivalent (if not greater) shear strength than hard pine. These results support the case that yellow-poplar could be used to produce cross-laminated timber panels from an adhesion standpoint, as hard pine is an accepted species for CLT manufacture under ANSI/APA PRG 320-2012. Further supporting this notion is the lack of a difference in the cyclic delamination tests.

Based on the results of this research, there is no difference between the achievable bond qualities between yellow-poplar and hard pine under the treatment parameters of the reference comparison. There appears to be nothing limiting the bond strength and durability of yellow-poplar as compared to hard pine in this scenario.

Chapter 5: Conclusions

5.1 Main Findings

Through this research, several conclusions can be drawn regarding how certain characteristics of yellow-poplar lumber affect adhesive bond quality. This information can be used in future research and in any additional efforts to prove yellow-poplar to be a feasible species for the manufacture of CLTs.

Testing has shown that adherend thickness significantly influences wood failure percentage of yellow-poplar shear block samples. 1.000 inch thick adherends produced bond line samples that had higher average wood failure than samples with 1.375 inch thick adherends. Adherend thickness also had a limited impact on bond durability as tested by a cyclic delamination test. In certain bonding situations, such as bonding perpendicular laminated yellow-poplar with radial or combined (one tangential and one radial) bonding surfaces, samples with 1.000 inch thick adherends yielded significantly lower average delamination than samples with 1.375 inch thick adherends.

Bonding surface plane was also shown to influence bond strength. Wood failure was shown to be greatest on samples with radial bonding surfaces, followed by samples with combined and tangential bonding surfaces, respectively. For shear strength, the effect of bonding surface plane was only observed through its interaction with lamination orientation: for perpendicular laminated samples, samples with radial bond surfaces had the highest average shear strength. For parallel laminated samples, tangential bonding surfaces resulted in the highest shear strength.

Lamination orientation had the most drastic effect on adhesive bond strength. Perpendicular laminated samples showed significantly lower average shear strength and average wood failure than parallel laminated samples. This warrants concern, as perpendicular bonding scenarios are characteristic of CLTs. However, as discussed in section 5.5, certain bonding situations using yellow-poplar can still meet the requirements of applicable standards regarding CLT production specifications.

Based on the results of testing yellow-poplar, it appears that if the goal is to produce CLT panels, then the ideal yellow-poplar adherends would be 1.000 inch thick with radial bonding surfaces. However, bond line samples with combined bonding surfaces were also shown to produce adequately strong and durable adhesive bonds as needed for use in CLTs.

Lastly, a reference species (hard pine) was tested to make comparisons to yellow-poplar. This research showed that for samples with 1.000 inch thick adherends that were parallel laminated with tangential bonding surfaces, no statistically significant difference was found between yellow-poplar and hard pine for shear strength, wood failure, or delamination.

5.2 Implications

Under ANSI/APA PRG 320-2012, CLTs are only approved for manufacture using certain softwood species (and potentially engineered wood products). Yellow-poplar is a non-dense hardwood that is successfully used in structural wood composite products such as plywood, oriented strandboard, parallel strand lumber, and laminated veneer lumber. The results of this research imply that if certain wood characteristics are controlled throughout manufacturing, from an adhesion standpoint, yellow-poplar could be used to produce CLTs panels with the required

bond quality. However, to be fully considered for use in CLTs, yellow-poplar would require testing of full CLT panels for a variety of mechanical and physical properties. Strictly from an adhesive bond quality standpoint, however, yellow-poplar was found to form adequately strong and durable adhesive bonds needed for use in CLTs.

Another potential use for yellow-poplar in CLTs would be as a solid wood facing material. Similar to plywood made of veneers of various species and faced with a more desirable species, CLTs could be manufactured from approved species and have yellow-poplar applied to outside layers in a parallel laminated scenario. This study showed the parallel laminated yellow-poplar produces adequately strong adhesive bonds; however, it was only shown to do so when bonded to yellow-poplar. Bonding dissimilar species would require additional research.

