Rolling Shear Strength and Modulus for Various Southeastern US Wood Species Using the Two-Plate Shear Test

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Abstract

Cross-Laminated Timber (CLT) is an engineered wood product made by laminating dimensional or structural composite lumber in alternating orthogonal layers. Compared to Canada and Europe, CLT is a novel product to the US. With the additions included in the 2021 International Building Code (IBC), CLT material properties, especially rolling shear, would need to be explored. The increasing demand for softwood lumber, along with the increase of demand of CLT panel production, could place a burden and surpass the domestic softwood supply. Rolling shear is a phenomenon that occurs when the wood fibers in the cross-layers roll over each other because of the shearing forces acting upon a CLT panel when it is loaded out-of-plane. This study used the two-plate shear test from ASTM D2718 to measure the rolling shear properties of various southeastern US wood species: southern pine, yellow-poplar, and soft maple. A secondary study was conducted, using the same two-plate shear test, to measure the rolling shear properties of re-manufactured southern pine for CLT cross-layer application. The soft maple had the greatest average rolling shear strength at 5.93 N/mm^2 and southern pine had the lowest average rolling shear strength at 2.51 N/mm^2. Using a single factor analysis of variance (ANOVA), the rolling shear strength values from soft maple were significantly greater than yellow-poplar, which was significantly greater than the southern pine. For the rolling shear modulus, the southern pine and soft maple were of equal statistically significant difference, and both were greater statistically significant different compared to the yellow-poplar. The most common failure found from testing was rolling shear.

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General Audience Abstract

Cross-Laminated Timber (CLT) is an engineered wood panel product, similar to plywood, constructed with solid-sawn or structural composite lumber in alternating perpendicular layers. The additions included in the incoming 2021 International Building Code (IBC) has placed an importance in expanding the research related to the mechanical and material properties of CLT. Also, with the increasing demand for softwood lumber and CLT panel production, the demand for the domestic softwood lumber could place a burden and surpass the domestic softwood supply. Rolling shear is a failure type that occurs when the wood fibers in the cross-layers roll over each other because of the shearing forces acting upon a CLT panel. This study used the two-plate shear test to measure the rolling shear properties of various southeastern US wood species: southern pine, yellow-poplar, and soft maple. A secondary study was conducted, using the same two-plate shear test, to measure the rolling shear properties of re-manufactured southern pine for CLT cross-layer application. The soft maple had the greatest average rolling shear strength at 5.93 N/mm^2 and southern pine had the lowest average rolling shear strength at 2.51 N/mm^2. Using a single factor analysis of variance (ANOVA), the rolling shear strength values from soft maple were significantly greater than yellow-poplar, which was significantly greater than the southern pine. For the rolling shear modulus, the southern pine and soft maple were of equal statistically significant difference, and both were greater statistically significant different compared to the yellow-poplar. The most common failure found from testing was rolling shear.

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Background and Literature Review

A. Background

1. Cross-Laminated Timber

Cross-laminated timber (CLT) is an engineered wood product constructed by laminating dimensional or structural composite lumber in alternating perpendicular layers with a minimum of three laminae (ANSI/APA 2020). The alternating layer in each panel allows for two-way strength and stiffness. Originating from Austria and widely popularized in Europe, CLT has been fabricated to be used for wall, floor, and roof panel assemblies (Crespell and Gagnon 2010). CLT has found success in Europe due to its advantages in manufacturing, installation, mechanical performance, and environmental impact (Crespell and Gaston 2011). In addition, CLT is cost competitive in comparison to standard building systems averaging 10%-50% shell cost savings, depending on building type and floor area (Crespell and Gaston 2011). According to FPInnovation's *Cross Laminated Timber: a Primer*, "CLT is cost competitive in 66% of the non-residential market, the most competitive being the mid-rise segment at nearly 75%;" (p. 20) this market analysis shows the viability of CLT in the construction industry (Crespell and Gagnon 2010). Furthermore, projects constructed with CLT accrue construction time savings with a 20% average compared to concrete (Karacabeyli and Douglas 2013).

The development and use of CLT in North America began in Canada. A Canadian version of the *CLT Handbook* coincided with the addition of CLT to the Canadian building codes under the "Alternative Solutions" option (Karacabeyli and Douglas 2013). Since then, several tall buildings have been constructed using CLT, including the University of British Columbia's

Brock Commons Tallwood House and District Energy Centre in Vancouver, Origine in Quebec City, and Cordova Bay Elementary School in Victoria, British Columbia to name a few.

Although the breakthrough of CLT in the US happened later compared to Canada, currently there are four established CLT manufacturers with a collective five plants based in the United States, mostly located in the Pacific Northwest; in comparison, Canada presently has three CLT manufacturers: Structurlam Mass Timber Corporation, Nordic Structures, and Kalesnikoff Mass Timber, Inc. (APA 2020). The APA recognized CLT manufacturers in the United States are DR Johnson in Oregon, SmartLam North America with plants in Montana and Alabama, Vaagen Timbers at Washington and Freres Lumber in Oregon (APA 2020). Currently, there are four planned CLT factories to be constructed in the near future. Structurlam is building a CLT plant in Conway, Arkansas with the backing of Walmart (Structurlam 2019). Texas CLT plans on building a plant in Tennessee and LignaTerra and SmartLam North America plan on building a plant in Maine (The Architect's Newspaper 2020). The Pacific Northwest is popular for CLT manufacturers because of the area's abundance of Douglas-fir, Larch, and Hem-fir, which are the primary feedstocks for CLT panels. CLT projects have been constructed throughout the US with Albina Yard and Carbon12 in Portland, Oregon; Oregon State University's Peavy Hall in Corvallis, Oregon; T3 Tower in Minneapolis, Minnesota; Common Ground High School in New Haven, Connecticut; and the Candlewood Suites hotel at the Redstone Arsenal, Alabama (Think Wood 2020). In preparation of the new set of building codes, a 12-story tall wood project has been proposed to be constructed, named the Seattle Mass Timber Tower, located in Seattle, Washington (Breneman et al. 2019).

Prior to the 2015 International Building Code (IBC), CLT was not recognized by the building code, and construction was limited to the areas and heights permitted by Types III, IV, and V for wood construction (ICC 2020-A). The 2015 IBC was the first building code version to define and recognize CLT as a building material. The IBC gives governance to ANSI/APA PRG-320 as the product standard. CLT was permitted for Type IV construction and approved for exterior application if protected by specified non-combustible materials. For the 2018 IBC, heavy timber was reorganized to provide more context to the requirements to build Type IV construction. The 2018 IBC included a new section called Type IV-HT, and also added special code provisions to allow use of heavy timber materials to buildings not previously classified as Type IV construction. The incoming 2021 IBC contains a number of changes to the CLT industry. First, the term "mass timber" was defined to be inclusive of CLT and other materials such as, Glulam, Dowel-Laminated Timber (DLT), and Mass Plywood Panels (MPP). Second, three new construction types were added: Types IV-A, IV-B, and IV-C (ICC 2020-B)(Figure 1). Type IV-A will allow for 18 stories, building height of 270 feet, and an allowable building area of 970,000 square feet. Type IV-B will allow for 12 stories, building height of 180 feet, and an allowable building area of 648,000 square feet. Type IV-C will allow for 9 stories, building height of 85 feet, and an allowable building area of 405,000 square feet. Type IV-HT was kept to provide legacy provisions for heavy timber buildings. According to the new provisions for Type IV construction types, type IV-A will require an 80-minute minimum burn time for the interior surfaces of the building. Type IV-B will require the same burn time as type IV-A, but some exceptions will be allowed. Comparatively, type IV-C and IV-HT do not require any minimum burn time (Figure 2). Third, the term noncombustible protection was defined and applied specifically to mass timber components (ICC 2020-B). The definition, use, governance, and continuing construction revisions are still fairly limited because the introduction of mass timber to commercial use is still relatively new compared to materials such as concrete and steel.

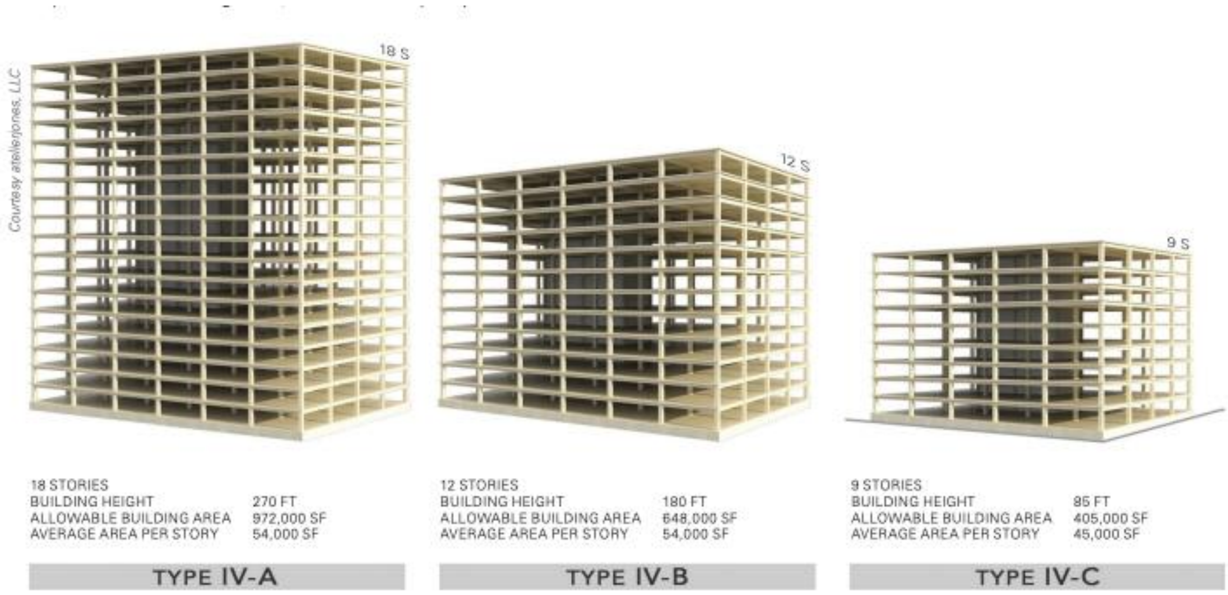
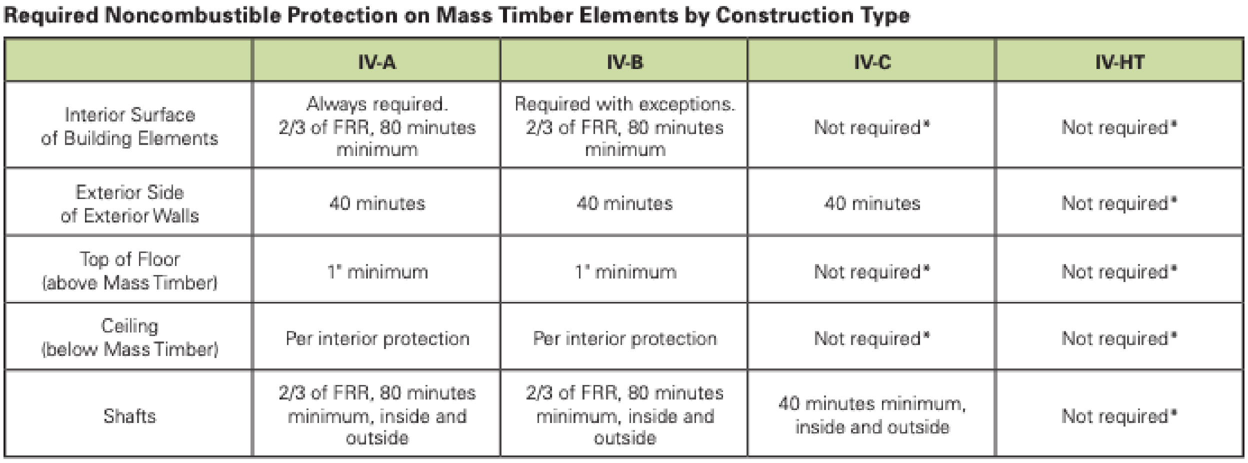


Figure 1. Building Types According to 2021 IBC (Breneman et al. 2019)



Required Noncombustible Protection on Mass Timber Elements by Construction Type

	IV-A	IV-B	IV-C	IV-HT
Interior Surface of Building Elements	Always required. 2/3 of FRR, 80 minutes minimum	Required with exceptions. 2/3 of FRR, 80 minutes minimum	Not required*	Not required*
Exterior Side of Exterior Walls	40 minutes	40 minutes	40 minutes	Not required*
Top of Floor (above Mass Timber)	1" minimum	1" minimum	Not required*	Not required*
Ceiling (below Mass Timber)	Per interior protection	Per interior protection	Not required*	Not required*
Shafts	2/3 of FRR, 80 minutes minimum, inside and outside	2/3 of FRR, 80 minutes minimum, inside and outside	40 minutes minimum, inside and outside	Not required*

Figure 2. Noncombustible Protection per 2021 IBC (Breneman et al. 2019)

The current CLT standard in the United States is *ANSI/APA PRG 320-2019 Standard for Performance-Rated Cross-Laminated Timber*, known as PRG-320 (ANSI/APA 2020). This document describes standards for manufacturing, assembly, material criteria, and performance;

although using PRG-320 is voluntary, manufacturers and specifiers use this document for CLT production, quality control and product grade definition. CLT panel grades include E grade panels, composed of machine stress-rated (MSR) softwood lumber in the longitudinal layers; V grade panels, composed of visual-graded softwood lumber for all layers; and S grade panels, composed of structural composite lumber (SCL) in the longitudinal layers. All ANSI/APA PRG-320 CLT grades contain visual-graded softwood lumber for the transverse layers. At the current time, all dimensional lumber used in structural graded CLT manufacture is softwood lumber (ANSI/APA 2020).

2. The Limiting Factor

For the continued growth of CLT, there are several limiting factors which should be addressed. The two limiting factors that will be focused on are the softwood supply in the United States, and the rolling shear performance of CLT cross-layers. In the author's opinion, these factors pose the greatest hurdles to expanding the CLT market. By increasing the number of allowable wood species for CLT production and understanding the mechanical properties of CLT cross-layers, mitigating these limiting factors may have a great impact upon the growing CLT market.

Softwood Lumber Supply for CLT Production

The continued growth of CLT demand will cause complications for the supply of softwood lumber. In order to construct a 1 ft^3 of CLT, a manufacturer will need 21.4 board feet of 2x6 and 2x8 lumber. With the current manufacturing and harvesting practices, it is projected that by the year 2025, lumber demand will be close to 389 million board feet to match the projected demand of 18.2 million cubic feet of CLT. This amount of lumber is equivalent to approximately 2.16

million logs, according to the Scribner short log scale (Beck 2008). The data is based on demand, consumption, and production in a region encompassing 17 western US states and 6 Pacific islands. This region contains the states of Washington, Oregon, and California, states with high presence of mass timber products.

