Mechanical Properties of Hybrid Softwood & Hardwood Cross-Laminated Timbers

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ABSTRACT

Cross Laminated Timber (CLT) is an engineered wood product consisting of an odd number (three to seven) of lumber layers, which are glued in an orientation of each layer perpendicular to other. After its introduction, CLT has been widely adopted in Europe since 1990s and has quickly become popular in the US in the last decade as a sustainable and cost-effective alternative to traditional building materials such as concrete and steel. The first version of PRG-320 was published in 2012 for the US and Canada to help designers and builders understand the properties of CLT and use it safely. The current version of PRG-320 only allows the use of softwood species for commercial production of cross-laminated timber (CLT) in the US. However, recent studies have investigated the possibility of using hardwood species for CLT and have shown promising results. In parallel to this, the next version of PRG-320 is being revised to include hardwood species. The inclusion of hardwood species is an effort to increase the value of underutilized wood species in the United States. This study presents the results from testing of three-layer and five-layer CLTs manufactured using yellow-poplar (*Liriodendron tulipifera*) as hardwood and southern pine (*Pinus spp.*) as softwood in different layers, defined as hybrid CLT. The purpose of this project was to compare the bending and shear properties in the major axis direction of hybrid CLT panels obtained from five-point, four-point, and three-point bending tests with the current ANSI/APA PRG-320 values, and also to evaluate their resistance to shear by compression loading and delamination according to ANSI A190.1 and AITC T110 standards, respectively. The bending strength and bending stiffness, except for some individual groups, as well as the shear strength and shear stiffness values exceeded the Grade V3 from PRG-320. However, the wood failure in resistance to shear by compression loading and face delamination in resistance to delamination were lower than the required values in the standards. The test results demonstrated that CLT groups consisting of yellow-poplar has strength and stiffness properties comparable to those consisting of southern pine. This suggests that yellow-poplar could be a promising alternative species to softwood in the production of CLTs.

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GENERAL AUDIENCE ABSTRACT

Cross Laminated Timber (CLT) is a wood composite material made of lumbers that are oriented perpendicular to each other and glued together. CLT has quickly gained popularity in Europe since its introduction in the early 1990s and has become an attractive material in the United States in the last decade due to its sustainability and cost-effectiveness compared to traditional building materials. As a standardization effort, the first standard for CLT, PRG-320, was published for both the US and Canada as a guide for designers and builders to understand the properties of CLT and has allowed only softwood for the commercial production of CLT in the US since its initial version. The promising results of research on the use of hardwoods in CLT production have enabled efforts to include hardwood species in the next version of the PRG-320. This study presents the results from testing of three-layer and five-layer CLTs manufactured using yellow-poplar as hardwood and southern pine as softwood in different layers, defined as hybrid CLT. The purpose of this project was to compare the bending and shear properties in the major axis direction of hybrid CLT beams obtained from five-point, four-point, and three-point bending tests with current industry guidelines, and also to evaluate their resistance to shear by compression loading and delamination. The test results indicated that yellow-poplar possesses similar strength and stiffness properties to southern pine, indicating that it has potential to be used as an alternative to softwood species in CLT production.

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1. INTRODUCTION

Invariably, materials have had great significance throughout human history, so much so that prehistoric periods such as the stone age, bronze age, and iron age were named after the predominant materials used by civilizations during those times. Throughout history, wood is another material that has played a consistently important role in people's interactions with nature since prehistoric times. It can even be said that working wood is one of the activities that has shaped the minds of humans and improved the skills of their hands. Over time, the unique nature and properties of wood have become better understood through experience, and, more recently, systematic research. With recent developments, wood has become a modern industrial and engineering material, and the demand for wood has gradually increased in construction.

Wood has been a versatile and useful building material for thousands of years and is still ubiquitously used worldwide more than any other building material (Perlin, 2005). However, the size and strength of traditional sawn timber is limited by the length or width of the tree from which it is cut. To overcome these limitations, engineered wood products (EWP) have been developed (Fig. 1). EWPs are mainly manufactured by transforming logs into lumber, veneers, strands, chips, or wood fibers, followed by gluing them with an adhesive under heat and pressure or securing them mechanically with fasteners to obtain a desired structural product (Lam & Prion, 2003). These production methods allow EWP boards to be produced in various sizes. Overcoming the size restriction has enabled professionals to design EWPs that can be used in various structural applications, including commercial and residential buildings.