5.3 Recommendations for Future Research

There are ample opportunities for further research to demonstrate the feasibility of hardwood CLTs. Specifically, more research is needed regarding adhesive bond quality of hardwoods for use in CLTs.

While this research demonstrated which adherend characteristics affect bond quality in yellow-poplar and showed that yellow-poplar can produce adequately strong adhesive bonds, all testing was done using samples with only one bond line. Full size yellow-poplar CLT panels could be produced and tested for adhesive bond quality, bearing in mind the various findings of this research. By testing full depth multilayer specimens, any concerns regarding the presence of additional layers could be addressed. For example, while it was shown that yellow-poplar

samples with a single bond line (two adherends) can produce durable bonds, would the additional stresses caused by the greater number of adherends affect bond durability?

The results of this research showed that for yellow-poplar, adherends with radial bonding surfaces produced the strongest, most durable adhesive bonds when perpendicular laminated. The employment of microscopy techniques to investigate adhesive penetration into perpendicular laminated adherends may provide useful insight.

Lastly, this project focused on the use of yellow-poplar for use in CLTs. However, there are many other low-value Appalachian hardwood species that could possibly be used to produce CLTs. American beech and sycamore are two examples of species that are commonly undervalued. If these species are able to produce the necessary adhesive bond quality for CLTs, they could also help provide market opportunities for CLTs in Appalachia.

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Appendix A: Adherend Information

Figure A- 1. Density distribution of 1.375" Yellow-poplar adherends.

Figure A- 2. Density distribution of 1.000" Yellow-poplar adherends.

Figure A- 3. Density Distribution of adherends that formed hard-pine reference samples.

Figure A- 4. Temperature and relative humidity data throughout 14 weeks of yellow-poplar adherend conditioning.

Appendix B: Test Results

Table B- 1. Sample averages of test results. Data formatted for use in JMP.

Species	Sample	Lamination Orientation	Bonding Planes	Adherend Thickness	Shear Strength Mean (psi)	Wood Failure Mean (%)	Delamination Mean (%)
Yellow-poplar	A1	Parallel	Tangential	1.375	1356.7	93.3	0.0
Yellow-poplar	A2	Parallel	Tangential	1.375	1697.4	96.7	0.0
Yellow-poplar	A3	Parallel	Tangential	1.375	1768.3	43.3	11.7
Yellow-poplar	A4	Parallel	Tangential	1.375	1457.3	95.0	0.0
Yellow-poplar	A5	Parallel	Tangential	1.375	1730.9	98.3	13.1
Yellow-poplar	A6	Parallel	Tangential	1.375	1622.0	88.3	0.0
Yellow-poplar	A7	Parallel	Tangential	1.375	1590.5	98.3	0.0
Yellow-poplar	A8	Parallel	Tangential	1.375	1619.2	98.3	4.4
Yellow-poplar	A9	Parallel	Tangential	1.375	1528.5	86.7	0.0
Yellow-poplar	A10	Parallel	Tangential	1.375	1583.2	95.0	0.0
Yellow-poplar	B1	Parallel	Radial	1.375	1300.0	95.0	4.8
Yellow-poplar	B2	Parallel	Radial	1.375	1771.3	85.0	1.7
Yellow-poplar	B3	Parallel	Radial	1.375	1560.3	96.7	9.1
Yellow-poplar	B4	Parallel	Radial	1.375	1674.5	95.0	0.0
Yellow-poplar	B5	Parallel	Radial	1.375	1267.0	98.3	1.4
Yellow-poplar	B6	Parallel	Radial	1.375	1660.8	96.7	0.0
Yellow-poplar	B7	Parallel	Radial	1.375	1502.2	96.7	0.0
Yellow-poplar	B8	Parallel	Radial	1.375	1647.1	96.7	0.0
Yellow-poplar	B9	Parallel	Radial	1.375	1502.5	93.3	4.3

Table B- 2. Sample averages of test results continued. Data formatted for use in JMP.