The demand for softwood lumber has increased since the recession of 2009. Softwood lumber production of the United States has increased from 23.4 to 32.7 billion of board feet from 2009 to 2016 (Adhikari et al. 2020). Because of this increasing CLT demand, the demand for softwood lumber could surpass domestic supply. According to Adhikari et al., "softwood lumber production in the US is insufficient to meet domestic demand… to meet the predicted demand for CLTs in 2025 would require approximately 17% of the total softwood lumber produced in the US" (p. 2, 2020). A conservative approximation of the required softwood supply share of CLT of 17% was based on 2017 lumber production (Adhikari et al. 2020). The international CLT market is projected to be valued at $1.833 billion by 2024. This growth is supported by the residential construction demand of North America, a higher and more luxurious standard of living for urban centers in the Asia-Pacific region, and Europe's majority share of CLT manufacturers. North America is expected to have the highest compounded annual growth rate (CAGR) from 2018 to 2024; in the global CLT market the anticipated CAGR for the same years at 16.2% (Energias Market Research 2018). CAGR is a measurement of an investment over time; it "assumes that an asset, cash flow, or some other random variable grows at a constant rate of return compounded over a sample period of time" (Ansen et al. 2010, p.489).

The growth projection of softwood CLT production and market needs will place a burden on the US softwood supply. This burden will trickle down to all levels of the supply chain, and could affect forest health and low-value wood, due to possible over- and early harvesting. If the demand of domestic softwood is not met, lumber needs could be met by imported sources. This situation could offset any green building initiatives or larger economic benefits of CLT from raw material production because of the additional need to purchase and transport raw materials. In the Commonwealth of Virginia, the number and volume of both softwood and hardwood on forest land have increased from 2011 to 2014. By volume, yellow-poplar (*Liriodendron tulipifera*), loblolly pine (*Pinus taeda*), and chestnut oak (*Quercus montana*) have been the most abundant. The recorded volume of yellow-poplar in 2014 was 6,000 million cubic feet. The recorded volume of loblolly pine and chestnut oak for the same year were 5,500 and 3,400 million cubic feet, respectively. The volume of softwood trees in Virginia for each survey year has been relatively constant compared to the volume levels of hardwood trees. As can be seen on Figure 3, softwood volume has been between 5 to 10 billion cubic feet and hardwood volume have steadily increased by about 5 billion cubic feet from 2001 to 2014 in Virginia (Rose 2016).

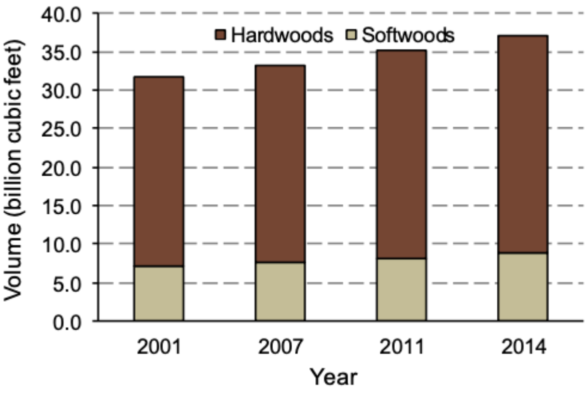


Figure 3. Live-tree volume (≥ 5.0 inches d.b.h.) on Virginia's forest land (Rose 2016)

Hardwood CLT panels have been manufactured for non-structural use for crane mats used in the oil and gas industry. Presently, two CLT manufacturers produce these hardwood panels using mixed hardwood species from oaks, beech, hickory, and other species. Difficulties in assembly were noted because of the very nature of hardwood lumber in the industry (Adhikari et al. 2020). Dimensions were not pre-set and required additional sorting according to manufacturer's needs, compared to softwood's industry-standard dimensions, creating an increase in production time. Hardwood lumber is often only dried to 15% moisture content at most, which is close but does not meet the ANSI/APA PRG-320 requirement of 12% ± 3%. Lastly, hardwood CLT panels take longer to press compared to softwood panels (Adhikari et al. 2020). Pressing is a known bottleneck in the CLT industry that could affect the use of hardwood panels given the lack of available of press capacity.

The assembly of hardwood CLT panels, as reported by two CLT manufacturers, did not present any additional manufacturing difficulties in finger jointing, bonding, and CNC finishing. The bulk of the complications stem from dimension non-uniformity, pressing time, and inefficiency in the early stages of hardwood implementation (Adhikari et al. 2020). Currently, CLT manufacturers are operating at approximately 70% efficiency. The upkeep of cutting tools would also need to be increased because of the density of some hardwoods since the increased density of some hardwoods will increase blade wear (Adhikari et al. 2020). Lastly, there are no established relationships between the CLT manufacturer and hardwood lumber suppliers. Because there is no approved standard for structural hardwood CLT panels, there has been no need for CLT manufacturers to reach out to hardwood mills for hardwood lumber supply. Also, there is the concern of maintaining the required quality of hardwood lumber, if demand suddenly increased for dimensional grade hardwood (Adhikari et al. 2020).

The highlighted concerns could be alleviated by restructuring the manufacturing process of hardwoods. Hardwood logs are usually sawn for the greatest yield of marketable grades, i.e., Select and Common grades. According to Thomas and Buehlmann, logs sawn for specific CLT use increased log utility and minimized the amount of wasted material (2017). Simulations were used to discover if there was a difference between prioritizing wider and/or longer versus shorter and/or narrower pieces with greater yields. The purpose of the simulations was to determine if better lamination pieces can be obtained from the low-grade logs, which can eliminate excess handling and increase inefficiency for CLT glue-ups. Simulations indicated that longer timbers can be achieved for CLT panels, which would decrease the need to finger-joint shorter lengths. Low-grade yellow-poplar trees have been historically used as low-value products "such as pallet parts, railroad ties, landscaping mulch, or chips for pulp," (p. 205) and a by-product of urban landscaping and forest logging operations. Finding a market for low-grade lumber will help its market price, which will then influence private forest landowners to plant more yellow-poplar trees (Thomas and Buehlmann 2017).

Rolling Shear Strength and Stiffness Concerns

The second limiting factor is rolling shear failure in the cross-layers observed when panels are loaded in flatwise bending, which include CLTs used as floor and roof panels. Rolling shear is one of the biggest mechanical concerns when CLT panels are loaded out-of-plane (Franzoni et al. 2016).

B. Rolling Shear

In Bodig and Jayne's *Mechanics of Wood and Wood Composites*, rolling shear is defined as "shearing forces which tend to roll the fibers across the grain… brought about by traction acting in the tangential direction in the R-T plane" (Bodig and Jayne 1982, p. 441). In terms of wood anatomy, rolling shear occurs when the compound middle lamella unbinds from the cell walls, causing a rolling motion from shear forces. This behavior is due to the amorphous nature of the primary cell wall for growth flexibility. Rolling shear in CLT mainly occurs in the vertical plane of the cross-layers during flatwise bending; this is due to the strength reduction of rolling shear resistance of up to 90% compared to the shear modulus in the horizontal plane (Bahmanzad et al. 2020). Supported by the *CLT Handbook*, "the product standard [for] the rolling shear modulus G_R is assumed to be 1/10 of the shear modulus parallel to the grain of the laminations, G_0" (Ch. 3 pg. 9, 2013). Although rolling shear strength is dictated by several factors, manufacturers control these possibilities by selecting lamination widths that will be able to resist rolling shear. According to the PRG-320, the required lamination width for the cross-layers "shall not be less than 3.5 times the net lamination thickness…" (p. 12, 2020). The behavior of rolling shear in CLTs is illustrated in Figure 4.

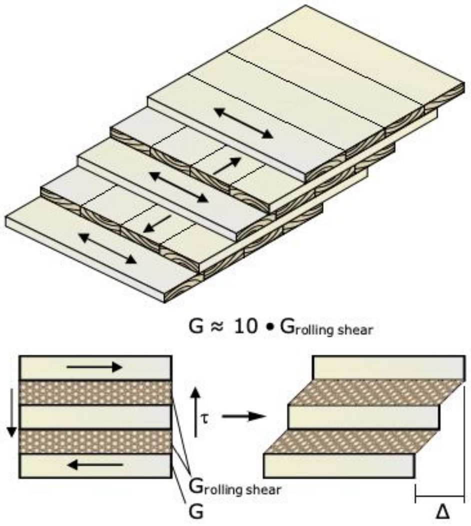


Figure 4. Rolling shear deformation of a 5-ply CLT panel (Karacabeyli and Douglas 2013)

According to the *Wood Handbook*, there have been few experiments to determine the rolling shear strength of solid-sawn lumber. Of these test values, “rolling shear strength averaged 18% to 28% of parallel-to-grain shear values” (p. 5-15, 2010). According to Sandoli and Calderoni, a correlation could be made between rolling shear strength and stiffness (2020). If the material’s rolling shear modulus is low, rolling shear strength will be low as well (Sandoli and Calderoni 2020).

In addition, studies have shown that rolling shear strength decreased when the slenderness ratio, L/h, decreased (Franzoni et al. 2016). The slenderness ratio, L/h, is defined as “the ratio of length to least cross-sectional dimension” (Bodig and Jayne 1982, p. 172). Low slenderness ratios, less than 11, appear when a material functions as a short, deep beam. A study by Sandoli and Calderoni investigated the influence of rolling shear on deflection and in-service stress state of a CLT floor panel, as well as the connection between span-to-length ratios and rolling shear (2020). The study found that an increase in the slenderness ratio can decrease the occurrence of rolling shear. In deflection, a slender panel of $L/h > 30$ can render the influence of rolling shear to a negligible percentage, less than 10% compared to the total deflection of the panel. Rolling shear also can be influenced by material density, sawing pattern, lamination ratio of the cross section, and annular ring growth (Sandoli and Calderoni 2020). PRG-320 does not contain a flatwise shear minimum value, but rather compare data to “the published shear stiffness in flatwise bending” (ANSI/APA 2020, p. 24).

1. Test Methods for Rolling Shear

There are two main methods commonly recognized for rolling shear evaluation. ASTM D2718 *Standard Test Methods for Structural Panels in Planar Shear (Rolling Shear)* is used to measure the shear strength and modulus of rigidity for structural panels in North America (ASTM 2006). ASTM D2718 was developed to “determine the shear properties of structural panels associated with shear distortion of the planes parallel to the edge planes of the panels. Primarily, the tests measure the planar shear (rolling shear) strength developed in the plane of the panel” (ASTM 2006, pg. 1). ASTM D2718 was designed to test structural panels such as plywood, oriented strand board, and similar materials. The standard describes two methods to determine shear properties: steel plates and a five-point bending test. Determining planar shear capabilities and values are important to understand the rigidity of wood-based structural panel materials. Planar shear can also be influenced by minimal span-depth ratios in certain scenarios such as, heavy loads and high pressure. To accurately determine rolling shear properties, it is crucial to measure the samples, “moisture content, specific gravity, and elapsed time-to-failure” (ASTM 2006, pg. 2).

There are two standard test methods prescribed in ASTM D2718. The first method entails using two steel plates to shear a portion of a Cross-Laminated Timber panel adhered to the steel plates. The second method uses a five-point bending test to determine the rolling shear strength loaded perpendicular of the material direction. Although both methods measure the shear strength of the material, the result from the five-point bending test is applicable for any moisture content (ASTM 2006). The two-steel plate planar shear test will be used to calculate the rolling shear strength and modulus in this study.

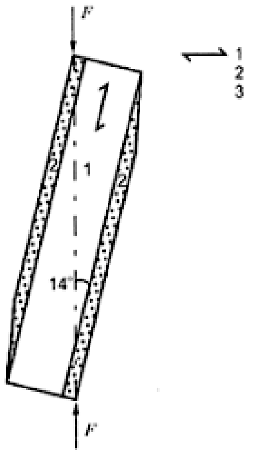
As mentioned previously, most of the CLT development was done in Europe. European researchers (Aicher 2016a and 2016b, Ehrhart and Brandner 2018, and Wang et. al 2017) have used EN 408: *Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties*, the European standard for testing timber materials (CEN 2012). EN 408 prescribes methods to determine modulus of elasticity in bending, tension, compression, shear modulus, bending strength, and shear strength. Similar to ASTM D 2718, EN 408 specifies the size, moisture content, and specific gravity of the test samples as well as test conditions and standards. Fracture description and presence of natural defects like, knots, slope of grain, etc. would be noted (CEN 2012).

Researchers following the European standard have used Test 18 to determine the rolling shear strength of various softwood and hardwood species for CLT application. The experiment uses steel plates, similar to ASTM D2718, to shear test samples. Test 18 prescribes the dimensions of the test samples, appropriate sample lay-up, displacement rate, and an equation to determine the shear strength (Equation 1). There are some limitations to this test. Unlike ASTM D2718, EN

408-Test 18 was originally written to test the shear strength of the timber samples parallel to grain. The original test lay-up prescribed by EN 408 for Test 18 is shown in Figure 5. Test specimen sizes were 300mm by 32 mm by 55 mm. Researchers have modified the test to fit their own experiments focusing on the shear strength perpendicular to the grain, where planar shear presents itself. In addition, a shear modulus equation is not present in the standard for this type of test (CEN 2012).

$$f_v = \frac{F_{max}\cos 14°}{\ell b} \qquad [1]$$

where:
f_v = Shear strength $\left({}^{N}/_{mm^2}\right)$
F_{max} = Maximum load (N)
ℓ = Length of test specimen (mm)
b = Smaller dimension of cross-section (mm)



Key:
1 Grain Direction
2 Steel Plate
3 Timber Test Piece

Figure 5. Steel plate shear test parallel to grain (CEN 2012)

Li (2017) used the plywood standard AS/NZS 2269 *Plywood—Structural* to comply to Australian and New Zealand standards. AS/NZS 2269 is comprised of three parts: Specifications, Test, and Evaluation methods. In particular, AS/NZS 2269.1 provides “test methods for evaluating the mechanical properties of structural plywood in both panel dimensions, that is, parallel to and perpendicular to the grain of the face veneer" (AS/NZS 2012).

2. Previous Evaluation of Rolling Shear Properties

Many previous studies have examined the rolling shear strength and stiffness using ASTM D2718, EN 408 and various modifications thereof. Several of the recent studies are highlighted below.

Aicher et al. (2016a) studied hybrid CLT panels comprised of European spruce (*Picea abies*) for the outer layers and European beech (*Fagus sylvatica*) for the inner layer. Specimens were tested through a five-point bending and planar shear test. Two methods of the planar shear test were conducted. Method A involved partially threading screws on the outer layers of the three-layer CLT. Method B involved a 1.0-2.0mm thin outer layer of spruce adhered to the steel plates to shear the beech cross-layer. The rolling shear strength from method A and B were 3.31 ± 0.61 N/mm^2 and 4.38 ± 0.44 N/mm^2, respectively.

Aicher et al. (2016b) examined the relation of rolling shear properties and the sawing pattern of beech (*Fagus sylvatica*) specimens. The mean rolling shear modulus of the specimens for all sawing patterns and pith inclusion was 370 N/mm^2. The mean rolling shear strength for the same group of specimens was 5.5 N/mm^2. The specimens were organized by sawing pattern and the inclusion or absence of pith.

Bahmanzad et al. (2020) tested eastern hemlock (*Tsuga canadensis*) considering the fiber orientation of each sample. The important finding in Bahmanzad's study is the difference of the rolling shear modulus value between 0° and 90° fiber orientation. The mean rolling shear modulus value for 0° specimens was 398 MPa and the 90° samples were 45 MPa. There is an 89% reduction in value. The mean rolling shear strength for 0° and 90° specimens were 6.6 MPa and 1.2MPa, respectively

Ehrhart and Brandner (2018) examined the rolling shear properties of six wood species; two softwood and four hardwoods. Norway spruce (*Picea abies*) was used as the reference species for the five other tested wood species. The correlation between rolling shear strength and modulus was examined for all the timber species tested, and showed a strong r^2 correlation of 0.85. It should be noted that the correlation between the rolling shear properties lowered when individual timber species are analyzed. According to the study, the correlation for the softwood species were less than the hardwood species correlation, asides from the Poplar (*Populus tremula L.*). For Norway spruce, the rolling shear modulus vs rolling shear strength correlation was, $r^2 = 0.03$. For pine (*Pinus sylvestris L.*) and poplar, the correlation was 0.14 and 0.08, respectively. European beech (*Fagus sylvatica L.*), European ash (*Fraximus excelsior L.*), and European birch (*Betula pendula*) were 0.37, 0.63, and 0.55, respectively.