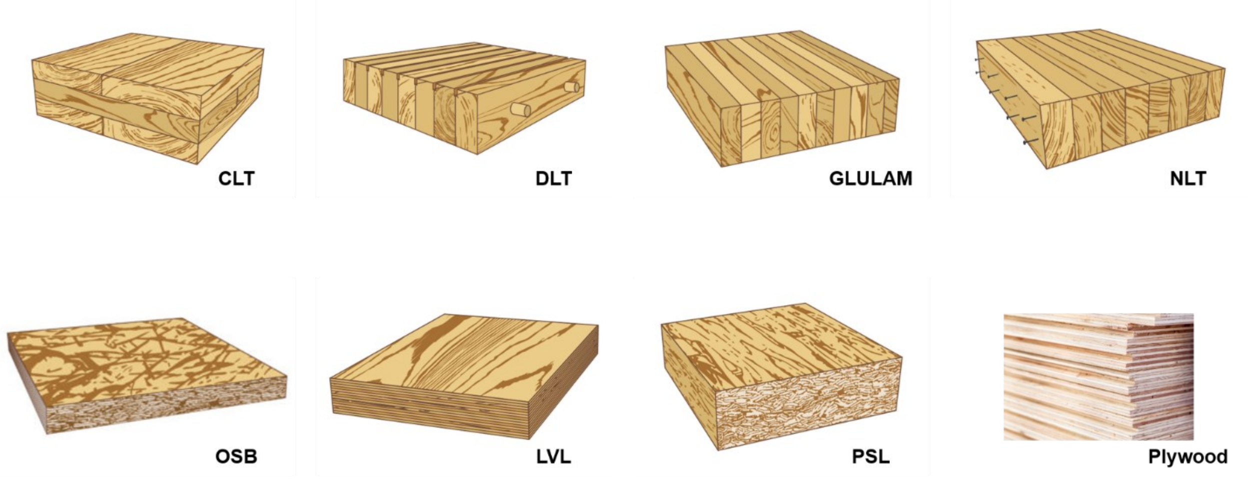


Figure 1. *Types of EWPs*

In recent years, mass timber has gained importance in construction due to its reduced environmental impact compared to steel and concrete, and become a strong competitor thanks to the developments in the production methods of EWPs. Mass timber can be defined as a type of construction system that utilizes a class of engineered wood products, including cross-laminated timber (CLT), glue-laminated timber (Glulam), dowel-laminated timber (DLT), and nail-laminated timber (NLT) rather than traditional dimension lumber (Kremer & Symmons, 2015). Due to this fact, the inherent structural properties of wood can be optimized, allowing mass timber elements to be used for walls, floors, and roofs in larger and taller structural applications (Smith et al., 2018).

Cross Laminated Timber (CLT), as one of the most important members of mass timber construction, has become the subject of interest in the last two decades due to its advantages, including fast construction, high strength-to-mass ratio, cost-effectiveness among other mass timber construction members, seismic and acoustic performance, energy efficiency, fire protection, and environmental advantages such as a lower carbon footprint (carbon sequestration) and less energy requirement during manufacturing process (Brandner et al., 2016). The American National Standards Institute (ANSI) defines CLT as "*a prefabricated engineered wood product made of at least three orthogonal layers of graded sawn lumber or structural composite lumber (SCL) that are laminated by gluing with structural adhesives*" (ANSI/APA, 2019). CLT panels are prefabricated in a variety number of laminations (Fig. 2) with the thickness of each lamination ranging from 1.875 to 20 in. (ANSI/APA, 2019) and assembled on-site, which enables faster construction (Brandner et al., 2016) and on-site labor (Schmidt & Griffin, 2013).

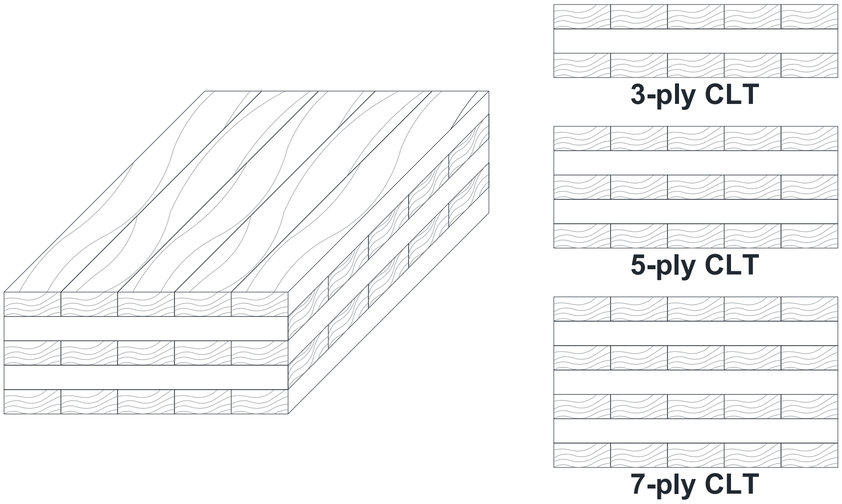


Figure 2. *CLT plate with different layer options*

Canada was the first country in North America to adopt CLT by publishing the Canadian version of the *CLT Handbook* in 2011 (Gagnon & Pirvu, 2011). This handbook was used as a basis for preparing the US version of the *CLT Handbook* in 2013 (Karacabeyli & Douglas, 2013). The technical information in these handbooks led CLT to be included into the *Canadian Standard for Engineering Design in Wood* (CSA, 2016) and the *National Design Specification for Wood Construction* (NDS) (AWC, 2018) in the United States. The inclusion of CLT into the International Building Code in the US (IBC) (ICC, 2021) as three new construction types, including Type IV-A, IV-B and IV-C, has allowed design and construction community to increase the use of wood in massive form in taller and larger buildings. There are several notable tall buildings in North America including Brock Commons Tallwood House located in Vancouver, BC (Fig. 3); Carbon12 in Portland, OR; INTRO in Cleveland, OH; Ascent in Milwaukee, WI (Fig. 3); 80 M Street in Washington, DC; Apex Clean Energy in Charlottesville, VA; 11 E. Lenox in Boston, MA; Heartwood in Seattle, WA; and Minnesota Places in Portland, OR.

Figure 3. *Mass timber buildings. Brock Commons Tallwood House in Vancouver, BC (18-storey, Left), Ascent in Milwaukee, WI (25-storey, Right)*

The work on implementing CLT products and systems is relatively new in the United States and Canada. According to APA (2022), there are currently a total of six CLT manufacturers in the USA: Boise Cascade Company, IB X-Lam LLC, D.R. Johnson Wood Innovations, SmartLam LLC, Freres Lumber Co. Inc. and Vaagen Timbers LLC in comparison with Canada which has four manufacturers: Structurlam Mass Timber Corporation, Nordic Structures, Kalesnikoff Mass Timber Inc. and Element5 Limited Partnership.

The current standard for CLT production in the US is ANSI/APA PRG-320 - *Standard for Performance-rated Cross-Laminated Timber* (ANSI/APA, 2019), which includes requirements and test methods for CLTs made only of softwood species. Several studies using hardwood species in CLT production have shown promising results (Aicher et al., 2016; Hematabadi et al., 2020; Kramer et al., 2014; Mohamadzadeh & Hindman, 2015). These results indicate an opportunity for hardwoods to be used in CLT production as well as softwoods and ensure that lumbers produced from hardwood species can be used in more value-added applications. Current efforts to modify the PRG-320 standard to include hardwoods are underway.