Species	Sample	Lamination Orientation	Bonding Planes	Adherend Thickness	Shear Strength Mean (psi)	Wood Failure Mean (%)	Delamination Mean (%)
Yellow-poplar	B10	Parallel	Radial	1.375	1572.7	95.0	0.0
Yellow-poplar	C1	Parallel	Combination	1.375	1913.4	76.7	16.6
Yellow-poplar	C2	Parallel	Combination	1.375	1657.0	98.3	0.0
Yellow-poplar	C3	Parallel	Combination	1.375	1399.5	93.3	1.4
Yellow-poplar	C4	Parallel	Combination	1.375	1865.3	80.0	0.0
Yellow-poplar	C5	Parallel	Combination	1.375	1403.3	96.7	0.0
Yellow-poplar	C6	Parallel	Combination	1.375	1676.9	75.0	0.0
Yellow-poplar	C7	Parallel	Combination	1.375	1618.2	96.7	0.0
Yellow-poplar	C8	Parallel	Combination	1.375	1447.3	96.7	0.0
Yellow-poplar	C9	Parallel	Combination	1.375	1818.0	90.0	16.9
Yellow-poplar	C10	Parallel	Combination	1.375	1780.1	95.0	1.9
Yellow-poplar	D1	Perpendicular	Tangential	1.375	772.6	90.0	9.1
Yellow-poplar	D2	Perpendicular	Tangential	1.375	761.6	83.3	2.3
Yellow-poplar	D3	Perpendicular	Tangential	1.375	636.2	95.0	0.0
Yellow-poplar	D4	Perpendicular	Tangential	1.375	718.3	88.3	0.0
Yellow-poplar	D5	Perpendicular	Tangential	1.375	717.6	48.3	0.0
Yellow-poplar	D6	Perpendicular	Tangential	1.375	868.0	68.3	0.0
Yellow-poplar	D7	Perpendicular	Tangential	1.375	645.0	8.3	1.5
Yellow-poplar	D8	Perpendicular	Tangential	1.375	704.6	91.7	1.0

Table B- 3. Sample averages of test results continued. Data formatted for use in JMP.

Species	Sample	Lamination Orientation	Bonding Planes	Adherend Thickness	Shear Strength Mean (psi)	Wood Failure Mean (%)	Delamination Mean (%)
Yellow-poplar	D9	Perpendicular	Tangential	1.375	666.0	88.3	0.0
Yellow-poplar	D10	Perpendicular	Tangential	1.375	719.9	68.3	0.0
Yellow-poplar	E1	Perpendicular	Radial	1.375	793.0	90.0	8.7
Yellow-poplar	E2	Perpendicular	Radial	1.375	668.1	95.0	0.0
Yellow-poplar	E3	Perpendicular	Radial	1.375	765.5	90.0	0.0
Yellow-poplar	E4	Perpendicular	Radial	1.375	635.9	96.7	0.0
Yellow-poplar	E5	Perpendicular	Radial	1.375	992.4	86.7	8.3
Yellow-poplar	E6	Perpendicular	Radial	1.375	1039.1	51.7	0.0
Yellow-poplar	E7	Perpendicular	Radial	1.375	850.8	96.7	0.2
Yellow-poplar	E8	Perpendicular	Radial	1.375	693.8	95.0	1.8
Yellow-poplar	E9	Perpendicular	Radial	1.375	947.4	95.0	0.0
Yellow-poplar	E10	Perpendicular	Radial	1.375	748.9	78.3	6.6
Yellow-poplar	F1	Perpendicular	Combination	1.375	782.3	30.0	3.2
Yellow-poplar	F2	Perpendicular	Combination	1.375	539.8	86.7	0.0
Yellow-poplar	F3	Perpendicular	Combination	1.375	860.5	43.3	0.9
Yellow-poplar	F4	Perpendicular	Combination	1.375	1039.3	83.3	0.0
Yellow-poplar	F5	Perpendicular	Combination	1.375	885.6	85.0	1.7
Yellow-poplar	F6	Perpendicular	Combination	1.375	853.8	93.3	0.3
Yellow-poplar	F7	Perpendicular	Combination	1.375	695.7	66.7	0.0

Table B- 4. Sample averages of test results continued. Data formatted for use in JMP.