Li et al. (2019) investigated the rolling shear strength of Douglas-fir (*Pseudotsuga menziesii*) and radiata pine (*Pinus radiata*) in a CLT cross-layer. According to the experimental results, the specimen type with a greater aspect ratio had a greater mean rolling shear strength compared to the specimen types with a lower aspect ratio for both bending and planar shear test. The coefficient of variation for most of the Douglas-fir specimens were much greater than the radiata pine specimens.

Li (2017) examined the rolling shear strength of radiata pine (*Pinus radiata*) with two different thickness laminations, 20 mm and 35mm. The 20mm samples tested produced a mean rolling shear strength of 2.33 MPa, which is significantly greater compared to its 35mm counterpart at 1.99MPa. The test produced a greater rolling shear strength compared to most other European and Canadian softwood CLT products.

Wang et al. (2017) examined several different macroscopic characteristics such as the existence and proximity of the pith and the sawing pattern of poplar (*Populus deltoides*) trees grown in China. The rolling shear modulus and strength were calculated from values obtained from the modified planar shear test conducted on all poplar samples. The mean rolling shear modulus and strength of all tested poplar samples were 177 and 3.06 MPa, respectively. These rolling shear properties exceed reported spruce-pine-fir values, reported by Wang et al. (2017).

Zhou et al. (2014) observed rolling shear properties of black spruce (*Picea mariana*) using the variable span bending test and the two-plate shear test. The black spruce were machined into clear wood strips, then separated by density and growth ring orientation. With the two-plate shear test, the average rolling shear strength and modulus were 2.09 and 72.6 MPa, respectively. The failure mode found in the two-plate shear test was rolling shear initiated close to the earlywood.

The average rolling shear strength and stiffness values of different species of wood from the previously discussed studies is listed in Table 1. All rolling shear strength and modulus values were obtained from two-plate or modified planar shear tests. Softwood species given in Table 1 include Norway spruce (*Picea abies*), pine (*Pinus sylvestris L.*), Douglas-fir (*Pseudotsuga menziesii*), radiata pine (*Pinus radiata*), black spruce (*Picea mariana*), and Eastern hemlock (*Tsuga canadensis*). Hardwood species include European beech (*Fagus sylvatica*), European birch (*Betula pendula*), European ash (*Fraximus excelsior L.*), and poplar (*Populus tremula L.*) and (*Populus deltoides*).

Table 1. Collective review of studies with respective species and rolling shear value.

Species	Reference	Rolling Shear	
		Strength (N/mm2)	Modulus (N/mm2)
Softwoods			
Norway spruce	Ehrhart and Brandner 2018	1.88	100
Pine	Ehrhart and Brandner 2018	2.29	158
Douglas-fir	Li et. al 2019	1.86	-
Radiata pine	Li et. al 2019	1.99	-
	Li - 20 mm 2017	2.33	-
	Li - 35 mm 2017	1.99	-
Black spruce	Zhou et. al 2014	2.09	73
Eastern hemlock	Bahmanzad et. al 2020	1.2	45
Average		1.95	94
Hardwoods			
European beech	Aicher, Hirsch, and Christian 2016a	4.38	-
	Aicher, Christian, and Hirsch 2016b	5.5	370
	Ehrhart and Brandner 2018	5.37	357
European birch	Ehrhart and Brandner 2018	3.45	188
European ash	Ehrhart and Brandner 2018	5.57	401
Poplar	Ehrhart and Brandner 2018	2.88	127
	Wang et. al 2017	3.06	177
Average		4.32	270

Softwood rolling shear strength ranged from 1.2 to 2.33 N/mm^2, and rolling shear modulus ranged from 45 to 158 N/mm^2. Hardwood rolling shear strength ranged from 2.88 to 5.57 N/mm^2, and rolling shear modulus ranged from 127 to 401 N/mm^2. The lowest rolling shear strength and modulus values came from the Eastern hemlock. The highest rolling shear strength and modulus values came from the European ash. It should be noted that the lowest shear strength value from the hardwood species was greater than all the recorded values of the softwoods. The lowest shear modulus of the hardwoods is the second highest modulus value of the softwoods.

The average rolling shear strength and modulus for all softwood studies in Table 1 were 1.95 and 94 N/mm^2, respectively, compared to the average for all hardwood studies in Table 1 of 4.32 and 270 N/mm^2, respectively. From this collection of studies, the softwoods were considerably weaker in resisting rolling shear compared to the hardwoods. The average rolling shear strength of the hardwood species was greater by 2.37 N/mm^2. This greater strength could lead to increased load capacity in flatwise bending because it has that increased resistance to rolling shear in the cross-section. As with the average rolling shear modulus, the hardwood value was greater by 176 N/mm^2. A greater shear modulus decreases the shear deflection by increasing the apparent bending stiffness of the panels. From the recorded strength and modulus values, it could be concluded that hardwood species use in CLT has the potential to increase the resistance of rolling shear for flat-wise bending. Supported by Mohamadzadeh and Hindman, “the bending stiffness, bending strength and interlaminar shear capacity were significantly greater than specified values for Grades V1 and V2 in PRG-320 (ANSI/APA 2020)" (2015, p. 17). Although, yellow-poplar CLT had significantly greater values, more study is needed.

3. Missing Piece

Since most CLT manufacture has used softwood lumber and/or engineered wood, there is little data of rolling shear properties for many hardwood species. Specifically, domestic US hardwood rolling shear properties have not been researched enough and established to be used for CLT manufacture. As the CLT industry is slowly taking off in the US construction market and more manufacturers are building plants around the country; the use of common hardwood species will propel the local wood suppliers, as well as the area surrounding the manufacturing plants.

Secondary CLT (CLST)

Another concern with rolling shear relates to a novel product called secondary CLT, or also known as cross-laminated secondary timber (CLST). CLST is described as using recycled timber as feedstock to construct new CLT panels (Rose et al. 2018). Since CLST is composed of used wood materials, there is the possibility for holes, gaps, etc. that could reduce the rolling shear properties because of a lack of contact area of the cross-layer. In a study by Rose et al., a combination of natural and man-made defects was used to test the elastic modulus (2018). The defects studied were as follows: small and large nail holes; screw holes; bolt holes; notches; small and large knots with respect to grain; and a mix of the man-made defects. Through the Rose et al. study, it was concluded that there were no significant differences between CLST and conventional CLT in terms of compression strength and stiffness. The study used finite element modelling and the theory of mechanically jointed beams to calculate and conclude the difference in value properties. The idea of CLST came from the amount of timber waste from the construction industry and repurposing it as a feedstock to CLST. Because it is being repurposed into a similar product, it is not considered to be downcycled of CLST compared to other recycled material like plastics and paper, feeding into the idea and practice of circular economy (Rose et al. 2018).

Bending tests were influenced by manufacturing problems because of the laboratory inexperience in manufacturing CLTs (Rose et al. 2018). The values affected were the elastic and rigidity moduli because of the quality of finger joints and delamination in the samples. The greater elastic and lower rigidity moduli values could also be attributed to material ageing; currently, it is unclear if the values were influenced by manufacturing problems or time. Although there were limitations on the CLT manufacturing, it can be concluded that "small defects like nail holes and screw holes, up to the concentrations found in a survey of secondary timber, would degrade MOE of CLST in compression, or bending, by less than 6% compared to a configuration with no defects" (Rose et al. 2018, p. 13). It can also be concluded that distributed defects can increase the elastic moduli value when compared to concentrated larger defects.

C. Goals and Objectives

The goal of this project is to measure the rolling shear strength and stiffness of different wood species for CLT cross-layer application. The ASTM D 2718 testing method will be used to evaluate the rolling shear strength and stiffness of southern pine (*Pinus spp.*), yellow-poplar (*Liriodendron tulipifera*), and soft maple (*Acer spp.*). In addition, a secondary study will measure the rolling shear properties of simulated lumber to quantify the effect of defects in the material placed in the cross-layer of CLST.

Materials and Methods

A. Materials

Each specimen group to be tested in this study was selected based on location accessibility, material property, and use of species in the industry. Southern pine (*Pinus spp.*) is a group of species commonly sourced from the southeastern United States. Southern pine is primarily comprised of: Loblolly (*Pinus taeda*), Shortleaf (*Pinus echinata*), Longleaf (*Pinus palustris*), and Slash pine (*Pinus elliottii*) (Koch 1972). Southern pine is currently included in the PRG-320 (ANSI/APA 2019) to be constructed as V3 grade CLT and previously evaluated by Hindman and Bouldin (2014). The specific gravity of Southern pine is 0.55 (AWC 2018). Southern pine was chosen because its abundantly grown, low cost, accessible to the Virginia Tech area, and provides a control species since southern pine is included in PRG-320 (ANSI/APA 2020).

Yellow-poplar (*Liriodendron tulipifera*) is a deciduous diffuse porous species grown on the East coast of the United States. This species was chosen because of its unique likeness to softwood properties, as well as its accessibility to the area and previous research work done for CLT use. Yellow-poplar has a specific gravity of 0.43, similar to the specific gravity of Hem-fir, Spruce-pine-fir, and Norway Spruce which are all used for the production of CLT (AWC 2018). Yellow-poplar is a commonly used hardwood in the United States. Furthermore, CLT panels have already been constructed using yellow-poplar (Mohammadzadeh and Hindman 2015, Thomas 2017).

Soft maple (*Acer spp.*) is a classified group of maple, similar to the Southern pine species group. The term soft maple is used to differentiate certain maple species from hard maple, although soft and hard do not correlate to density. Species considered as soft maple are red maple (*Acer rubrum*), silver maple (*Acer saccharinum*), and boxelder (*Acer negundo*) (Center for Wood Anatomy Research n.d.). Soft maple was chosen because of its common use, local availability, and low cost. Also, soft maple is similar to yellow-poplar as a diffuse porous species. According to the *National Design Specification (NDS) Supplement: Design Values for Wood Construction*, the specific gravity of red maple is 0.58 and mixed maple is 0.55 similar to southern pine at 0.55 (AWC 2018).

Southern pine will also be used for the CLST evaluation. Southern pine is a great candidate for the CLST study because, as mentioned, it is widely used in the construction industry as framing lumber. For the secondary study, this set of southern pine will be re-manufactured with man-made defects. Defects that will be introduced for the CLST study will include, but not limited to, 1/2" – 3/4" holes, notches, and surface area reduction. The original samples were remanufactured with nail and bolt holes, using 16d nail and 5/8" bolt. The bolt samples were replaced with a different nail hole treatment because of adhesive and drying issues that were discovered after sample testing. Because of the bolt hole size, the adhesive would not dry and cure within the 24-hour cure time. The final samples used had two different nail hole treatments, six with 6 nail holes and six with 12 nail holes. Nail holes are one of the most common "defects" that can be found in a construction site, if these samples were procured from various building construction sources. Natural defects, like knots and pith, will be noted. Because rolling shear properties are affected by defects, this method of repurposing southern pine can be a good indication if this application is viable in CLT production. The abundance of southern pine in the construction and manufacturing industry makes this material the best candidate for the secondary study.

B. Methods

1. Rolling Shear Strength and Modulus

Specimen Preparation

Sample size was calculated using ASTM D2915, *Standard Practice for Sampling and Data-Analysis for Structural Wood and Wood-Based Products*, Equation 4.4.2 with a 75% confidence interval and a 13.2% coefficient of variation (ASTM 2010) (Eq. 2). The 13.2% coefficient of variation was taken from the average of previous evaluations of rolling shear studies' coefficient of variation. Based on calculations, 12 samples were chosen in each of the 4 groups: southern pine, yellow-poplar, soft maple, and simulated reclaimed southern pine will be tested for a total of 48 specimens.

$$n = \left(\frac{ts}{\alpha\bar{X}}\right)^2 = \left(\frac{t}{\alpha}CV\right)^2 \qquad [2]$$

where:
$n =$ sample size
$s =$ standard deviation of specimen values
$\bar{X} =$ specimen mean value
$CV =$ coefficient of variation $(s/\bar{X})$
$\alpha =$ estimate of precision (0.05)
$t =$ value of the t statistic from Table 1 from ASTM D2915

A total of 48 samples were machined from lumber stored inside the Wood Engineering Laboratory at the Brooks Forest Products Center. The average moisture content for Virginia is 8%, ranging from 6-10%. The wood specimens were cut and planed to 6 inches long, 6 inches wide, and 1-3/8 inch thick, as shown in Figure 6. The steel plates used were machined to 12 inches long, 6 inches wide, and 1 inch thick. The steel plates were prepared by wiping the surface with a cloth rag soaked with lacquer thinner. The adhesive used to bond the wood samples to the steel plates was Loctite PL Premium Fast Grab Polyurethane. The adhesive was applied to both the wood and metal surfaces, then pressed for at least 24 hours using a hydraulic press to cure as recommended by the product technical data sheet (Loctite 2019), as shown in Figure 7.

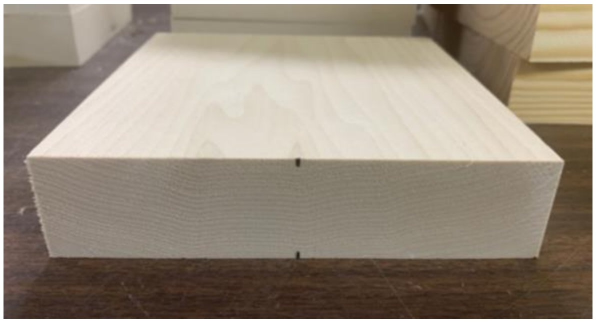


Figure 6. Yellow-poplar sample

Figure 7. Finished Samples in Press

The samples were tested using an MTS 50k capacity machine (Figure 8). A 2-inch long LVDT (0.1% resolution) was attached to one plate, and contacted a clip attached to the other plate. The sample placed in the test machine is shown in Figure 8. The displacement rate of the load head was 0.0825 in/min and calculated through Equation 7.2 found on ASTM D2718 (2006) (Equation 3). Specimens were loaded until failure when the specimen cleaved or the load decreased below 10% of the maximum load. An attached data acquisition system continuously recorded load and displacement throughout the test.