There is still a need for more studies on the inclusion of hardwoods in the production of CLTs with softwood species. In this context, manufacturing a hybrid CLT with a softwood species whose mechanical properties are tabulated in PRG-320 and a hardwood species having inherent physical properties, which makes it suitable for CLT production will add a new perspective and opportunities for the industry.

2. GOALS and OBJECTIVES

The goal of this study is to evaluate the mechanical properties of hybrid CLT produced using various combinations of softwood and hardwood lumber. The species used in this study are yellow-poplar (*Liriodendron tulipifera*) as hardwood and southern pine species including loblolly pine (*P. taeda*), longleaf pine (*P. palustris*), shortleaf pine (*P. echinata*), and slash pine (*P. elliotii*) as softwood. The objectives of this research are;

1) To measure the strength and stiffness of both bending and shear of CLTs;
2) To measure the bond-line shear and delamination of CLTs;
3) To compare the allowable stress design values to CLT Grade V3 from PRG-320, and the bond-line shear and delamination to ANSI A190.1 and AITC T110, respectively.

3. LITERATURE REVIEW

3.1. The Classification of Engineered Wood Products

Even though the lamination of wood dates back to ancient times, the first known EWP, plywood, was developed commercially at the beginning of the 20th century (APA, 2018). Thanks to the superior performance properties of these products as well as reaching a size beyond the limit of the raw materials, wood materials have found better uses in the construction industry. EWPs that are used as construction members can be classified into two groups by their section sizes: (1) Light-frame Construction Members and (2) Mass Timber Construction Members (Table 1). Both groups have unidirectional and cross-layer construction elements, and in addition, there is composite construction element considered as both lumber and veneer/strand-based material.

Table 1. *The classification of engineered wood products*

Engineered Wood Products

Light-frame Construction Members	*Mass Timber Construction Members*
• OSB (Oriented Strand Board)	• Glulam (Glue Laminated Timber)
• LVL (Laminated Veneer Lumber)	• CLT (Cross- Laminated Timber)
• PSL (Parallel Strand Lumber)	• NLT (Nail Laminated Timber)
• Plywood	• DLT (Dowel Laminated Timber)

Light-frame construction members are a category of engineered wood products that are typically made of smaller or thinner wood particles for floor and roof systems consisting of closely-spaced and repeating framing and sheathing members attached together with fasteners (APA, 2014). In contrast to light-frame construction members, mass timber is defined as a group of large panels within the EWP family (Harte, 2017). Mass timber products have exceptional mechanical, physical, and environmental properties and large section sizes, which make them a feasible alternative to steel and concrete in construction. The main idea behind the mass timber products is to take advantage of the inherent structural behavior of wood and create homogeneous structural products in a wide range of dimensions. With the emergence of engineered wood products, wood has regained popularity in the construction materials market. The main reason for this development is the commercialization of CLT as a construction material (Brandner et al., 2016).

3.2. History of Cross Laminated Timber (CLT)

CLT was developed in Austria and Germany in the early 1990s to seek a remedy to use mill waste in an application that could add more value to them. The manufacturing and construction techniques of CLT were not fully matured when it was first introduced, and the structures erected using CLTs were mostly for experimental purposes (Brandner et al., 2016). After a slow start, CLT production reached its full-scale state quickly due to its capabilities and performance, and CLT took off in Europe with the contribution of the green building movement by the early 2000s (Divekar, 2016). In the following years, it was widely adopted in Central Europe (Karacabeyli & Gagnon, 2019), and the first standard related to the requirements for CLT to be used as a construction material was published in 2011 (CEN, 2011). It has rapidly gained popularity in the US in the last decade, and as a result of this, a consensus-based product standard for inclusion of CLT, among other heavy construction materials, was required by designers and producers. In 2012, the first version of CLT standard, ANSI/APA PRG-320, was published for both the US and Canada by American National Standard Institute (ANSI) in collaboration with APA-The Engineered Wood Association (ANSI/APA, 2019).

A total of eleven CLT classes within three groups, machine stress rated (E) and visually graded (V), and structural composite lumbers (SCL) members (S) are categorized and the requirements for manufacturing, qualification, and quality assurance of CLTs are discussed in ANSI/APA PRG-320. The standard also presents allowable design values for these CLT grades, including effective bending strength (F_bS_{eff}), effective bending stiffness (EI_{eff}), shear strength (V_s) and effective shear stiffness (GA_{eff}), for three-, five- and seven-layer CLT. Additionally, component requirements such as laminations, adhesives and joints, dimensions, and test methods for CLTs are also specified in the standard. In the last version of PRG-320, which was published in 2019, these values are only valid for softwood species.

3.3. Analytical Design Methods for CLT Elements

CLT is a strong and versatile building material that withstands in-plane loads when used as wall and beam elements, and out-of-plane loads when used as floor and roof panels. In order to fully utilize the potential of CLT, it is important to understand its mechanical properties thoroughly. For this purpose, experimental and analytical design methods have been used since the introduction of CLT (Karacabeyli & Douglas, 2013). Even though experimental methods are more accurate than analytical methods, these methods may require more testing when changes in material, layup or even manufacturing methods are made. Alternatively, for determining the basic mechanical properties of CLT, three analytical methods, including the Gamma method, k-method, and Shear analogy, have been created. The Gamma method is derived from mechanically jointed beam theory as outlined in Annex B of Eurocode 5 (CEN, 2009). In this method, the net moment of inertia is replaced with an effective moment of inertia, which takes into account the effect of the rolling shear strain on the transverse layers caused by a slip between two adjacent longitudinal layers in CLT panels. The K-method was developed by Blass and Fellmoser (2004) and, similar to the Gamma method, does not consider the effects of shear deformation in the longitudinal layers, so it is only appropriate for analyzing CLT panels with a span-to-depth ratio of more than 30, where shear deflection is negligible. The shear analogy (Kreuzinger, 1999) method includes the deformation caused by shear forces in both the longitudinal and cross layers of a panel, regardless of the number of layers in the panel. This method is more suitable for evaluating and predicting the mechanical properties of cross-layered solid panels and is therefore used to calculate the stiffness properties in the PRG-320 (ANSI/APA, 2012, 2019). The shear analogy method is the only analytical method presented in the US CLT Handbook.