Species	Sample	Lamination Orientation	Bonding Planes	Adherend Thickness	Shear Strength Mean (psi)	Wood Failure Mean (%)	Delamination Mean (%)
Yellow-poplar	F8	Perpendicular	Combination	1.375	828.0	90.0	0.0
Yellow-poplar	F9	Perpendicular	Combination	1.375	851.9	73.3	0.8
Yellow-poplar	F10	Perpendicular	Combination	1.375	678.1	90.0	2.9
Yellow-poplar	G1	Parallel	Tangential	1.000	1536.6	98.3	0.0
Yellow-poplar	G2	Parallel	Tangential	1.000	1829.2	90.0	0.0
Yellow-poplar	G3	Parallel	Tangential	1.000	1537.2	96.7	0.0
Yellow-poplar	G4	Parallel	Tangential	1.000	1777.6	95.0	0.0
Yellow-poplar	G5	Parallel	Tangential	1.000	1609.8	96.7	0.0
Yellow-poplar	G6	Parallel	Tangential	1.000	1846.0	96.7	0.0
Yellow-poplar	G7	Parallel	Tangential	1.000	1861.3	95.0	0.0
Yellow-poplar	G8	Parallel	Tangential	1.000	2136.7	96.7	0.0
Yellow-poplar	G9	Parallel	Tangential	1.000	1892.5	91.7	0.0
Yellow-poplar	G10	Parallel	Tangential	1.000	1733.8	93.3	0.0
Yellow-poplar	H1	Parallel	Radial	1.000	1935.1	95.0	8.4
Yellow-poplar	H2	Parallel	Radial	1.000	1657.5	95.0	0.0
Yellow-poplar	H3	Parallel	Radial	1.000	1553.6	96.7	0.0
Yellow-poplar	H4	Parallel	Radial	1.000	1311.5	98.3	0.0
Yellow-poplar	H5	Parallel	Radial	1.000	1408.0	100.0	0.0
Yellow-poplar	H6	Parallel	Radial	1.000	1597.8	95.0	0.0

Table B- 5. Sample averages of test results continued. Data formatted for use in JMP.

Species	Sample	Lamination Orientation	Bonding Planes	Adherend Thickness	Shear Strength Mean (psi)	Wood Failure Mean (%)	Delamination Mean (%)
Yellow-poplar	H7	Parallel	Radial	1.000	1714.5	96.7	0.0
Yellow-poplar	H8	Parallel	Radial	1.000	1373.4	98.3	0.0
Yellow-poplar	H9	Parallel	Radial	1.000	1624.9	96.7	0.0
Yellow-poplar	H10	Parallel	Radial	1.000	1482.0	98.3	8.6
Yellow-poplar	I1	Parallel	Combination	1.000	1415.5	100.0	0.0
Yellow-poplar	I2	Parallel	Combination	1.000	1781.1	96.7	0.0
Yellow-poplar	I3	Parallel	Combination	1.000	1511.6	95.0	0.0
Yellow-poplar	I4	Parallel	Combination	1.000	1402.4	93.3	0.0
Yellow-poplar	I5	Parallel	Combination	1.000	1684.3	93.3	8.0
Yellow-poplar	I6	Parallel	Combination	1.000	1426.4	100.0	0.0
Yellow-poplar	I7	Parallel	Combination	1.000	1649.6	100.0	0.0
Yellow-poplar	I8	Parallel	Combination	1.000	1427.0	93.3	0.0
Yellow-poplar	I9	Parallel	Combination	1.000	1495.9	95.0	0.0
Yellow-poplar	I10	Parallel	Combination	1.000	1786.1	96.7	0.0
Yellow-poplar	J1	Perpendicular	Tangential	1.000	1326.4	76.7	4.9
Yellow-poplar	J2	Perpendicular	Tangential	1.000	727.9	93.3	0.0
Yellow-poplar	J3	Perpendicular	Tangential	1.000	630.0	20.0	0.0
Yellow-poplar	J4	Perpendicular	Tangential	1.000	729.4	88.3	3.0
Yellow-poplar	J5	Perpendicular	Tangential	1.000	517.7	90.0	0.0

Table B- 6. Sample averages of test results continued. Data formatted for use in JMP.