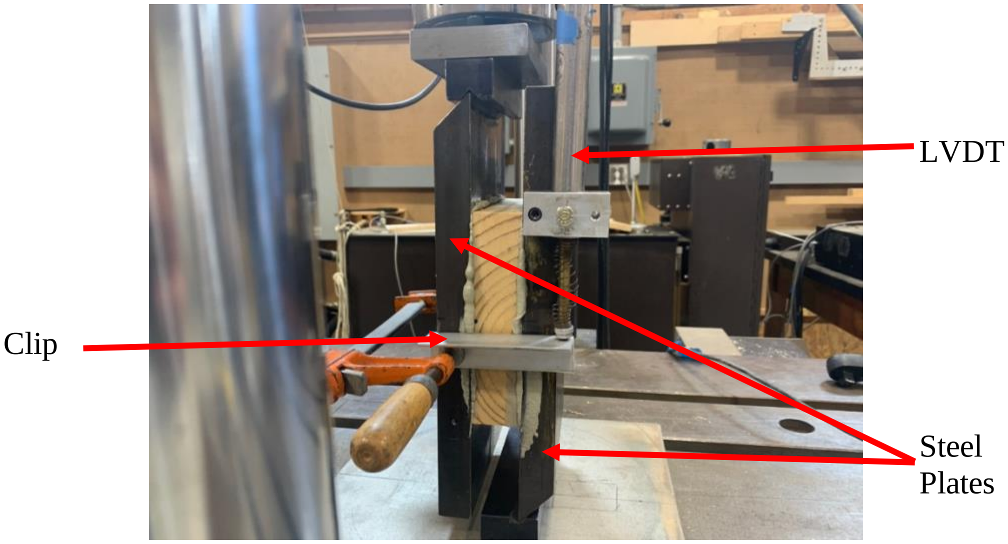


Figure 8.MTS machine with Southern Pine sample

$$N = 0.0075 \left(\sum T_1 + R \sum T_{\perp}\right) \qquad [3]$$

where:

N=Crosshead speed $\left({}^{in}/_{min}\right)$

$\sum T_1$=Total thickness of plies having grain parallel to direction of shear force (in)

R=8 (assumed ratio of shear modulus of parallel plies to shear modulus of perpendicular plies)

$\sum T_{\perp}$=Total thickness of plies having grain perpendicular to direction of shear force (in)

After the specimen failed, it was unloaded from the MTS machine and examined. Specimens that had at least 85% wood failure were accepted. Failure modes and location were documented. Additional photos were taken of specimens that failed, but did not cleave, and then separated to reveal the internal failure.

After sample collection for moisture content and specific gravity, the steel plates were placed on a hot plate for adhesive removal. The steel plates were heated until the adhesive released the wood sample from the steel plate. Any extra adhesive still adhered on the steel plates was scraped off with a putty knife. The plates were then wiped down with lacquer thinner to fully clean the bonding surface to be used again.

2. Moisture Content and Specific Gravity

To get an accurate reading for the moisture content and specific gravity of each sample, samples from each shear test were sectioned after testing was completed. These samples were weighed to determine the air-dry weight, then placed into a drying oven. These samples were then periodically checked to determine if it achieved oven-dry conditions. Oven-dry condition was achieved when the sample weight was constant within a 3-hour time frame as described by ASTM D4442 (ASTM 2020). The samples were then weighed to determine the oven-dry weight.

Individual samples are then placed into a wax bath to coat the outside of the specimens. Wax-coated samples were submerged in a water bath, making sure that the sample does not touch any surface to measure the volumetric displacement of water. This will give the volume of the sample in relation to the water. The process was designed from ASTM D2395 – Test Method B

Mode II (ASTM 2017). The oven-dry weight and water displacement were used to calculate the oven-dry specific gravity.

3. Data Analysis

The data gathered from the two-plate shear test was inputted in an Excel® spreadsheet designed to automatically calculate the shear strength and modulus of rigidity of each sample. The equations used in the Excel spreadsheet were taken from ASTM D2718, equations 9.1 and 9.2 to determine the shear strength and rolling shear modulus, respectively, which were reproduced as Eq. 4 and 5. The output values were converted from psi to N/mm^2 for easy comparison between the literature and experiment.

$$f_v = P/(L \cdot W) \qquad [4]$$

where:
f_v=Shear stress (psi)
P =Maximum limit load (lbf)
L= Specimen length (in)
$W =$ Specimen width (in)

$$G = (P/\Delta)[t/(L \cdot W)] \qquad [5]$$

where:
G= apparent modulus of rigidity of entire specimen (psi)
t =specimen thickness (in)
${}^{P}/_{\Delta}$ =slope of force-deformation curve below proportional limit load (lbf/in)

The data gathered from the moisture content and specific gravity measurements were inputted into an Excel® spreadsheet to calculate the samples' specific gravity and moisture content. The moisture content formula used in the Excel spreadsheet were taken from ASTM D4442-20 Equation 5.5.1 (2020) (Eq. 6). The specific gravity formula used in the Excel spreadsheet were taken from ASTM D2395-17 Equation 15.3.1.2 (2017) (Eq. 7).

$$MC\ (\%) = (A - B)/B \times 100 \qquad [6]$$

where:
$MC\ (\%)$=Percentage of moisture content
A =original mass (g)
B =oven-dry mass (g)

$$S_0 = \frac{Km_0}{V_0} \qquad [7]$$

where:
S_0=Specific gravity at oven-dry
K=constant (1.000 cm^3/g)
m_0=oven-dry mass of specimen
V_0=oven-dry volume of specimen

Value comparisons will be done in the form of a single factor ANOVA test. This comparison will determine if there are any significant difference in each comparison's species group means. There will be two primary statistical analysis conducted: between the different species and between the CLST groups. The null hypothesis is that all means are equal and the alternative hypothesis is that the means are not equal. A Tukey's Honest Significant Difference (HSD) test will be conducted as needed.

Results and Discussion

A. Results and Descriptive Statistics

Table 2. Rolling Shear Averages per Species Variation

Species	Rolling Shear Average (N/mm2)			
	Strength	COV	Modulus	COV
Southern Pine	2.51	16.8%	277	64.1%
Yellow-poplar	3.12	17.3%	153	26.7%
Soft Maple	5.93	12.3%	277	37.0%
CLST	3.01	16.3%	239	50.4%
CLST 6	3.51	11.8%	153	12.7%
CLST 12	2.65	8.20%	332	31.5%

COV = Coefficient of Variation
CLST6 = 6-nail hole treatment
CLST12 = 12-nail hole treatment

The average and coefficient of variation (COV) of the rolling shear strength and rolling shear modulus are shown in Table 2. The average rolling shear strength of the southern pine and CLST was 2.51 N/mm^2 and 3.01 N/mm^2. In contrast, the hardwood groups achieved a greater average rolling shear strength of 3.12 N/mm^2 and 5.93 N/mm^2 for the yellow-poplar and soft maple, respectively. Similar to the literature review values, the softwood had a lower average rolling shear strength compared to the hardwood groups. The COV of the rolling shear strength of the experiment groups ranged from 12.3% to 17.3%.

The average rolling shear strength relationship between the softwood and hardwood species groups was not observed in the average rolling shear modulus values. The southern pine and soft maple average rolling shear modulus were 277 N/mm^2, compared to the yellow-poplar average of 153 N/mm^2 and CLST average of 239 N/mm^2. This disparity could be explained by the greater COV of the experiment groups, ranging from 26.7% to 64.1%, more notably the southern pine group with 64.1% and CLST with 50.4%. The COV for Ehrhart and Brandner (2018) pine was 19% compared to the southern pine and CLST COV of 64.1% and 50.4%, respectively. For the hardwood groups, the COV of poplar from Ehrhart and Brandner 2018 and Wang et. al 2017 was 15% and 22% to be compared to yellow-poplar and soft maple of 26.7% and 37%, respectively. The large COV values could be explained by the relative size of the linear displacement reading. Because there was little movement gathered by the LVDT, this could have caused a great disparity in the rolling shear modulus values in each experiment group. The LVDT movement could range from 0.0107 to 0.0678 inches. These were calculated by randomly selecting a sample from each species group and finding its range difference.

B. Moisture Content and Specific Gravity

Table 3. Average Moisture Content and Specific Gravity

Species	**Moisture Content**		**Specific Gravity**	
	Average (%)	COV (%)	Average	COV (%)
Southern Pine	6.99%	8.19%	0.510	15.8%
Yellow-poplar	6.51%	6.36%	0.433	13.1%
Soft Maple	6.92%	5.24%	0.572	5.55%
CLST	8.34%	11.7%	0.513	11.8%

The average moisture content and specific gravity for each species group are listed in Table 3. The average moisture content for all four species group, ranged from 6.51% to 8.34% within the regional average of 6%-10%. The COV of the soft maple and yellow-poplar were low at 5%-6%, compared to the COV of the CLST of 12%. The average specific gravity of both southern pine and CLST southern pine samples was 0.51, lower than the industry average of 0.55. The COV of both groups were 12% and 16%, respectively. This could be attributed to the wider growth rings in the samples, producing variability and a lighter wood product. The average specific gravity of the yellow-poplar was 0.43, equal to the industry average of 0.43. Lastly, the average specific gravity of the soft maple was 0.57, similar to the published specific gravity of red maple of 0.58.

C. Percent Difference

Table 4. Percent Difference compared to Southern Pine

Species	Difference of Average Values	
	Rolling Shear Strength (N/mm2)	Rolling Shear Modulus (N/mm2)
Yellow-poplar	24.3%	-44.8%
Soft Maple	136%	0.0%
CLST	19.9%	-13.7%

The values were compared to the southern pine results (2.51 N/mm^2 and 277 N/mm^2, respectively).
% Difference = ((Species – Southern Pine)/ Southern Pine) * 100%

The data shown in Table 4 are the percent difference of the average rolling shear strength and modulus compared to southern pine. The average of the rolling shear strength and modulus were compared to the average of the southern pine values. The average rolling shear strength of the yellow-poplar was 24% greater, while the average rolling shear modulus was 45% lower than the southern pine values. The average rolling shear strength of soft maple was 136% greater than the southern pine values, much greater compared to the yellow-poplar and southern pine. The soft maple had a rolling shear modulus average equal to the southern pine value. Lastly, the CLST southern pine average rolling shear strength was greater by 20% but the average rolling shear modulus was 14% less than the southern pine values. With the CLST southern pine, the rolling shear strength may have been influenced by the mechanical interface between the adhesive and wood sample. Because the adhesive was able to cure inside the nail hole and gather around the treatment sites, this may have allowed the wood specimen and steel plate to bond better and increase the shear resistance of the sample lay-up. Overall, all other sample groups tested had a greater average rolling shear strength when compared to the southern pine; this greatly contrasts the percent differences of the average rolling shear modulus.

D. Failure Analysis

Southern Pine

Figure 9. Rolling Shear in sample SP 2

Figure 10. Rolling Shear in sample SP 7

Figure 11. Rolling Shear in sample SP 11

The most common failure in the southern pine samples was rolling shear. The variations of rolling shear failure are shown in Figures 9 to 11. In Figure 9, the rolling shear propagated across and along the annual tree rings. The break then continued along the bond line between the steel plate and the wood sample. In Figure 10, the break stayed along the growth ring without crossing to another growth ring. Figures 9 and 11 were similar with how the rolling shear traveled across the tested sample. The difference between these two failures was how the break propagated depending on the grain of the samples. The sawing pattern of SP 2 that produced Figure 9 rolling shear failure is categorized as flat sawn, while the sawing pattern of SP 11 that produced Figure 11 rolling shear failure is categorized as rift sawn.

Yellow-poplar

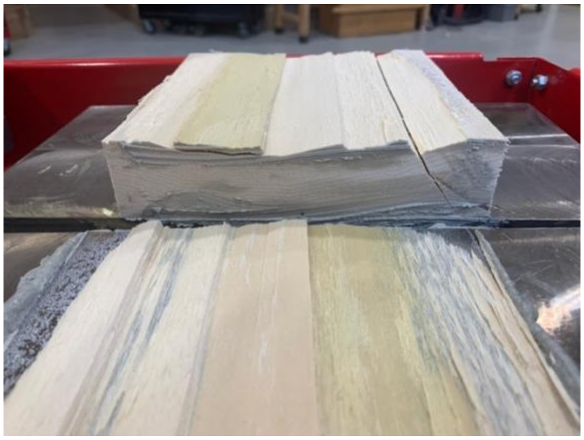


Figure 12. Rolling Shear in sample YP 7

Figure 13. Rolling Shear in sample YP 7

The most common failure in the yellow-poplar samples was a combination of rolling shear and adhesive failure (Figures 12 and 13). The rolling shear failure in the yellow-poplar propagated along and across the growth rings, similar to Figure 11. Yellow-poplar samples that had less than 15% adhesive failure were accepted. There was no difference in the rolling shear failure between the southern pine and yellow-poplar samples, except for the shear strength values obtained between the two species groups.

Soft Maple

Figure 14. Rolling Shear in sample SM 2

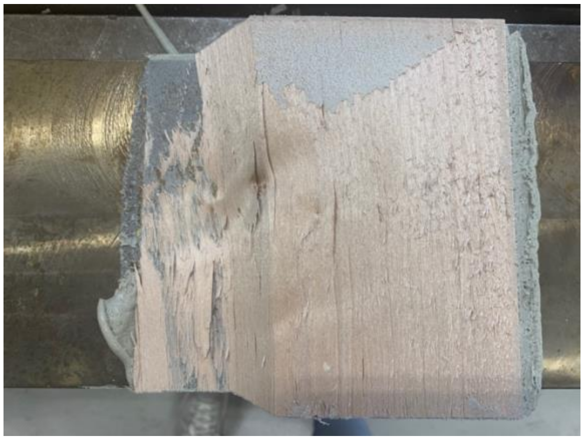


Figure 15. Adhesive Failure in sample SM 5

The rolling shear failure depicted in Figure 14 was the most common failure found in the soft maple samples. Similar to Figures 11 and 13, the rolling shear failure traveled along and across the annual growth rings. The break then continued toward the bond line between the steel plate and wood sample. The soft maple specimens had more glue failures because of the material's greater shear resistance compared to the shear resistance of the adhesive, illustrated in Figure 15. Soft maple samples that had less than 20% adhesive failure were accepted.

CLST

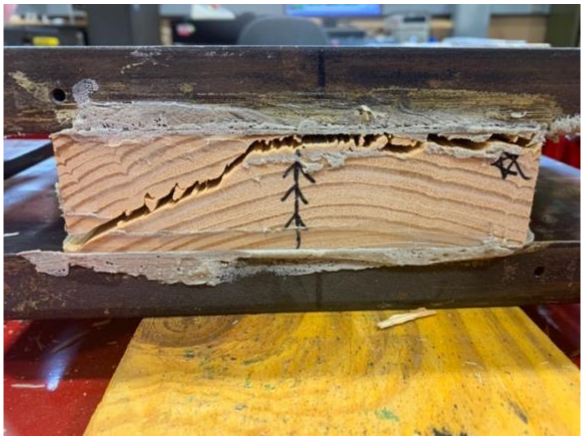


Figure 16. Rolling Shear in sample N1

Figure 17. Rolling Shear in sample N3

Figure 18. Rolling Shear and Adhesive Failure in sample N4

The typical failures found in the CLST samples were a combination of rolling shear and adhesive failure. As can be seen in Figure 16, the rolling shear failure traveled across and along the growth ring towards the bond line of the sample set-up. In Figure 17, the rolling shear failure had a more catastrophic break. Similar to other rolling shear failures, the failure propagated across the material towards the bond line. Figure 18 depicts a sample with rolling shear and adhesive failure. The initial failure was rolling shear and upon unloading from the MTS machine after testing, the adhesive failure was discovered. CLST samples that had less than 15% adhesive failure were accepted. Some of the samples were experiencing more adhesive failure because the material's shear strength has surpassed the adhesive shear strength.