3.4. Studies on CLT Made of Softwood Species

Softwood species, particularly spruce, were initially used in the production of CLT in Europe due to availability and ease of processing. Additionally, the structural properties of softwoods, such as their strength and stiffness, made them an attractive option for early CLT manufacturers which further contributed to their widespread use in CLT production. With the growing recognition of the capabilities and efficacy of CLT as a building material, various research studies have been conducted to evaluate the mechanical properties including bending strength and stiffness, rolling shear, compression, and tension, of other softwood species.

In 2015, the mechanical properties including bending strength, bending stiffness, shear strength, resistance to shear by compression loading strength, and resistance to delamination of five-layer CLTs made of southern pine (*Pinus spp.*) were studied by Hindman and Bouldin (Hindman & Bouldin, 2015). The results were compared with the values of the Grade V3 provided in PRG-320 (ANSI/APA, 2012). The allowable bending strength and bending stiffness were above the required values of the Grade V3 in PRG-320. Since no shear strength values were included in the 2012 version of PRG-320, no comparison to shear values were made. However, the shear strength values were greater than the values given in the 2019 version of PRG-320 (ANSI/APA, 2019). The percentage of wood failure in shear by compression loading was found 81.6% which is greater than the minimum acceptable value (≥ 80% for softwoods) presented in ANSI/AITC A

190.1 (ANSI/AITC, 2007). Resistance to delamination was found 17.3% and this value was greater than the requirement of bondline delamination for softwoods specified as 5% in the AITC T110 (AITC, 2007a), which could be attributed to the deviation from the required moisture content during the pressing phase (Hindman & Bouldin, 2015).

Crovella et al. (2019) studied the mechanical properties of three-layer CLTs made of white pine, red maple, and white ash and compared the results with Grade V2 from PRG-320. The lumbers used in the manufacturing of CLT panels were low grade and the visual grading for softwood species was done according to the "*Standard Grading Rules for Northeastern Lumber*" published by Northeastern Lumber Manufacturers Association (NeLMA) (2006). The average bending stiffness of CLTs made of white pine was 29% less than the tabulated value for Grade V2. The theoretical bending stiffness value was calculated using the shear analogy method, and compared with the experimental value obtained from the bending test. The theoretical value was 5% less than the experimental value. The average shear strength value for CLTs made of white pine was 54% less than the shear strength value for the Grade V2 in PRG-320. According to these results, CLTs made of lower grade white pine did not meet the requirement in terms of both bending and shear.

He et al. (2018) focused on the bending performances in both the major strength direction and the minor strength direction of CLTs manufactured with Canadian hemlock. For bending strength calculation, the local bending stiffness ($EI_{m,l}$) defined in EN 408 (CEN, 2012) was used instead of the effective bending stiffness (EI_{eff}). Bending and compressive properties of CLTs made of Canadian hemlock were found to be between the values for CLT grades E1 and E2 defined in PRG-320 (ANSI/APA, 2012).

CLT made of Canadian black spruce (*Picea mariana*) in both 3- and 5-layer CLTs were tested for bending and shear properties by He et al. (2020). The mechanical properties obtained were compared to the values in the literature as well as E1 and E2 grades defined in PRG-320 (ANSI/APA, 2019). It was reported that CLTs with 3-layer showed even higher flexural MOE (E_b) than those of E1 grade CLT while CLTs with 5-layer were similar to those of E2 grade except for the f_b, but this value was still higher than some of those found in other literature.

3.5. Opportunities for Hardwoods in the Production of CLT

According to 2019 version of PRG-320 (ANSI/APA, 2019), each CLT grade defined is made of a single softwood species using various grades of lumbers of that species in longitudinal and transverse layers. The reason for softwood lumber use in CLTs is due to the fact that hardwood species have more complex cell structures than softwoods, and even within themselves, and using lumbers from different species may cause adhesion problems affecting the bonding performance (Quesada, 2018). Furthermore, the utilization of only softwood species also requires less time and pressure during pressing compared to hardwoods due to the physical differences (specific gravity (SG), stiffness) between these two species and prevents possible design defects that may arise in the meantime (Quesada, 2018).

Due to all positive properties of softwoods for the production of CLT, the domestic demand has gradually increased to 87.56 million m^3 in 2021 while the production of softwood in the US could not meet the demand although it has reached to 63.16 million m^3 for the same period (UNECE/FAO, 2022). According to Forest Products Market Review 2020-2021 (UNECE/FAO, 2021), the estimation of actual CLT capacities for structural applications in the US in 2020 was 656,000 m^3 which requires approximately 1.23 million m^3 raw material (Forest2Market, 2021). The demand for CLT is expected to increase annually through 2030 (Brandt et al., 2021), and as a result of this, the demand for softwood lumber is bound to increase as well. This situation could pose a challenge to the domestic softwood supply, possibly leading to shortages of CLTs in the US. This problem can be addressed by the inclusion of hardwoods as an alternative species to softwoods (Adhikari et al., 2020). The use of hardwood species in layers where mechanical effects are intense has the potential to improve the mechanical properties of CLT panels without requiring changes in their physical properties (Brandner, 2013).

There have been several studies on the inclusion of hardwoods in the manufacturing of CLT. Kramer et al. (2014) conducted non-destructive bending, bending strength and stiffness, and shear tests in accordance with the test methods in PRG-320 (ANSI/APA, 2012) using three-layer CLT panels made of low specific gravity hybrid poplar (*Pacific albus*) to evaluate the utilization of low specific gravity (SG) species in CLT production. Block shear tests were also done on the specimens based on ASTM D905 (ASTM, 2013). The values of modulus of rupture (*MOR*) were greater than the Grade E3 values specified in PRG-320, while the modulus of elasticity (*MOE*) values was less than the values defined for the same grade. Kramer et al. (2014) suggested the use of hybrid poplar in combination with other high-SG wood species could lead to the production of more efficient CLT panels.