Species	Sample	Lamination Orientation	Bonding Planes	Adherend Thickness	Shear Strength Mean (psi)	Wood Failure Mean (%)	Delamination Mean (%)
Yellow-poplar	J6	Perpendicular	Tangential	1.000	857.0	75.0	8.1
Yellow-poplar	J7	Perpendicular	Tangential	1.000	647.4	80.0	0.0
Yellow-poplar	J8	Perpendicular	Tangential	1.000	673.6	95.0	0.0
Yellow-poplar	J9	Perpendicular	Tangential	1.000	673.0	45.0	0.0
Yellow-poplar	J10	Perpendicular	Tangential	1.000	793.0	60.0	0.2
Yellow-poplar	K1	Perpendicular	Radial	1.000	893.4	95.0	4.0
Yellow-poplar	K2	Perpendicular	Radial	1.000	1153.5	85.0	0.0
Yellow-poplar	K3	Perpendicular	Radial	1.000	662.9	93.3	0.0
Yellow-poplar	K4	Perpendicular	Radial	1.000	783.5	96.7	0.0
Yellow-poplar	K5	Perpendicular	Radial	1.000	1231.5	81.7	0.0
Yellow-poplar	K6	Perpendicular	Radial	1.000	1080.8	88.3	0.9
Yellow-poplar	K7	Perpendicular	Radial	1.000	544.3	100.0	0.0
Yellow-poplar	K8	Perpendicular	Radial	1.000	541.0	100.0	0.0
Yellow-poplar	K9	Perpendicular	Radial	1.000	591.2	95.0	0.0
Yellow-poplar	K10	Perpendicular	Radial	1.000	729.5	60.0	0.0
Yellow-poplar	L1	Perpendicular	Combination	1.000	705.0	96.7	0.0
Yellow-poplar	L2	Perpendicular	Combination	1.000	567.8	96.7	0.0
Yellow-poplar	L3	Perpendicular	Combination	1.000	1040.1	86.7	7.3
Yellow-poplar	L4	Perpendicular	Combination	1.000	624.6	95.0	0.0

Table B- 7. Sample averages of test results continued. Data formatted for use in JMP.

Species	Sample	Lamination Orientation	Bonding Planes	Adherend Thickness	Shear Strength Mean (psi)	Wood Failure Mean (%)	Delamination Mean (%)
Yellow-poplar	L5	Perpendicular	Combination	1.000	817.5	95.0	0.0
Yellow-poplar	L6	Perpendicular	Combination	1.000	713.7	86.7	0.0
Yellow-poplar	L7	Perpendicular	Combination	1.000	819.8	76.7	0.0
Yellow-poplar	L8	Perpendicular	Combination	1.000	991.3	88.3	3.9
Yellow-poplar	L9	Perpendicular	Combination	1.000	792.9	68.3	0.0
Yellow-poplar	L10	Perpendicular	Combination	1.000	1112.4	75.0	0.0
Hard Pine	Z1	Parallel	Tangential	1.000	1492.8	93.3	0.0
Hard Pine	Z2	Parallel	Tangential	1.000	1254.1	93.3	0.0
Hard Pine	Z3	Parallel	Tangential	1.000	1492.7	93.3	0.0
Hard Pine	Z4	Parallel	Tangential	1.000	1295.6	96.7	0.0
Hard Pine	Z5	Parallel	Tangential	1.000	1713.4	93.3	0.0
Hard Pine	Z6	Parallel	Tangential	1.000	1331.1	88.3	0.0
Hard Pine	Z7	Parallel	Tangential	1.000	1514.3	95.0	0.0
Hard Pine	Z8	Parallel	Tangential	1.000	1392.4	96.7	0.0
Hard Pine	Z9	Parallel	Tangential	1.000	1384.7	93.3	0.0
Hard Pine	Z10	Parallel	Tangential	1.000	1459.8	93.3	0.0

Figure B- 1. Percentage of delamination of all bond line samples.