E. Statistical Analysis

1. Rolling Shear Strength

Southern Pine v Hardwoods

A single factor analysis of variance (ANOVA) test was conducted to compare the difference between the average rolling shear strength of the yellow-poplar, soft maple, and southern pine. This softwood versus hardwood comparison could show if there is a difference between its rolling shear strength. The reported p-value was 2.55 x 10^{-5} compared to an alpha-value (α) of 0.05, thus signaling a statistically significant difference between the groups rolling shear strength. A Tukey's HSD test was conducted to determine the location of the statistical different mean. According to Table 5, there was a statically significant difference between all of the groups' average rolling shear strength. The soft maple had a greater statistically significant difference than the yellow-poplar, which had a greater statistically significant difference compared to the southern pine.

Table 5. Tukey's HSD Southern Pine and Hardwoods

Tukey's HSD			
Treatments	*diff-means*	*crit-diff*	*sig-diff*
YP v SM	2.81	0.500	yes
YP v SP	0.606	0.500	yes
SM v SP	3.42	0.500	yes

Diff-means = Difference in mean values from ANOVA test (N/mm^2)
Crit-diff = Critical difference for Tukey's HSD
Sig-diff = Significant difference for Tukey's HSD

Southern Pine v CLST

A comparison was conducted to determine if there was a significant difference between the rolling shear strength means of the southern pine and CLST group. The reported p-value between the southern pine and CLST group was 0.0184 compared to an α of 0.05, indicating a statistically significant difference.

Table 6. Tukey's HSD between three Southern Pine groups

Tukey's HSD			
Treatments	*diff-means*	*crit-diff*	*sig-diff*
SP v CLST6	0.855	0.345	yes
SP v CLST12	0.137	0.345	no
CLST6 v CLST12	0.718	0.345	yes

Diff-means = Difference in mean values from ANOVA test (N/mm^2)
Crit-diff = Critical difference for Tukey's HSD
Sig-diff = Significant difference for Tukey's HSD

Because the CLST group had different treatments, an ANOVA comparison was conducted to determine if there was a significant difference between the two treatments in the CLST and southern pine for its rolling shear strength means. The p-value reported was 0.00138 compared to an α of 0.05. This indicated that there was a significant difference in the three groups. To determine the location of the significant difference, a Tukey's HSD test was conducted. The test indicated that there was a statistically significant difference of the means between the southern pine and CLST with the 6-nail hole treatment. Additionally, there was a statistically significant difference between the two different treatment groups of the CLST. Lastly, there was not a significant difference between the southern pine and the CLST 12-nail hole treatment group. Overall, the CLST6 had a greater statistically significant difference than the southern pine and CLST12; however, the CLST12 was not less than the southern pine, rather the southern pine could be greater than or equal to the CLST12. This could be attributed to the limited sample size, large COV values, and moisture content. Based on the study by Rose et al. (2018), the greater significant difference of CLST6 compared to the CLST12 could be explained by the increased elastic moduli. Because of the higher concentration of defects found in CLST12 samples, this could have affected the elastic modulus of the material compared to the lower concentration of defects found in the CLST6 samples.

2. Rolling Shear Modulus

Southern Pine v Hardwoods

Table 7. Tukey's HSD SoftwoodvHardwoods Modulus

Tukey's HSD			
Treatments	*diff-means*	*crit-diff*	*sig-diff*
YP v SM	124	105	yes
YP v SP	124	105	yes
SM v SP	0	105	no

Diff-means = Difference in mean values from ANOVA test (N/mm^2)
Crit-diff = Critical difference for Tukey's HSD
Sig-diff = Significant difference for Tukey's HSD

A comparison was conducted to determine if there is a statistically significant difference between the groups' average rolling shear modulus (Table 7). The groups compared were the yellow-poplar, soft maple, and southern pine. The reported p-value of the comparison was 0.0309 compared to an α of 0.05, thus indicating a statistically significant difference in the groups' means. After conducting a post-hoc Tukey's HSD test there were two locations where a significant difference was found. There was a statistically significant difference between the two hardwoods and between the yellow-poplar and southern pine. Overall, the soft maple and southern pine had an equal statistically significant difference, but a greater statistically significant difference compared to the yellow-poplar.

Southern Pine v CLST

The next rolling shear modulus comparison test was conducted on the southern pine and CLST. With a reported p-value of 0.555 compared to an α of 0.05, this indicated that there was no statistically significant difference between the means of the rolling shear modulus of the two groups. Lastly, a comparison was conducted between the southern pine and the two different treatment groups of the CLST. The reported p-value of this comparison was 0.0915 compared to an α of 0.05 and signifies that the means are not significantly different. Because there was no significant difference in these last two comparisons, a Tukey's HSD test was not conducted. The result was similar to the Rose et al. (2018) study.

F. Literature Review Comparisons

Table 8. Literature Softwood Comparison of Rolling Shear Properties

Softwoods			
Species	Reference	Rolling Shear (% diff)	
		Strength (N/mm^2)	Modulus (N/mm^2)
Southern Pine	Experimental Study	2.51	277
Pine	Ehrhart and Brandner 2018	2.29 (-8.76%)	158 (-43.0%)
Radiata pine	Li et. al 2019	1.99 (-20.7%)	-
	Li - 20 mm 2017	2.33 (-7.17%)	-
	Li - 35 mm 2017	1.99 (-20.7%)	-

The values were compared to the southern pine results.
% Difference = ((Species – Southern Pine)/ Southern Pine) * 100%

The tested southern pine samples achieved the greatest average for both the rolling shear strength and modulus when compared to the other pine values from the literature review are shown in Table 8. Ehrhart and Brandner (2018) average rolling shear strength was about 9% lower, and the average rolling shear modulus was lower by 43% than the experimental values. This disparity could be explained by the coefficient of variation between the two studies. The COV of southern pine was 17% and 69% for the strength and modulus, compared to 10% and 19% of Ehrhart and Brandner (2018), respectively. The average rolling shear strength of radiata pine by Li et. al (2019) and Li (2017) were lower by 7% to 21% compared to the average rolling shear strength of the tested southern pine samples. The COV of the radiata pine from Li (2017) were 12% and 13% for the 20mm and 35mm samples, respectively. In addition, the COV of the radiata pine from Li et. al (2019) was 19%. These species were picked to be compared because of its close relativity. Overall, the experimental southern pine was stronger and stiffer than previous evaluations of rolling shear properties.

Table 9. Literature Hardwood Comparison of Rolling Shear Properties

Hardwoods			
Species	Reference	Rolling Shear (% diff)	
		Strength (N/mm^2)	Modulus (N/mm^2)
Yellow-poplar	Experimental Study	3.12	153
Soft Maple	Experimental Study	5.93 (90.1%)	277 (81.0%)
Poplar	Ehrhart and Brandner 2018	2.88 (-7.69%)	127 (-17.0%)
	Wang et. al 2017	3.06 (-1.92%)	177 (15.7%)

The values were compared to yellow-poplar results.
% Difference = ((Species – Yellow-poplar)/ Yellow-poplar) * 100%

The average rolling shear strength and modulus of yellow-poplar was compared to the values of the soft maple from this study and poplar obtained from Ehrhart and Brandner (2018) and Wang et. al (2017). The soft maple had the highest average rolling shear strength and modulus in Table 9. The average rolling shear strength of soft maple was greater by 90% and its average rolling shear modulus was greater by 81%. Ehrhart and Brandner (2018) had an 8% lower average rolling shear strength and 17% lower average rolling shear modulus. Wang et. al (2017) had a 2% lower average rolling shear strength and 16% greater average rolling shear modulus. Overall, the soft maple was stronger and stiffer compared to the experimental values of yellow-poplar and values obtained from Ehrhart and Brandner (2018) and Wang et. al (2017).

Conclusions

A. Summary

The goal of this research was to measure rolling shear strength and stiffness values of different wood species for CLT cross-layer application. The growing demand for softwood lumber and CLT panels have caused concern for the domestic softwood production. The demand for softwood lumber could surpass the domestic softwood supply, thus hindering any green building initiatives or economic advantages of using CLTs. Rolling shear properties of the selected wood species were measured by using a two-plate shear test described in ASTM D2718. The wood species that were selected for the experiment included southern pine, yellow-poplar, and soft maple. The southern pine was selected as a control group because of its inclusion in the PRG-320; although, PRG-320 does not list a minimum value for rolling shear. Yellow-poplar, as a deciduous diffuse porous species, was chosen because of its similarity to softwood attributes. Although yellow-poplar has a lighter specific gravity than southern pine, previous research work has shown that yellow-poplar could attain greater rolling shear properties. Finally, the soft maple was chosen because of its common use in the forest products industry. Also, it has a similar specific gravity to the southern pine species group.

For a secondary experiment, southern pine samples were re-manufactured with “man-made” defects to determine its rolling shear properties if reclaimed lumber were to be used as feedstock for new CLT panels. The defects that were applied to the southern pine samples were nail holes, one group with 6 holes and another with 12 holes.

Each sample was machined to 6 inches wide, 6 inches long, and 1 3/8” inch thick, then glued to the steel plates. These sample set-ups were then pressed in a hydraulic jack for 24 hours, according to the adhesive product technical report. The set-ups were loaded on a MTS machine with a LVDT for its displacement measurement. The data were inputted in an Excel file that was designed to calculate the rolling shear strength and modulus. Moisture content and specific gravity samples were taken from each material set-up to quality control. The methods for the moisture content and specific gravity test were from ASTM D4442 and ASTM D2395, respectively. Data comparisons were done to determine if there was a significance difference and its location. A single factor analysis of variance (ANOVA) was conducted on the data comparisons, and when appropriate a post-hoc Tukey’s HSD test. The data were also compared to referenced studies.

B. Conclusions

- The greatest average rolling shear strength was calculated to be 5.93 N/mm^2 from the soft maple. The lowest average rolling shear strength was calculated to be 2.51 N/mm^2 from the southern pine. The greatest average rolling shear modulus was 153 N/mm^2 from yellow-poplar. The lowest average rolling shear modulus was 277 N/mm^2 from southern pine and soft maple. The CLST southern pine samples averaged at 3.01 N/mm^2 and 239 N/mm^2 for its strength and modulus.
- The average moisture content of the samples was around 7%-8%. The average moisture content of the samples was within the regional average. The average specific gravity of the samples was consistent with published values.
- When compared to southern pine, the yellow-poplar achieved a greater average rolling shear strength by 24% but a lower average rolling shear modulus by 45%. The soft maple had a greater average rolling shear strength by 136%. The CLST southern pine had a greater average rolling shear strength by 20% but a lower rolling shear modulus by 14%. The hardwood species had a greater average rolling shear strength compared to the softwoods.
- The most common failure for all the samples was rolling shear. The rolling shear failure would propagate along and across growth rings, towards the bond line between the sample and steel plate. The differences in rolling shear failures could be attributed to the materials growth ring and sawn patterns. This could be seen more prominently in the southern pine samples. The soft maple experienced more glue failures because the material’s resistance to shear has surpassed the adhesive’s shear resistance.

- There were statistically significant differences between the means of the experiment groups. For the rolling shear strength, from greatest to least in statistically significant difference, the soft maple was greater than the yellow-poplar, which was greater than the southern pine. From greatest to least statistically significant difference, the CLST6 was greater than the southern pine, which could be equal to or greater than CLST12. For the rolling shear modulus, the southern pine and soft maple had an equal statistically significant difference and greater statistically significant difference than the yellow-poplar. There was no statistically significant difference between the southern pine and CLST.
- The southern pine samples had a greater average rolling shear strength and modulus when compared to Ehrhart and Brandner (2018) pine and Li et. (2019) and Li (2017) radiata pine. The tested yellow-poplar and soft maple were compared against the Ehrhart and Brandner (2018) and Wang et. al (2017) poplar average values. The yellow-poplar and soft maple achieved greater average rolling shear strength compared to the published poplar values. The soft maple achieved the greatest average rolling shear strength in the compared group.
- The continual research and data collection of the material properties of CLT could and will push the CLT market to be further integrated into the current mass timber and building construction industry. The data collected from this study could help CLT manufacturers with expanding their product range, as well as provide insight into future CLT possibilities.

C. Limitations of Work

- There are limited adhesives that can be strong enough and market available to bond the metal plate and wood sample together, especially for vertical shear applications. The original adhesive to be used was hot glue, but was not used because it was not strong enough to bond the steel plate and wood sample together and produced a 100% adhesive failure. Finding a stronger adhesive is especially important when testing stronger species.
- The adhesive required a cure and press time of 24 hours. This restricted how many samples can be tested each week. In addition, the process of cleaning each metal plate took time because each plate is heated to 500-600° to scrape off the remaining adhesive. The metal plates needed to cool off before a new sample can be made.
- The intended CLST parameter was to reduce the sample's surface area by 5%. A 5% surface area reduction on the sample with a 16d nail required 85 nail holes. This proved unrealistic when compared to day-to-day construction practices.
- Bolt holes were intended to be part of the CLST study; however, adhesive and curing issues arose because of the irregular spread of the adhesive, thus producing mostly glue failures when tested.

D. Recommendations for Future Work

- Expand species selection to include more domestic hardwood species. A wider range of hardwood species, such as, Ash, Birch, Cherry, and Hickory should be studied. This does not only expand the information for rolling shear properties, but it also provides more options for hybrid CLTs.

- Increasing the sample size for each tested material would provide a more accurate representation of rolling shear properties across each species.
- Additional CLST defects, like bolt holes and notches, should be tested. Bolt holes and notches are prevalent in construction job sites. The tested CLST samples were mostly clear wood. It would be beneficial if more CLST samples contained knots and other natural defects.
- Discover better adhesives to bond the metal plates to wood samples. Testing stronger hardwood species could result in multiple glue failures, due to a lower adhesive strength compared to the wood material strength.

Reference

Adhikari, S., Quesada, H., Bond, B. and Hammett, T. 2020. Potential of Hardwood Lumber in Cross Laminated Timber in North America: A CLT Manufacturer's Perspective. *Mass Timber Construction Journal* 3(1): 1-9.

Aicher, S., Hirsch, M., and Christian, Z. 2016a. Hybrid cross-laminated timber plates with beech wood cross-layers. *Construction and Building Materials* 124: 1007-1018.

Aicher, S., Christian, Z., and Hirsch, M. 2016b. Rolling shear modulus and strength of beech wood laminations. *Holzforschung* 70(8): 773-781.

American National Standards Institute/APA – The Engineered Wood Association (ANSI/APA). (2020). "Standard for Performance-Rated Cross-Laminated Timber." PRG 320, APA, Tacoma, Washington.

American Society for Testing and Materials (ASTM). 2006. Standard Test Methods for Structural Panels in Planar Shear (Rolling Shear). D2718-00, West Conshohocken, Pennsylvania.

American Society for Testing and Materials (ASTM). 2010. Standard Practice for Sampling and Data-Analysis for Structural Wood and Wood-Based Products. D2915-10, West Conshohocken, Pennsylvania.

American Society for Testing and Materials (ASTM). 2017. Standard Test Methods for Density and Specific Gravity (Relative Density) of Wood and Wood-Based Materials. D2395-17, West Conshohocken, Pennsylvania.

American Society for Testing and Materials (ASTM). 2020. Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Based Materials. D4442-20, West Conshohocken, Pennsylvania.

American Wood Council (AWC). 2018. National Design Specification (NDS) Supplement: Design Values for Wood Construction. Leesburg, Virginia.

Ansen, M.J.P., Fabozzi, F.J., and Jones, F.J. 2010. The Handbook of Traditional and Alternative Investment Vehicles: Investment Characteristics and Strategies. John Wiley & Sons, Hoboken, New Jersey.

APA (The Engineered Wood Association). 2020. *Cross Laminated Timber (CLT)*.