Mohamadzadeh and Hindman (2015) investigated the mechanical properties including strength and stiffness for both bending and shear, resistance to shear by compression loading strength, and resistance to delamination of three-layer CLTs made of low and high quality yellow-poplar (*Liriodendron tulipifera*) lumbers. The mechanical test results obtained in the study were compared to that of the Grade V1 and V2 specified in the PRG-320 (ANSI/APA, 2012). The allowable bending strength, bending stiffness and shear stiffness for both low and high quality CLTs were greater than the values of Grade V1 and V2 in PRG-320 (ANSI/APA, 2012). Face delamination on the CLTs was also less than 5%, which is the maximum allowable value specified by AITC T110 (AITC, 2007a). However, wood failures in resistance to shear by compression loading test for both low quality (61%) and high quality (72%) were less than 80% required by AITC T107 (AITC, 2007b).

Crovella et al. (2019) also examined the mechanical properties of CLTs produced using white ash and red maple and bending, and shear test results from the specimens tested in this study were compared to Grade V2 in PRG-320. The lumbers of both species were No.3A-common grade according to the "*Rules for the Measurement & Inspection of Hardwood & Cypress*" published by the National Hardwood Lumber Association (NHLA) (2015). Both of the average bending stiffness and shear strength values of CLTs made of white ash and red maple exceeded values tabulated for Grade V2 in PRG-320. The shear analogy method was performed for the calculation of the theoretical bending stiffness value and those were compared to the experimental value obtained from the bending tests. The theoretical value was found to be 25% lower than the experimental value. These results showed that low grade hardwoods could be a viable option for producing CLT in the future.

Hematabadi et al. (2020) studied the modulus of rupture (*MOR*), apparent modulus of elasticity (MOE_{app}), effective bending stiffness, effective shear stiffness, and maximum shear stress of CLT panels made of hand planted Iranian poplar wood (*Populus alba*) in both the major and minor directions at different span-to-depth ratios (SDR). The experimental results were compared with predictions using both the shear analogy model and finite element method (FEM) to evaluate the accuracy of these modeling approaches. MOR and MOE values in both the major and minor directions increased as the SDR of the specimens increased. Furthermore, the average effective bending stiffness (EI_{eff}) in the major strength direction was calculated 9% and 12% less than the shear analogy and global method, respectively, while in the minor direction, only the average effective bending stiffness (EI_{eff}) calculated with the shear analogy method was found lower in comparison with other two methods. Average effective shear stiffness (GA_{eff}) values in the major strength direction calculated using experimental regression methods was 510% greater than the values calculated using the shear analogy method. In the minor strength direction, however, the values obtained from the shear analogy method was found to be 9.2% greater than the GA_{eff} calculated by a regression method.

Hybrid three-layer CLTs with European beech (*Fagus sylvatica*) at the center layer and European spruce (*Picea abies*) at the outer layers were studied by Aicher et al. (2016) for out-of-plane bending and two different configurations of shear tests including Method A: attaching screws on the outer layers and Method B: gluing steel plates on the outer layers planed down to 1.0-2.0 mm. The rolling shear strength results obtained from both methods were 3.31 ± 0.61 N/mm^2 and 4.38 ± 0.44 N/mm^2, respectively.

While CLT made of softwood species is well-established, the increase in domestic demand for softwood lumber may cause a shortage for CLT production in the future. Although studies have shown promising results on the inclusion of hardwoods in CLT production, there is still a need for more research in this regard. The most convenient way to address this gap is to manufacture a hybrid CLT using a softwood species with a hardwood species that possess physical and mechanical properties suitable for CLT production. Further studies in this topic can ultimately lead to the development of more sustainable and efficient methods of producing CLT with improved properties and reduced environmental impact.

4. MATERIALS and METHODS

4.1. Materials

The southern pine wood used in this study was nominal No.2 2 x 6 obtained from the company Texas CLT, located in Magnolia AR, and the yellow-poplar wood was 6/4 No.2 Common, which was regraded to No.2 Better yellow-poplar, obtained from various Virginia saw mills. CLT panels were only face-bonded using a one-component polyurethane adhesive, then assembled in a cold press for 60 minutes with a press pressure of 90 psi. A total of 21 panels with different layup options were manufactured at Texas CLT, and each panel was cut into seven CLT beams, having approximately 12 in. of width and 120 in. of length, which is within the dimensions stated in PRG-320. The average of the actual depths for three-layer and five-layer CLTs were 4.2 in. and 6.9 in., respectively. CLT beams were individually wrapped in polyethylene sheets and taped for transportation. After unloading, the beams were stored at the Wood Engineering Lab at Virginia Tech at 65°F of average temperature and approximately 50% relative humidity for seven weeks between April and May.

For testing purposes, only 90 of all CLT beams manufactured were used in nine groups, four were three-layer and five were five-layer (Table 2). The first groups of each layer option were all southern pine. The second group for both layer options was all yellow-poplar. The beams for the third group were manufactured using yellow-poplar in the core layer(s) and southern pine in the outer layers, and the beams for the fourth group were manufactured in the opposite layup of the third groups as southern pine in the core layer(s) and yellow-poplar in the outer layers. The last group of five-layer CLTs was manufactured in a way where different species were used in adjacent layers starting from yellow-poplar in the outer layers.