Figure B- 2. Occurrences of delamination of all bond line samples.

Appendix C: Statistical Analysis

Table C- 1. Check for normality of means of test results on yellow-poplar samples. A p-value less than 0.05 indicates that the distribution of means for that treatment/test does not follow a normal distribution.

Treatment	Shear Strength p-value	Wood Failure p- value	Delamination p-value
A	0.8342	<.0001	0.0001
B	0.5072	0.0007	0.0008
C	0.3216	0.0165	<.0001
D	0.3835	0.0078	<.0001
E	0.5072	0.0007	0.0008
F	0.6664	0.0219	0.0137
G	0.4685	0.2132	---
H	0.8451	0.191	<.0001
I	0.0581	0.0415	<.0001
J	0.0059	0.0745	0.0003
K	0.2273	0.017	<.0001
L	0.6403	0.1412	<.0001

*Table C- 2. Comparison matrix for wood failure interaction of lamination orientation * bonding surface plane.*

Differences of Layup_Ang*Saw_Patter Least Squares Means Adjustment for Multiple Comparisons: Tukey-Kramer									
Saw_Pattern	Layup_Angle	_Saw_Pattern	_Layup_Angle	Estimate	Standard Error	DF	t Value	Pr > t	Adj P
RadRad	0	TanRad	0	0.03053	0.03254	108	0.94	0.3503	0.9357
RadRad	0	TanTan	0	0.04029	0.03262	108	1.23	0.2195	0.8187
RadRad	0	RadRad	90	0.08048	0.03296	108	2.44	0.0162	0.1514
RadRad	0	TanRad	90	0.1802	0.03387	108	5.32	<.0001	<.0001
RadRad	0	TanTan	90	0.2775	0.03478	108	7.98	<.0001	<.0001
TanRad	0	TanTan	0	0.009760	0.03288	108	0.30	0.7671	0.9997
TanRad	0	RadRad	90	0.04995	0.03321	108	1.50	0.1355	0.6625
TanRad	0	TanRad	90	0.1497	0.03412	108	4.39	<.0001	0.0004
TanRad	0	TanTan	90	0.2470	0.03501	108	7.05	<.0001	<.0001
TanTan	0	RadRad	90	0.04019	0.03329	108	1.21	0.2300	0.8325
TanTan	0	TanRad	90	0.1399	0.03419	108	4.09	<.0001	0.0011
TanTan	0	TanTan	90	0.2373	0.03509	108	6.76	<.0001	<.0001
RadRad	90	TanRad	90	0.09971	0.03451	108	2.89	0.0047	0.0517
RadRad	90	TanTan	90	0.1971	0.03540	108	5.57	<.0001	<.0001
TanRad	90	TanTan	90	0.09736	0.03625	108	2.69	0.0084	0.0865

Table C- 3. Comparison matrix for three-way effect interaction on delamination.