The Architect's Newspaper. 2020, February. Mapping the Industry. *The Architect's Newspaper* 18(2): 22-25. (A)

Bahmanzad, A., Clouston, P., Arwade, S, and Schreyer, A. 2020. Shear Properties of Eastern Hemlock with Respect to Fiber Orientation for Use in Cross Laminated Timber. *Journal of Materials in Civil Engineering* 32(7): 04020165.

The Beck Group (BECK). 2018. Mass Timber Market Analysis. The Beck Group, Forest Products Planning & Consulting, Portland, Oregon.

Bodig, J. and Jayne, B. 1982. Mechanics of Wood and Wood Composites. Krieger Publishing Company, Malabar, Florida.

Breneman, S., Timmers, M., and Richardson, D., 2019. Tall Wood Buildings and the 2021 IBC: Up to 18 Stories of Mass Timber. American Wood Council, Leesburg, Virginia.

Center for Wood Anatomy Research. n.d. technology transfer fact sheet Acer spp. USDA Forest Service, Madison, Wisconsin.

Crespell, P. and Gagnon, S. 2010. Cross Laminated Timber: A Primer. FPInnovations, Pointe-Claire, Quebec City, Canada.

Crespell, P. and Gaston, C. 2011. The Value Proposition for Cross-Laminated Timber. FPInnovations, Pointe-Claire, Quebec City, Canada.

Ehrhart, T. and Brandner, R. 2018. Rolling shear: Test configurations and properties of some European soft- and hardwood species. *Engineering Structures* 172: 554-572.

Energias Market Research. 2018. Global Cross Laminated Timber (CLT) Market Outlook, Trend and Opportunity Analysis, Competitive Insights, Actionable Segmentation & Forecast 2024. Energias Market Research Pvt. Ltd., Buffalo, New York.

European Committee for Standardization (CEN). 2012. Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties. EN 408:2010+A1: 2012, Avenue Marnix 17, Brussels, Belgium

Franzoni, L., Lebée, A., Lyon, F., and Foret, G. 2016. Influence of orientation and number of layers on the elastic response and failure modes on CLT floors: modeling and parameter studies. *European Journal of Wood and Wood Products* 74: 671-684.

Hindman, D. and Bouldin, J. 2014. Mechanical Properties of Southern Pine Cross-Laminated Timber. *Journal of Materials in Civil Engineering* 27(9): 04014251

International Code Council (ICC). 2020-A. AWC and ICC Release Mass Timber Buildings and the IBC. International Code Council, Washington, District of Columbia.

International Code Council (ICC). 2020-B. Mass Timber Buildings and the IBC. International Code Council, Washington, District of Columbia.

Joint Standards Australia/Standards New Zealand Committee (AS/NZS). 2012. Plywood—Structural—Part 1: Determination of structural properties—Test methods. AS/NZS 2269.1:2012, Sydney, Australia and Wellington, New Zealand.

Karacabeyli, E. and Douglas, B. 2013. CLT handbook: cross-laminated timber. FPInnovations, Pointe-Claire, Quebec City, Canada.

Koch, P. 1972. Utilization of the Southern Pines – Volume 1. U.S. Department of Agriculture-Forest Service, Asheville, North Carolina.

Li, M. 2017. Evaluating rolling shear strength properties of cross-laminated timber by short-span bending tests and modified planar shear tests. *Journal of Wood Science* 63: 331-337.

Li, M., Dong, W., and Hyungsuk, L. 2019. Influence of Lamination Aspect Ratios and Test Methods on Rolling Shear Strength Evaluation of Cross-Laminated Timber. *Journal of Materials in Civil Engineering* 31(12): 04019310.

Loctite. 2019. PL® Premium Fast Grab Construction Adhesive Technical Data Sheet.

Mohamadzadeh, M. and Hindman, D. 2015. Mechanical Performance of Yellow-Poplar Cross Laminated Timber. The Charles E. Via, Jr. Department of Civil and Environmental Engineering, Virginia Polytechnic Institute and State University Blacksburg, Virginia.

ReThink Wood. 2020. Mass Timber in North America: Expanding the Possibilities of Wood Building Design. Think Wood, West Linn, Oregon.

Rose, A.K. 2016. Forests of Virginia, 2014. Resource Update FS-94. U.S. Department of Agriculture Forest Service, Southern Research Station, Asheville, North Carolina.

Rose, C. M., Bergsagel, D., Dufresne, T., Unubreme, E., Lyu, T., Duffour, P., and Stegemann, J. 2018. Cross-Laminated Secondary Timber: Experimental Testing and Modelling the Effect of Defects and Reduced Feedstock Properties. *Sustainability* 10(11): 4118.

Sandoli, A. and Calderoni, B. 2020. The Rolling Shear Influence on the Out-of-Plane Behavior of CLT Panels: A Comparative Analysis. *Buildings* 10(3): 42

Structurlam. 2019. Structurlam Selects Conway, Arkansas, for Its First U.S. Plant. Structurlam Mass Timber Corporation, Penticton, British Columbia, Canada.

Thomas, R. E. and Buehlmann, U. 2017. Using Low-Grade Hardwoods for CLT Production: A Yield Analysis. *International Scientific Conference on Hardwood Processing* 199-206.

Wang, Z., Dong, W., Wang, Z., Zhou, J., and Gong, M. 2017. Effect of macro characteristics on rolling shear properties of fast-growing poplar wood laminations. *Wood Research* 63(2): 227-238.

Zhou, Q., Gong, M., Chui, Y., and Mohammad, M. 2014. Measurement of Rolling Shear Modulus and Strength of Cross-Laminated Timber using Bending and Two-plate Shear Tests. *Wood and Fiber Science* 46(2): 259-269.

Appendix

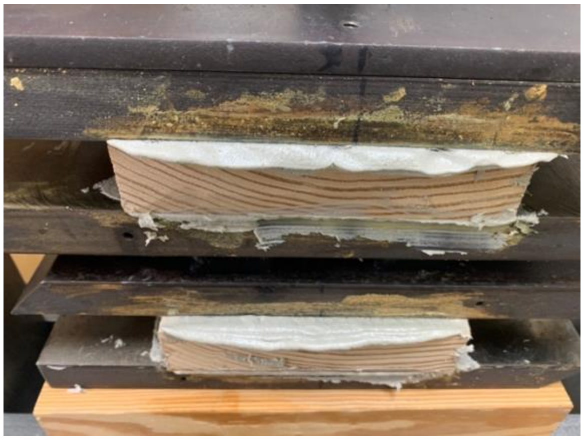
A. Methodology Pictures

Steel Plates

Adhesive

Hydraulic Jack

Samples under Pressure



MTS Machine Set-up

Moisture Content and Specific Gravity Samples

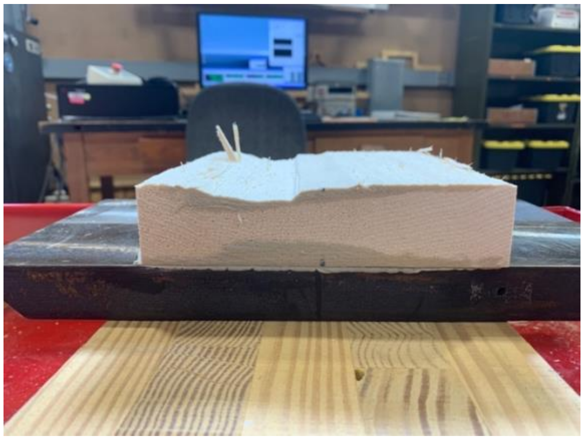
B. Sample Failure Pictures

1. Yellow-poplar

YP 1

YP 2

YP 3



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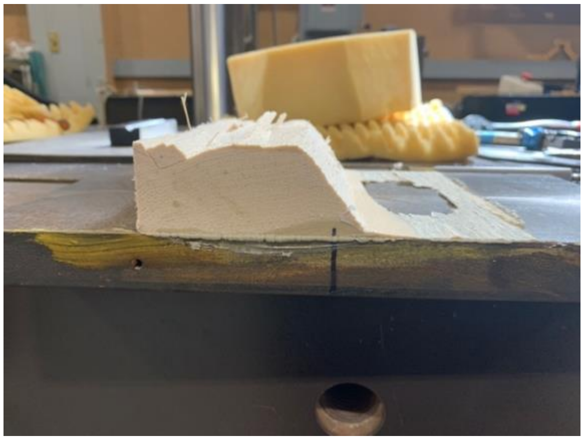

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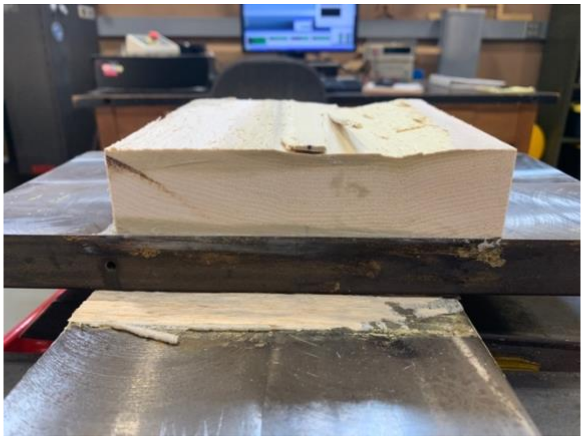

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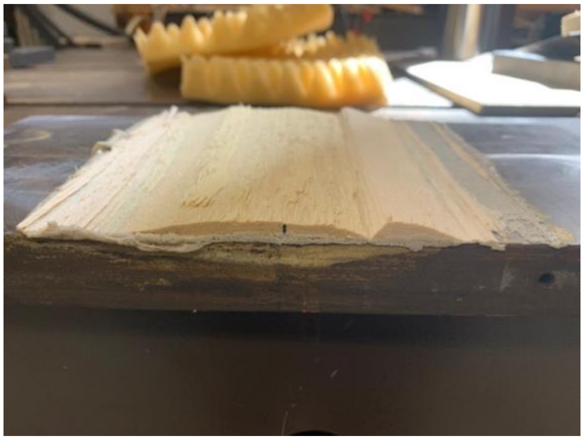

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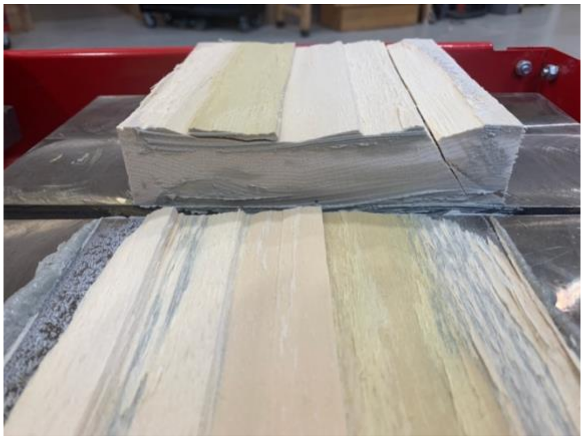

YP 8

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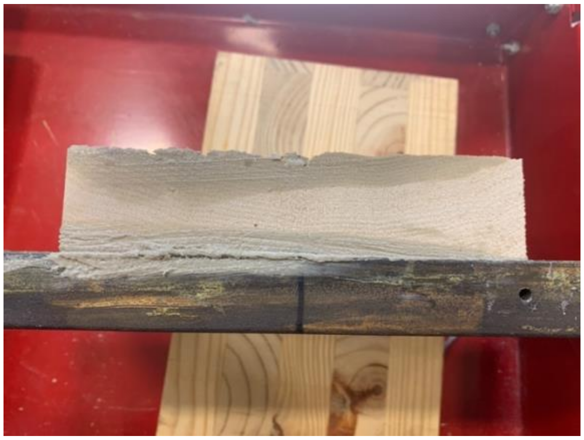

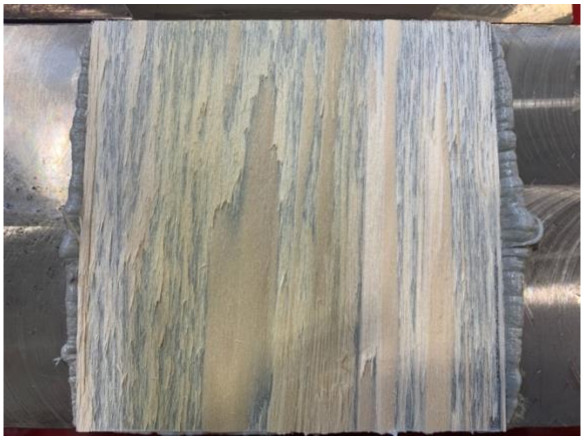

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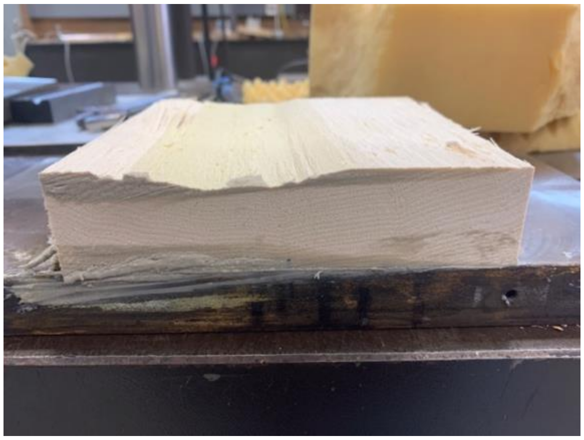

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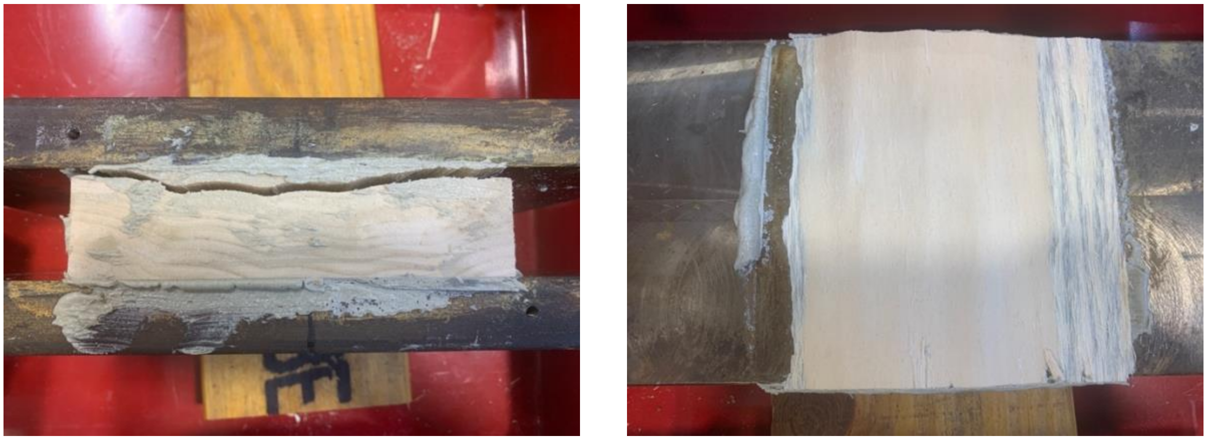
YP 12