Table 2. *Layup combinations used for test purposes*

Layers	Group No	Combinations	Pieces	Layers	Group No	Combinations	Pieces
Three-layer CLTs	1	S/S/S	16	**Five-layer CLTs**	1	S/S/S/S/S	10
	2	Y/Y/Y	10		2	Y/Y/Y/Y/Y	7
	3	S/Y/S	10		3	S/Y/Y/Y/S	10
	4	Y/S/Y	10		4	Y/S/S/S/Y	7
					5	Y/S/Y/S/Y	10
		Total	46			Total	44

4.2. Methods

To evaluate the bending strength, bending stiffness and shear stiffness, five-point and four-point bending tests were conducted on CLT beams. Following the completion of the bending tests, a 40 in. long pieces were cut from undamaged sections of the each CLT for shear testing. Smaller test specimens were then cut from the CLT beams for moisture content and specific gravity (1 x 1 in.), resistance to shear by compression loading (2 x 2 in.) and resistance to delamination (3 x 3 in.) tests. All tests were carried out at the Brooks Forest Products Center at Virginia Tech except for the resistance to delamination test, which was conducted in the facility of Wood Science and Technology Program at West Virginia University, as an autoclave with large volume were present.

Five-point and four-point bending tests were conducted according to Bradtmueller et al. (1998) and ASTM D198 (ASTM, 2015), respectively, and all the other tests were done according to the test methods described in appropriate ASTM (ASTM, 2015, 2017, 2020, 2022) and AITC (AITC, 2007a) standards (Fig 4).

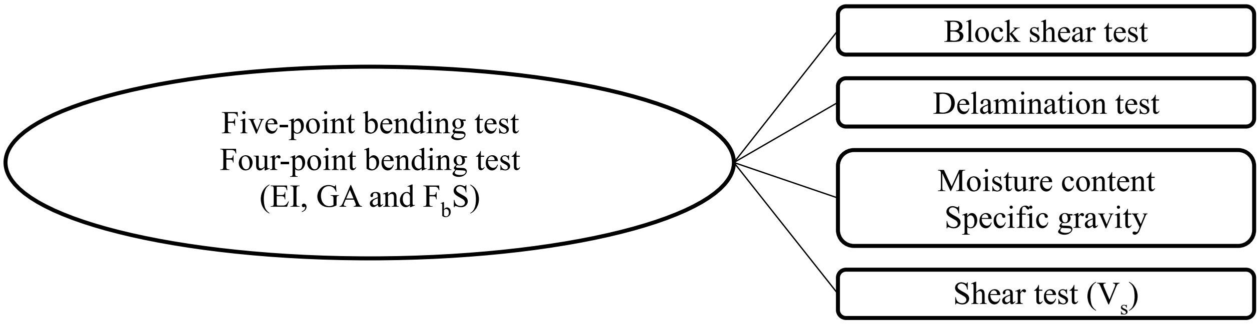
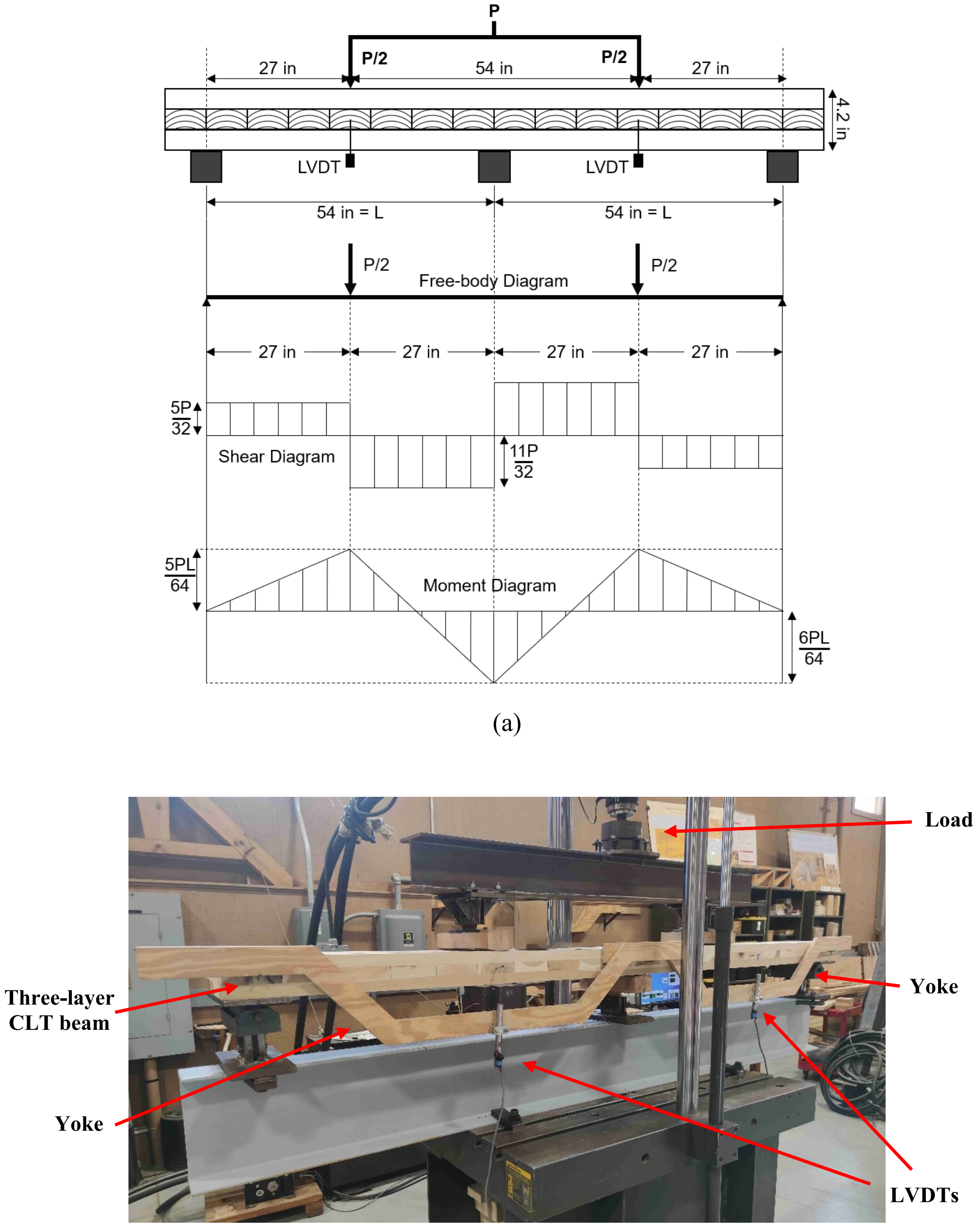