Differences of Layup_*Saw_Pa*Thickn Least Squares Means Adjustment for Multiple Comparisons: Tukey-Kramer											
Saw_Pattern	Thickness	Layup_Angle	_Saw_Pattern	_Thickness	_Layup_Angle	Estimate	Standard Error	DF	t Value	Pr > t	Adj P
RadRad	Thick	0	RadRad	Thin	0	0.2342	0.3254	108	0.72	0.4733	0.9999
RadRad	Thick	0	TanRad	Thick	0	-0.5439	0.2719	108	-2.00	0.0480	0.6922
RadRad	Thick	0	TanRad	Thin	0	0.9883	0.4153	108	2.38	0.0191	0.4286
RadRad	Thick	0	TanTan	Thick	0	-0.3129	0.2846	108	-1.10	0.2740	0.9941
RadRad	Thick	0	TanTan	Thin	0	15.4529	490.43	108	0.03	0.9749	1.0000
RadRad	Thick	0	RadRad	Thick	90	-0.1832	0.2928	108	-0.63	0.5329	1.0000
RadRad	Thick	0	RadRad	Thin	90	1.4676	0.4998	108	2.94	0.0041	0.1431
RadRad	Thick	0	TanRad	Thick	90	0.7799	0.3858	108	2.02	0.0457	0.6778
RadRad	Thick	0	TanRad	Thin	90	0.6458	0.3688	108	1.75	0.0828	0.8399
RadRad	Thick	0	TanTan	Thick	90	0.4369	0.3452	108	1.27	0.2084	0.9817
RadRad	Thick	0	TanTan	Thin	90	0.2769	0.3294	108	0.84	0.4024	0.9995
RadRad	Thin	0	TanRad	Thick	0	-0.7781	0.2937	108	-2.65	0.0093	0.2665
RadRad	Thin	0	TanRad	Thin	0	0.7541	0.4299	108	1.75	0.0822	0.8384
RadRad	Thin	0	TanTan	Thick	0	-0.5471	0.3055	108	-1.79	0.0761	0.8194
RadRad	Thin	0	TanTan	Thin	0	15.2187	490.43	108	0.03	0.9753	1.0000
RadRad	Thin	0	RadRad	Thick	90	-0.4174	0.3132	108	-1.33	0.1854	0.9729
RadRad	Thin	0	RadRad	Thin	90	1.2334	0.5120	108	2.41	0.0177	0.4091
RadRad	Thin	0	TanRad	Thick	90	0.5457	0.4015	108	1.36	0.1769	0.9686
RadRad	Thin	0	TanRad	Thin	90	0.4116	0.3852	108	1.07	0.2876	0.9954
RadRad	Thin	0	TanTan	Thick	90	0.2027	0.3627	108	0.56	0.5774	1.0000
RadRad	Thin	0	TanTan	Thin	90	0.04268	0.3476	108	0.12	0.9025	1.0000
TanRad	Thick	0	TanRad	Thin	0	1.5322	0.3909	108	3.92	0.0002	0.0082
TanRad	Thick	0	TanTan	Thick	0	0.2310	0.2477	108	0.93	0.3531	0.9986
TanRad	Thick	0	TanTan	Thin	0	15.9968	490.43	108	0.03	0.9740	1.0000
TanRad	Thick	0	RadRad	Thick	90	0.3607	0.2571	108	1.40	0.1635	0.9605
TanRad	Thick	0	RadRad	Thin	90	2.0115	0.4797	108	4.19	<.0001	0.0032
TanRad	Thick	0	TanRad	Thick	90	1.3238	0.3594	108	3.68	0.0004	0.0179
TanRad	Thick	0	TanRad	Thin	90	1.1897	0.3412	108	3.49	0.0007	0.0327
TanRad	Thick	0	TanTan	Thick	90	0.9808	0.3155	108	3.11	0.0024	0.0937
TanRad	Thick	0	TanTan	Thin	90	0.8208	0.2981	108	2.75	0.0069	0.2154
TanRad	Thin	0	TanTan	Thick	0	-1.3012	0.3999	108	-3.25	0.0015	0.0637
TanRad	Thin	0	TanTan	Thin	0	14.4646	490.43	108	0.03	0.9765	1.0000
TanRad	Thin	0	RadRad	Thick	90	-1.1714	0.4057	108	-2.89	0.0047	0.1605
TanRad	Thin	0	RadRad	Thin	90	0.4793	0.5733	108	0.84	0.4049	0.9995
TanRad	Thin	0	TanRad	Thick	90	-0.2084	0.4772	108	-0.44	0.6632	1.0000
TanRad	Thin	0	TanRad	Thin	90	-0.3425	0.4636	108	-0.74	0.4616	0.9998