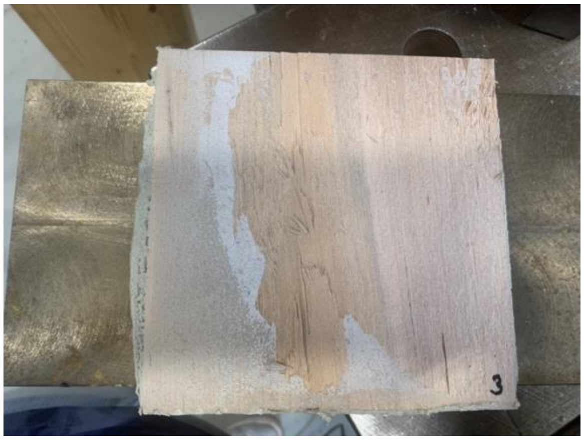


2. Soft Maple

SM 1

SM 2

SM 3



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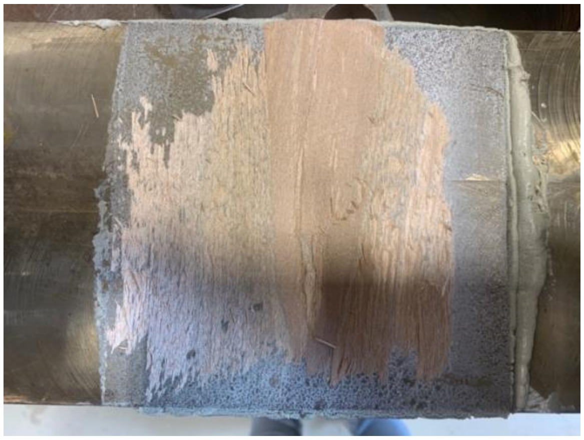

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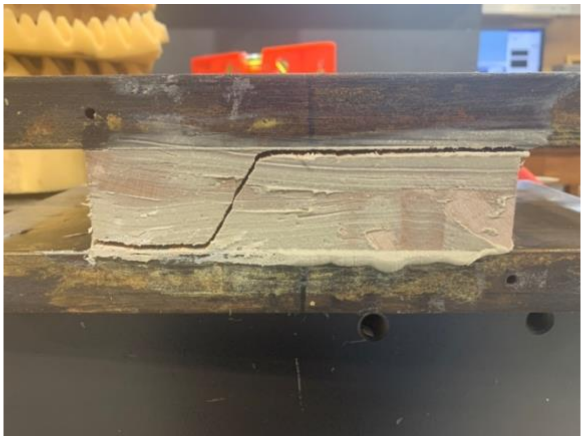

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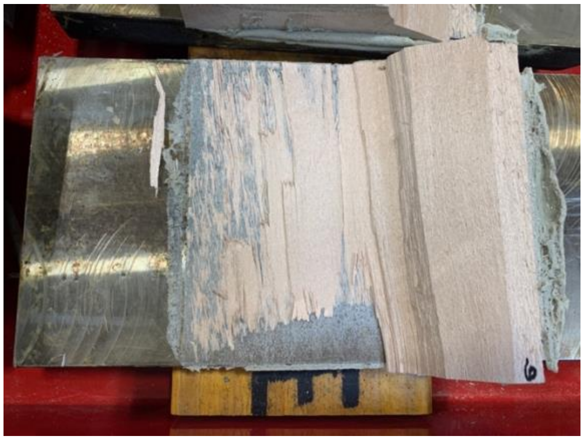

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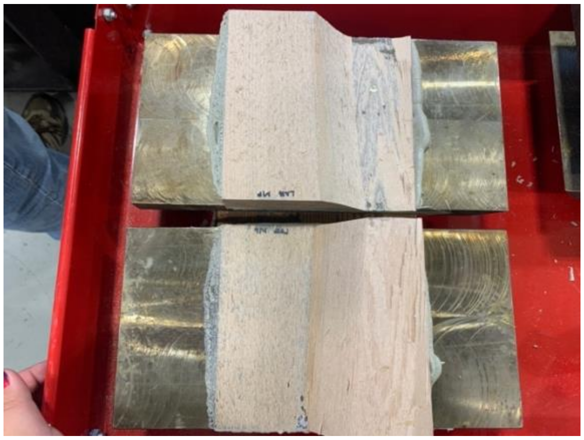

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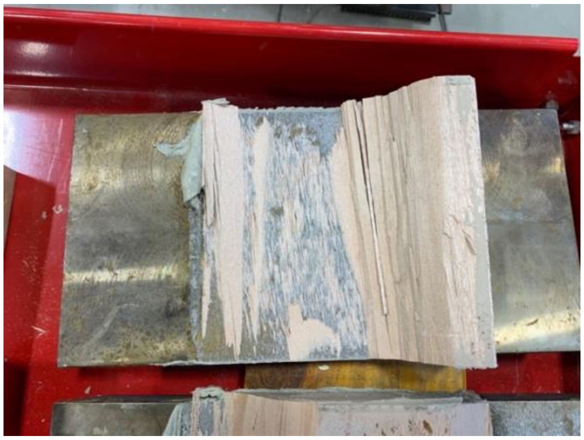

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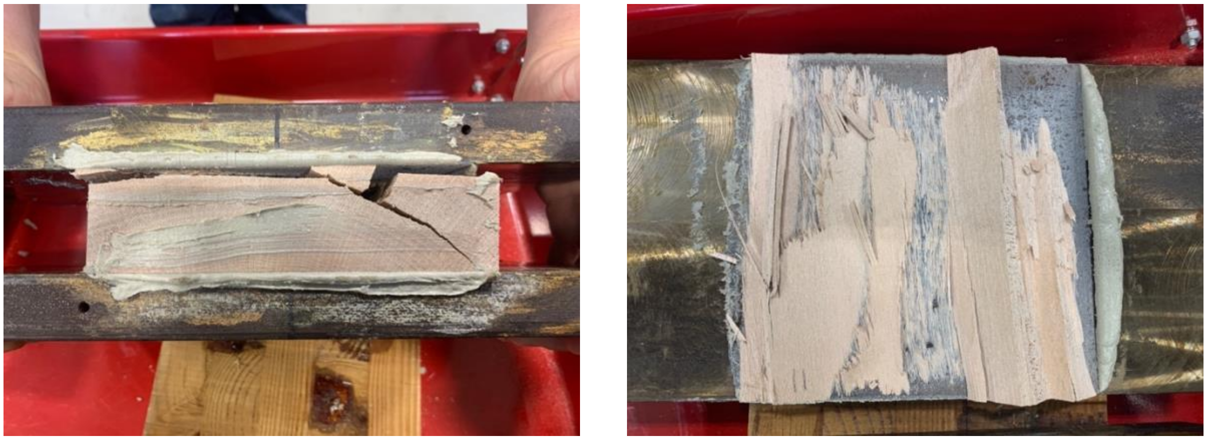
SM 10

SM 11



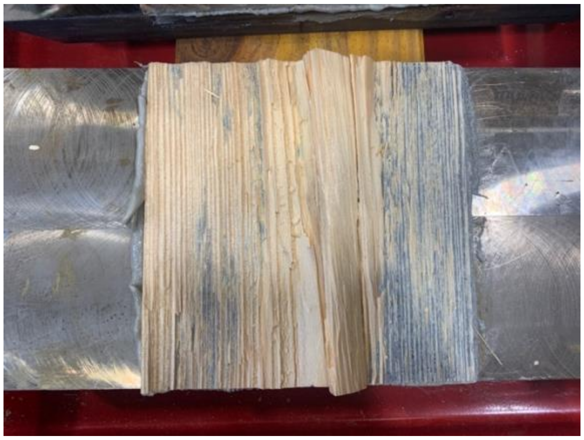
SM 12

3. Southern Pine

SP 1

SP 2

SP 3



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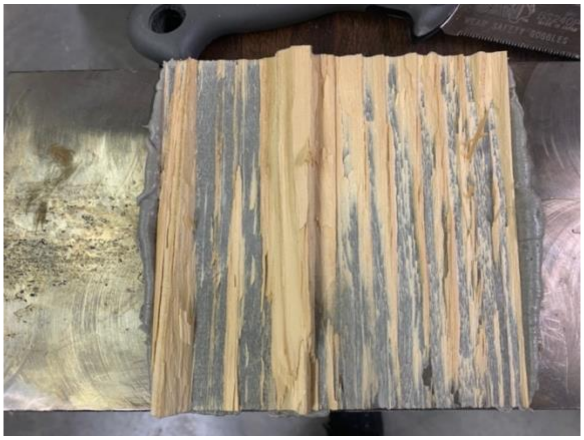

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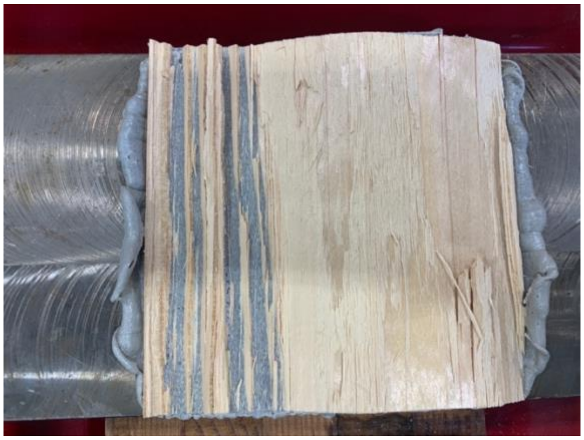
SP 7



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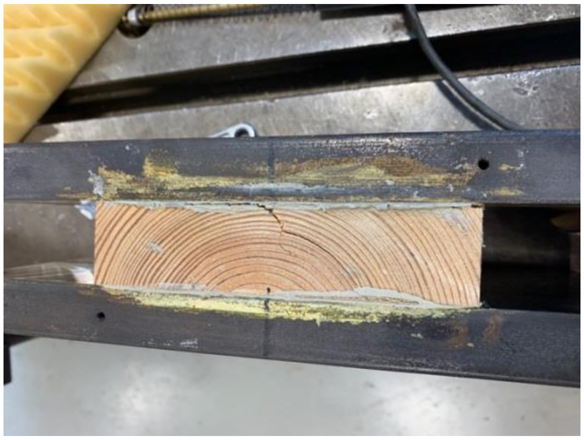

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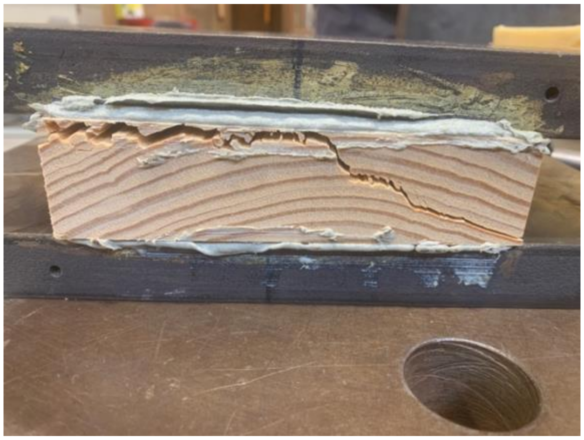

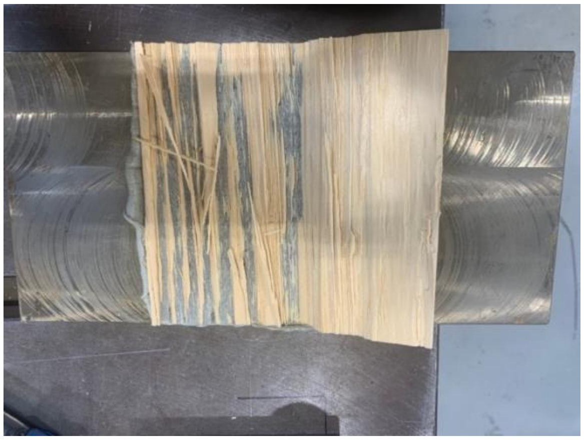

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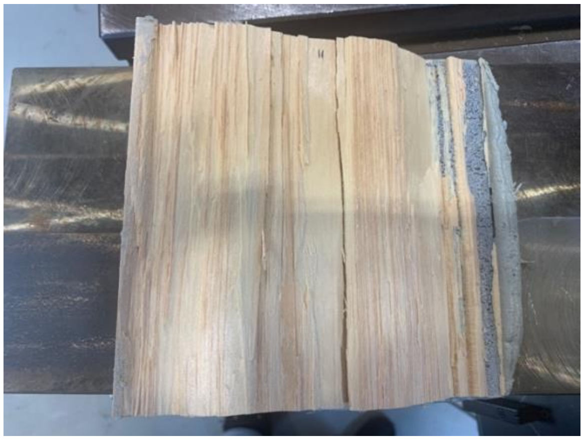

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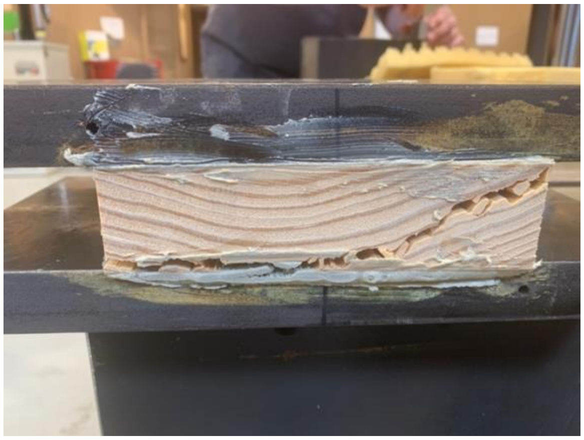
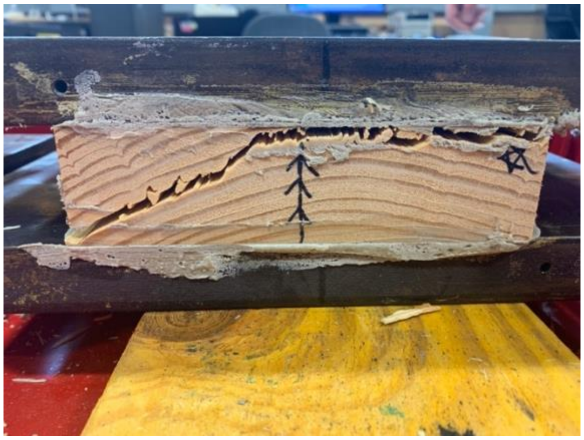
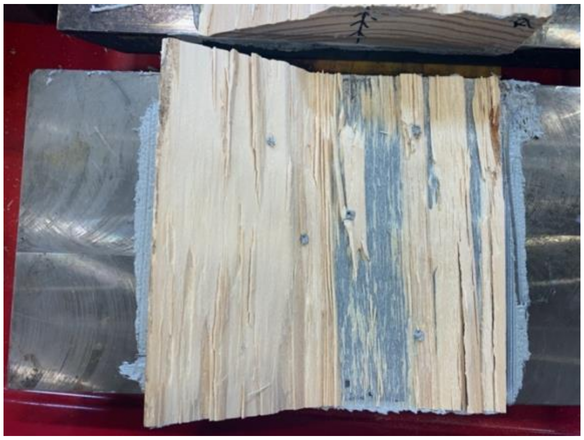


4. CLST – Southern Pine

N1





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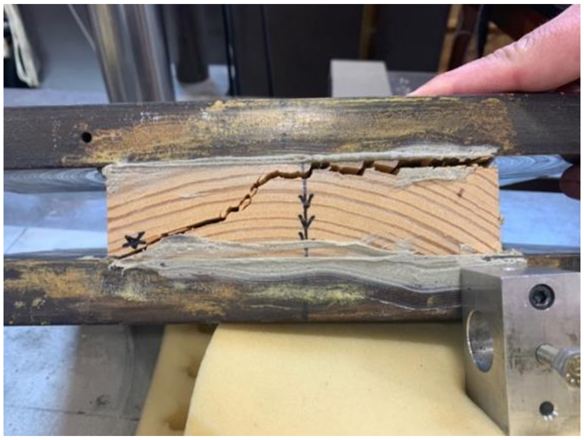