Figure 4. *Design of mechanical tests*

4.2.1. <u>Five-point bending tests</u>

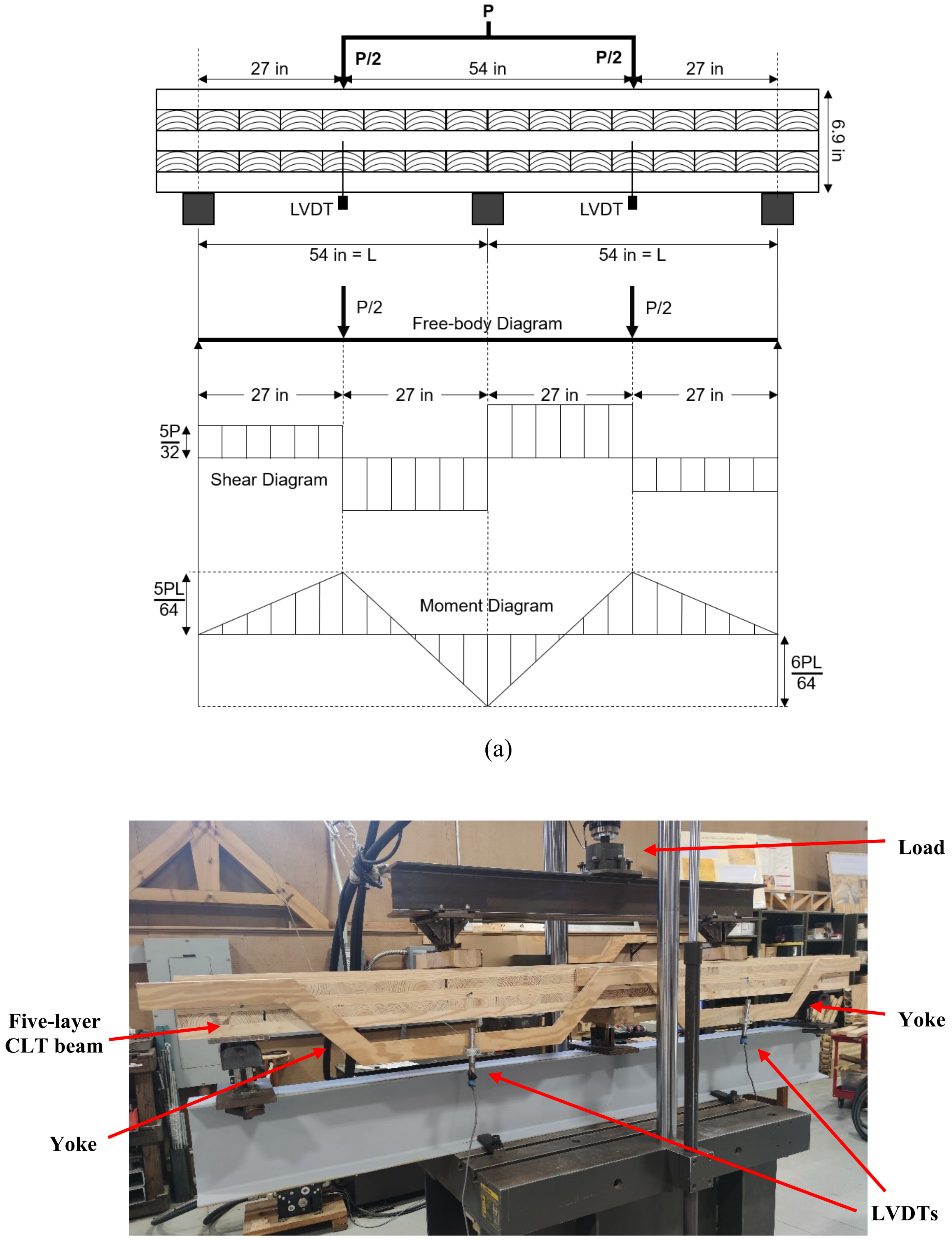
All three-layer and five-layer CLT beams were tested in the five point bending test following procedures described by Bradtmueller et al. (1998). Schematic with free-body, shear and moment diagrams and photographs of the experimental set up for three-layer and five-layer CLT beams are shown in Fig. 5a – b and Fig. 6a – b, respectively. CLT beams were placed on two end supports and a middle support with the spans equal to 54 in. between the middle and end supports. Two point-loads perpendicular to the surface of the beams were applied to each specimen at the mid-points of the spans between the middle and end supports (27. in from the mid support to both directions). An MTS universal testing machine (Eden Prairie, Minnesota) having a built-in load cell with a capacity of 50,000 lbs. sensitivity was utilized to collect data from bending tests. A displacement rate of 0.1 in./min was used and the test ended when loading reached 2,000 lbs. for three-layer, and 4,000 lbs. for five-layer CLT beams. From prior testing, these forces were within the elastic range of the CLT beams which prevents permanent deformation. Two small yokes, each carrying an LVDT, were attached to the screws aligned vertically with the supports and LVDTs were hooked to the screws mounted at the mid-points of each span (Fig. 5b and 6b). LVDTs (2 in. max range and 0.0001 in. sensitivity) were used to measure the deflection at the neutral axis. The inverse slopes (Y_{FP}) obtained from the load and deflections recorded by the LVDTs was used in the calculations of bending stiffnesses (EI) and shear stiffnesses (GA) (Eq. 1 and 2), respectively.