Differences of Layup_*Saw_Pa*Thickn Least Squares Means Adjustment for Multiple Comparisons: Tukey-Kramer											
Saw_Pattern	Thickness	Layup_Angle	_Saw_Pattern	_Thickness	_Layup_Angle	Estimate	Standard Error	DF	t Value	Pr > t	Adj P
TanRad	Thin	0	TanTan	Thick	90	-0.5514	0.4451	108	-1.24	0.2181	0.9845
TanRad	Thin	0	TanTan	Thin	90	-0.7114	0.4329	108	-1.64	0.1032	0.8887
TanTan	Thick	0	TanTan	Thin	0	15.7658	490.43	108	0.03	0.9744	1.0000
TanTan	Thick	0	RadRad	Thick	90	0.1297	0.2705	108	0.48	0.6324	1.0000
TanTan	Thick	0	RadRad	Thin	90	1.7805	0.4870	108	3.66	0.0004	0.0195
TanTan	Thick	0	TanRad	Thick	90	1.0928	0.3691	108	2.96	0.0038	0.1352
TanTan	Thick	0	TanRad	Thin	90	0.9587	0.3513	108	2.73	0.0074	0.2269
TanTan	Thick	0	TanTan	Thick	90	0.7498	0.3265	108	2.30	0.0236	0.4857
TanTan	Thick	0	TanTan	Thin	90	0.5898	0.3097	108	1.90	0.0595	0.7539
TanTan	Thin	0	RadRad	Thick	90	-15.6360	490.43	108	-0.03	0.9746	1.0000
TanTan	Thin	0	RadRad	Thin	90	-13.9852	490.43	108	-0.03	0.9773	1.0000
TanTan	Thin	0	TanRad	Thick	90	-14.6729	490.43	108	-0.03	0.9762	1.0000
TanTan	Thin	0	TanRad	Thin	90	-14.8071	490.43	108	-0.03	0.9760	1.0000
TanTan	Thin	0	TanTan	Thick	90	-15.0160	490.43	108	-0.03	0.9756	1.0000
TanTan	Thin	0	TanTan	Thin	90	-15.1760	490.43	108	-0.03	0.9754	1.0000
RadRad	Thick	90	RadRad	Thin	90	1.6508	0.4919	108	3.36	0.0011	0.0479
RadRad	Thick	90	TanRad	Thick	90	0.9631	0.3755	108	2.56	0.0117	0.3128
RadRad	Thick	90	TanRad	Thin	90	0.8289	0.3580	108	2.32	0.0225	0.4725
RadRad	Thick	90	TanTan	Thick	90	0.6201	0.3337	108	1.86	0.0659	0.7817
RadRad	Thick	90	TanTan	Thin	90	0.4600	0.3173	108	1.45	0.1500	0.9503
RadRad	Thin	90	TanRad	Thick	90	-0.6877	0.5523	108	-1.25	0.2157	0.9838
RadRad	Thin	90	TanRad	Thin	90	-0.8218	0.5406	108	-1.52	0.1313	0.9317
RadRad	Thin	90	TanTan	Thick	90	-1.0307	0.5248	108	-1.96	0.0521	0.7160
RadRad	Thin	90	TanTan	Thin	90	-1.1908	0.5145	108	-2.31	0.0225	0.4730
TanRad	Thick	90	TanRad	Thin	90	-0.1341	0.4373	108	-0.31	0.7597	1.0000
TanRad	Thick	90	TanTan	Thick	90	-0.3430	0.4177	108	-0.82	0.4133	0.9996
TanRad	Thick	90	TanTan	Thin	90	-0.5030	0.4047	108	-1.24	0.2165	0.9840
TanRad	Thin	90	TanTan	Thick	90	-0.2089	0.4020	108	-0.52	0.6044	1.0000
TanRad	Thin	90	TanTan	Thin	90	-0.3689	0.3885	108	-0.95	0.3444	0.9984
TanTan	Thick	90	TanTan	Thin	90	-0.1600	0.3662	108	-0.44	0.6630	1.0000

Figure C- 1. T-test on mean shear strength of reference comparison samples.

Figure C- 2. T-test on mean wood failure results for reference comparison.