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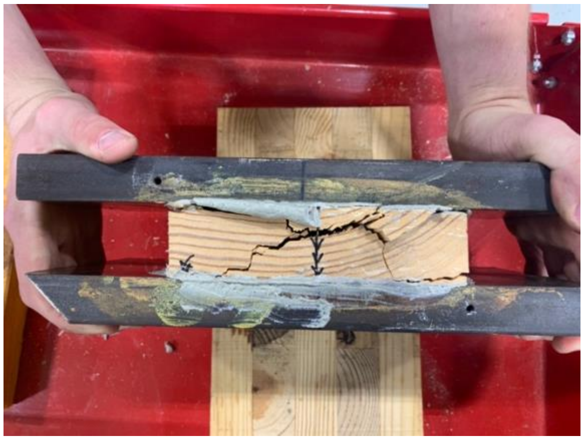
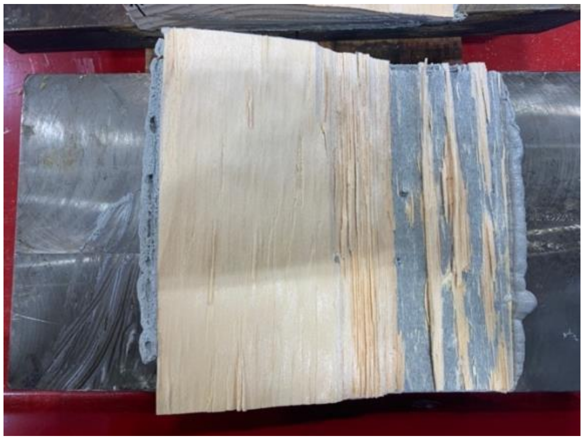


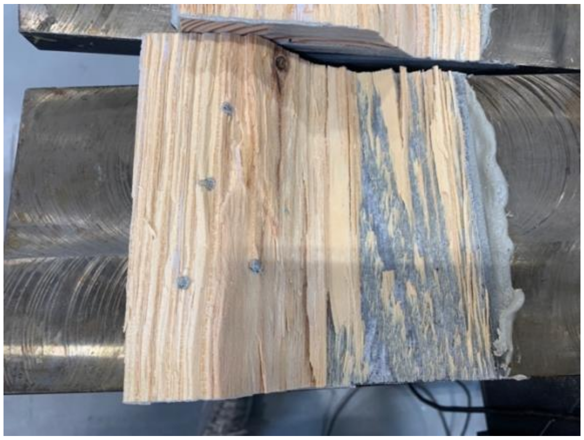
N4

N5



N6


N7

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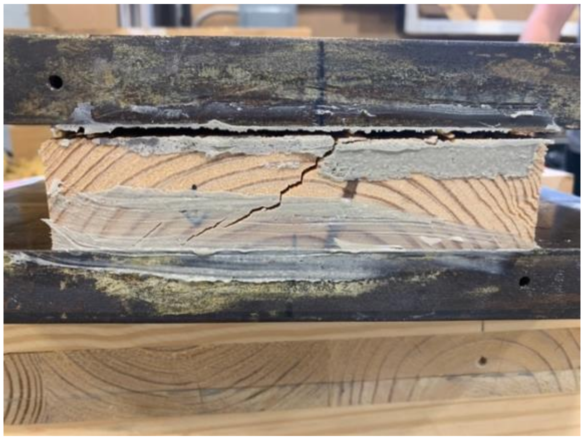
N9



N10

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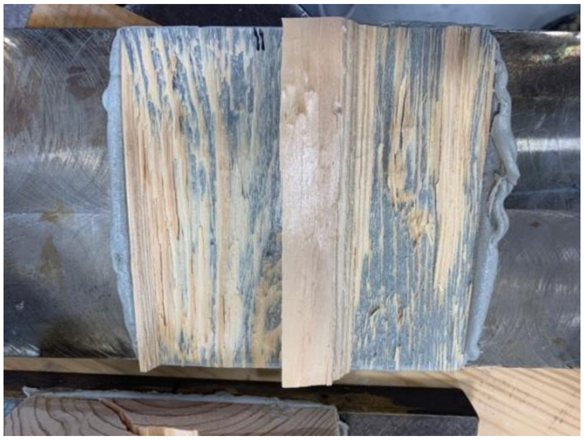

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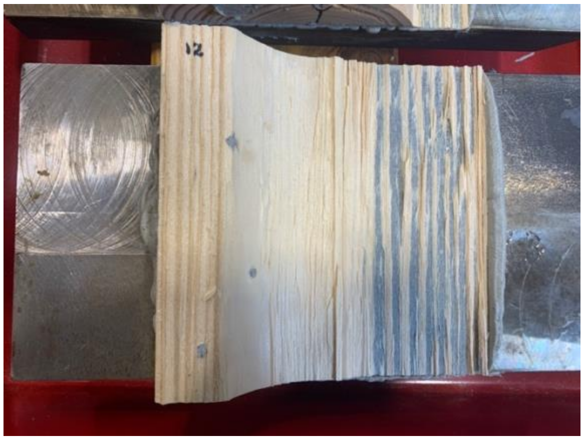

C. Summary of Data Sheets

1. Two-Plate Shear Test Data Sheets

Table 10. Yellow-poplar Two-Plate Shear Test Data

Species	Sample No.	Peak Load (lbf)	Shear Stress (psi)	Shear Stress (N/mm2)	Slope of force-deformation	Modulus of Rigidity (psi)	Modulus of Rigidity (N/mm2)
Yellow-poplar	1	19,780	549	3.79	948,444	36225	249.76
	2	14,743	410	2.82	443,349	16933	116.75
	3	14,878	413	2.85	437,410	16707	115.19
	4	14,360	399	2.75	678,065	25898	178.56
	5	15,739	437	3.01	524,392	20029	138.09
	6	15,565	432	2.98	431,427	16478	113.61
	7	14,237	395	2.73	492,477	18810	129.69
	8	16,123	448	3.09	653,614	24964	172.12
	9	11,866	330	2.27	419,670	16029	110.52
	10	15,532	431	2.97	519,943	19859	136.92
	11	21,961	610	4.21	708,476	27060	186.57
	12	20,416	567	3.91	726,118	27734	191.22

Table 11. Soft Maple Two-Plate Shear Test Data

Species	Sample No.	Peak Load (lbf)	Shear Stress (psi)	Shear Stress (N/mm2)	Slope of force-deformation	Modulus of Rigidity (psi)	Modulus of Rigidity (N/mm2)
Soft Maple	1	30,491	847	5.84	809,119	30904	213.07
	2	27,565	766	5.28	744,304	28428	196.01
	3	28,608	795	5.48	786,422	30037	207.10
	4	31,728	881	6.08	1,291,637	49333	340.14
	5	30,284	841	5.80	2,095,130	80022	551.73
	6	28,316	787	5.42	635,175	24260	167.27
	7	38,938	1082	7.46	891,597	34054	234.79
	8	29,831	829	5.71	909,728	34747	239.57
	9	30,612	850	5.86	1,060,771	40516	279.34
	10	38,496	1069	7.37	1,012,120	38657	266.53
	11	30,612	850	5.86	1,504,582	57467	396.22
	12	25,861	718	4.95	898,894	34333	236.72

Table 12. Southern Pine Two-Plate Shear Test Data

Species	Sample No.	Peak Load (lbf)	Shear Stress (psi)	Shear Stress (N/mm2)	Slope of force-deformation	Modulus of Rigidity (psi)	Modulus of Rigidity (N/mm2)
Southern Pine	1	11,205	311	2.15	848,417	32405	223.42
	2	10,606	295	2.03	1,013,071	38694	266.78
	3	13,563	377	2.60	1,510,090	57677	397.67
	4	13,154	365	2.52	2,751,763	105102	724.65
	5	11,583	322	2.22	946,964	36169	249.37
	6	12,121	337	2.32	1,218,496	46540	320.88
	7	11,497	319	2.20	474,003	18104	124.82
	8	15,328	426	2.94	886,453	33858	233.44
	9	13,107	364	2.51	1,823,062	69631	480.09
	10	14,644	407	2.80	423,702	16183	111.58
	11	11,595	322	2.22	287,873	10995	75.81
	12	18,845	523	3.61	456,064	17419	120.10

Table 13. CLST Two-Plate Shear Test Data

Species	Sample No.	Peak Load (lbf)	Shear Stress (psi)	Shear Stress (N/mm2)	Slope of force-deformation	Modulus of Rigidity (psi)	Modulus of Rigidity (N/mm2)
CLST							
Nail (6 Holes)	1	19,974	555	3.83	679,138	25939	178.85
	2	14,816	412	2.84	607,544	23205	159.99
	3	20,711	575	3.97	527,389	20143	138.88
	4	17,892	497	3.43	505,180	19295	133.03
	5	15,949	443	3.05	529,263	20215	139.38
	6	16,062	446	3.08	452,821	17295	119.25
Nail (12 Holes)	7	14,574	405	2.79	1,251,367	47795	329.54
	8	14,937	415	2.86	1,029,977	39339	271.24
	9	14,476	402	2.77	2,028,919	77493	534.30
	10	13,161	366	2.52	723,399	27630	190.50
	11	14,169	394	2.71	1,353,743	51705	356.50
	12	11,605	322	2.22	1,184,082	45225	311.82

2. Moisture Content and Specific Gravity Data Sheets

Table 14. Yellow-poplar MC/SG Data

Species	Sample No.	Original Mass (g)	Oven-Dry Mass (g)	**Moisture Content (%)**	Oven-Dry Volume	**Specific Gravity**
Yellow-poplar	1	1.63	1.52	7%	3.2	0.48
	2	4.93	4.62	7%	12.1	0.38
	3	4.69	4.41	6%	10.9	0.40
	4	3.77	3.52	7%	10.3	0.34
	5	12.36	11.63	6%	23.9	0.49
	6	10.64	10.03	6%	25.4	0.39
	7	10.15	9.58	6%	21.2	0.45
	8	6.95	6.54	6%	17.9	0.37
	9	10	9.43	6%	22.7	0.42
	10	10.89	10.24	6%	23.4	0.44
	11	13.78	12.89	7%	23.8	0.54
	12	10.48	9.81	7%	19.8	0.50
Average				**7%**		**0.43**

Table 15. Soft Maple MC/SG Data

Species	Sample No.	Original Mass (g)	Oven-Dry Mass (g)	**Moisture Content (%)**	Oven-Dry Volume	**Specific Gravity**
Soft Maple	1	12.84	12.03	7%	20.5	0.59
	2	6.84	6.42	7%	11.0	0.58
	3	3.77	3.53	7%	6.0	0.59
	4	5.22	4.91	6%	7.8	0.63
	5	7.48	7.00	7%	12.6	0.56
	6	7.92	7.40	7%	12.7	0.58
	7	13.61	12.65	8%	22.8	0.55
	8	9.86	9.23	7%	16.0	0.58
	9	7.45	6.96	7%	11.9	0.58
	10	5.92	5.50	8%	11.3	0.49
	11	7.11	6.65	7%	11.6	0.57
	12	5.19	4.86	7%	8.6	0.57
Average				**7%**		**0.57**

Table 16. Southern Pine MC/SG Data

Species	Sample No.	Original Mass (g)	Oven-Dry Mass (g)	**Moisture Content (%)**	Oven-Dry Volume	**Specific Gravity**
Southern Pine	1	3.48	3.23	8%	7.3	0.44
	2	6.69	6.32	6%	17.8	0.36
	3	6.01	5.63	7%	12.3	0.46
	4	8.02	7.53	7%	13.7	0.55
	5	9.61	9	7%	18.5	0.49
	6	6.82	6.39	7%	12	0.53
	7	8.41	7.8	8%	13.3	0.59
	8	5.16	4.84	7%	7.5	0.65
	9	10.31	9.66	7%	17.7	0.55
	10	7.84	7.31	7%	13.8	0.53
	11	9.72	9.02	8%	22.5	0.40
	12	8.49	7.91	7%	13.5	0.59
Average				**7%**		**0.51**

Table 17. CLST MC/SG Data

Species	Sample No.	Original Mass (g)	Oven-Dry Mass (g)	**Moisture Content (%)**	Oven-Dry Volume	**Specific Gravity**
CLST	1	7.32	6.82	7%	12.0	0.57
	2	8.6	8	8%	18.3	0.44
	3	5.44	5.05	8%	9.9	0.51
	4	7.66	7.12	8%	11.9	0.60
	5	5.07	4.7	8%	9.3	0.51
	6	2.72	2.52	8%	5.2	0.48
	7	3.57	3.29	9%	5.8	0.57
	8	8.48	7.81	9%	15.0	0.52
	9	5.13	4.63	11%	8.2	0.56
	10	6.16	5.64	9%	10.6	0.53
	11	5.39	4.93	9%	13.4	0.37
	12	11.45	10.63	8%	21.1	0.50
Average				**8%**		**0.51**

3. Anova: Single Factor

Rolling Shear Strength

Table 18. Anova SoftwoodvHardwoods

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Yellow-poplar	12	37.3850731	3.115422762	0.31574079		
Soft Maple	12	71.1197861	5.926648841	0.57774077		
Southern Pine	12	30.11639	2.509699168	0.19499611		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	79.7817529	2	39.89087643	109.944957	2.55335E-15	3.28491765
Within Groups	11.9732543	33	0.362825887			
Total	91.7550071	35				

Table 19. Anova SPvCLST

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Southern Pine	12	30.11639	2.50969917	0.19499611		
CLST	12	36.0682542	3.00568785	0.260327403		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.476029	1	1.47602866	6.483428216	0.01840385	4.300949502
Within Groups	5.008559	22	0.22766176			
Total	6.484587	23				

Table 20. Anova SPvCLSTs

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Southern Pine	12	30.11639	2.509699168	0.19499611		
CLST (6 Holes)	6	20.1871247	3.364520785	0.2071437		
CLST (12 Holes)	6	15.8811295	2.646854921	0.05655001		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3.02116154	2	1.510580768	9.15919621	0.001380534	3.46680011
Within Groups	3.46342576	21	0.164925036			
Total	6.4845873	23				

Rolling Shear Modulus

Table 21. Anova SoftwoodvHardwoods Modulus

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Yellow-poplar	12	1839.01478	153.251231	1826.65977		
Soft Maple	12	3328.49955	277.374963	11470.1443		
Southern Pine	12	3328.62598	277.385498	34488.6785		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	123264.068	2	61632.034	3.86929444	0.0309301	3.28491765
Within Groups	525640.308	33	15928.4942			
Total	648904.376	35				

Table 22. Anova SPvCLST Modulus

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Southern Pine	12	3328.62598	277.385498	34488.6785		
CLST	12	2863.26579	238.605482	15752.2014		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	9023.33778	1	9023.33778	0.35920301	0.55507175	4.3009495
Within Groups	552649.68	22	25120.44			
Total	561673.017	23				

Table 23. Anova SPvCLSTs

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Southern Pine	12	3328.62598	277.385498	34488.6785		
CLST (6 Holes)	6	869.378528	144.896421	449.12365		
CLST (12 Holes)	6	1993.88726	332.314543	13130.3881		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	114399.995	2	57199.9974	2.68560786	0.09150314	3.46680011
Within Groups	447273.023	21	21298.7154			
Total	561673.017	23				