(a)

(b)

Figure 5. *a) Schematic with free-body, shear and moment diagrams, and b) Experimental setup of five-point bending test for three-layer CLT beams*



(a)

(b)

Figure 6. *a) Schematic with free-body, shear and moment diagrams, and b) Experimental setup of five-point bending test for five-layer CLT beams*

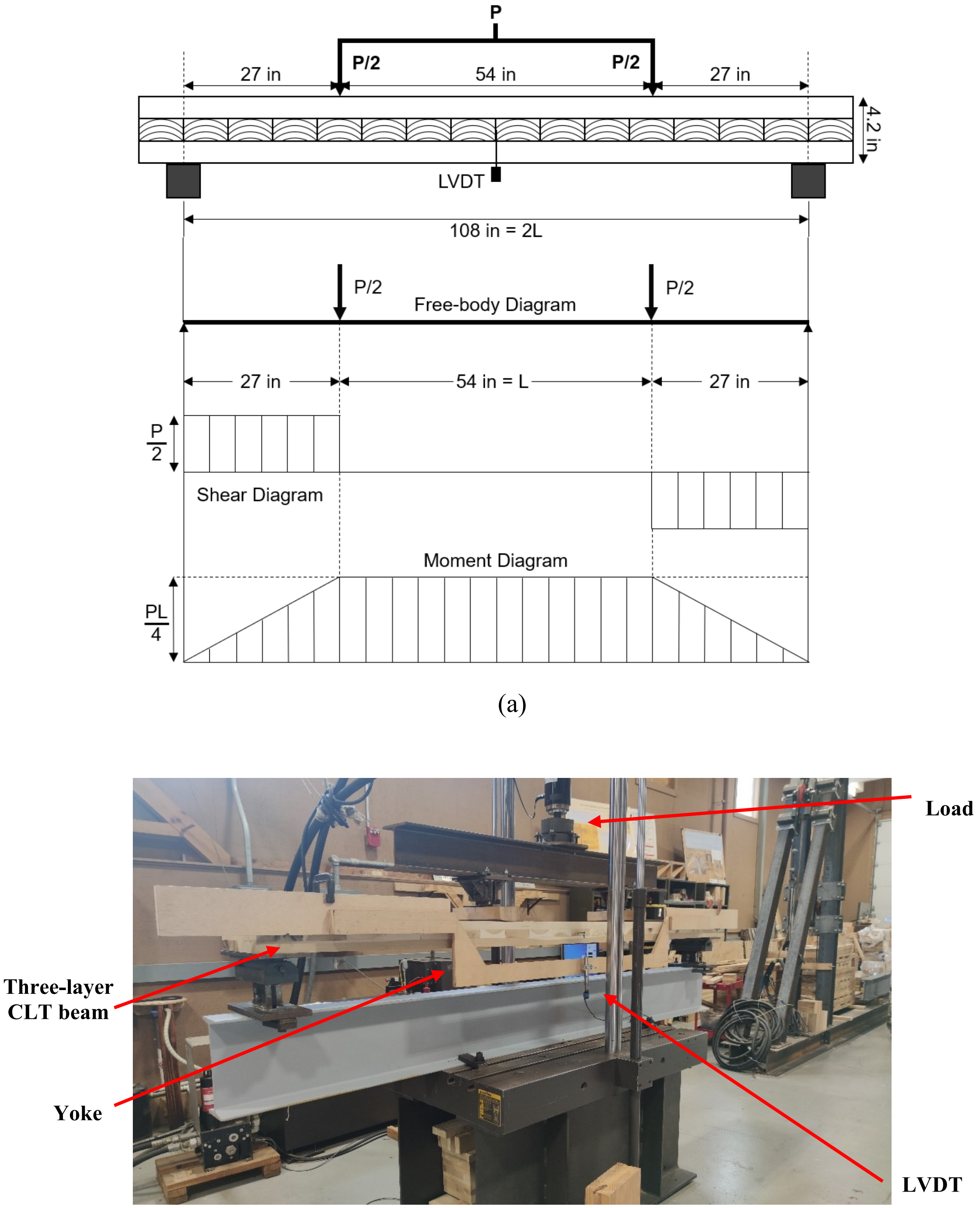
4.2.2. Four-point bending tests

Four-point bending test was done according to ASTM D198 (ASTM, 2015). For this test, the support in the middle shown in Figure 5a and 6a was removed and the specimens were tested in bending to calculate the ultimate bending strength (F_bS). Schematic with free-body, shear and moment diagrams and photographs of the experimental set up for the three-layer and five-layer CLT beams are shown in Fig. 7a – b and Fig. 8a – b, respectively. The span between two end supports was 108 in. with a span-to-depth ratios of 26:1 for three-layer and 16:1 for five-layer CLTs, as compared to a value of 30:1 specified by PRG-320 (ANSI/APA, 2019), and two point-loads perpendicular to the surface of the beams were applied at the same points in the previous bending test. Same MTS universal testing machine was utilized to collect data from four-point bending tests. Testing speed was constant with the rate of 0.1 in./min and the yoke was removed when the load reached 10,000 lbs. for three-layer, and 15,000 lbs. for five-layer CLT beams without interrupting the test. After the removal of the yoke, the tests were continued until the specimens failed. A large yoke with an LVDT was attached to the screws aligned vertically with the supports and LVDT was hooked to the screw mounted at the mid-point of the specimens (Fig. 7b and 8b). LVDTs (2 in. max range and 0.0001 in. sensitivity) were used to measure the deflection at the neutral axis. The ultimate loads were used for bending strength (F_bS) calculations (Eq. 1) and the inverse slopes (Y_{QP}) obtained from the relationship between loads and average deflections recorded by an LVDT were used in the calculations of bending stiffnesses (EI) and shear stiffnesses (GA) (Eq. 2 and 3 (Bradtmueller et al., 1998)), respectively:

$$F_bS = \frac{P_{max}L}{4} \quad (1) \qquad EI = \frac{249L^3}{\left\{4096\left[\frac{73}{128}Y_{QP} - Y_{FP}\right]\right\}} \quad (2)$$

$$GA = \frac{747L}{\left\{5632K\left[Y_{FP} - \frac{7}{176}Y_{QP}\right]\right\}} \quad (3)$$

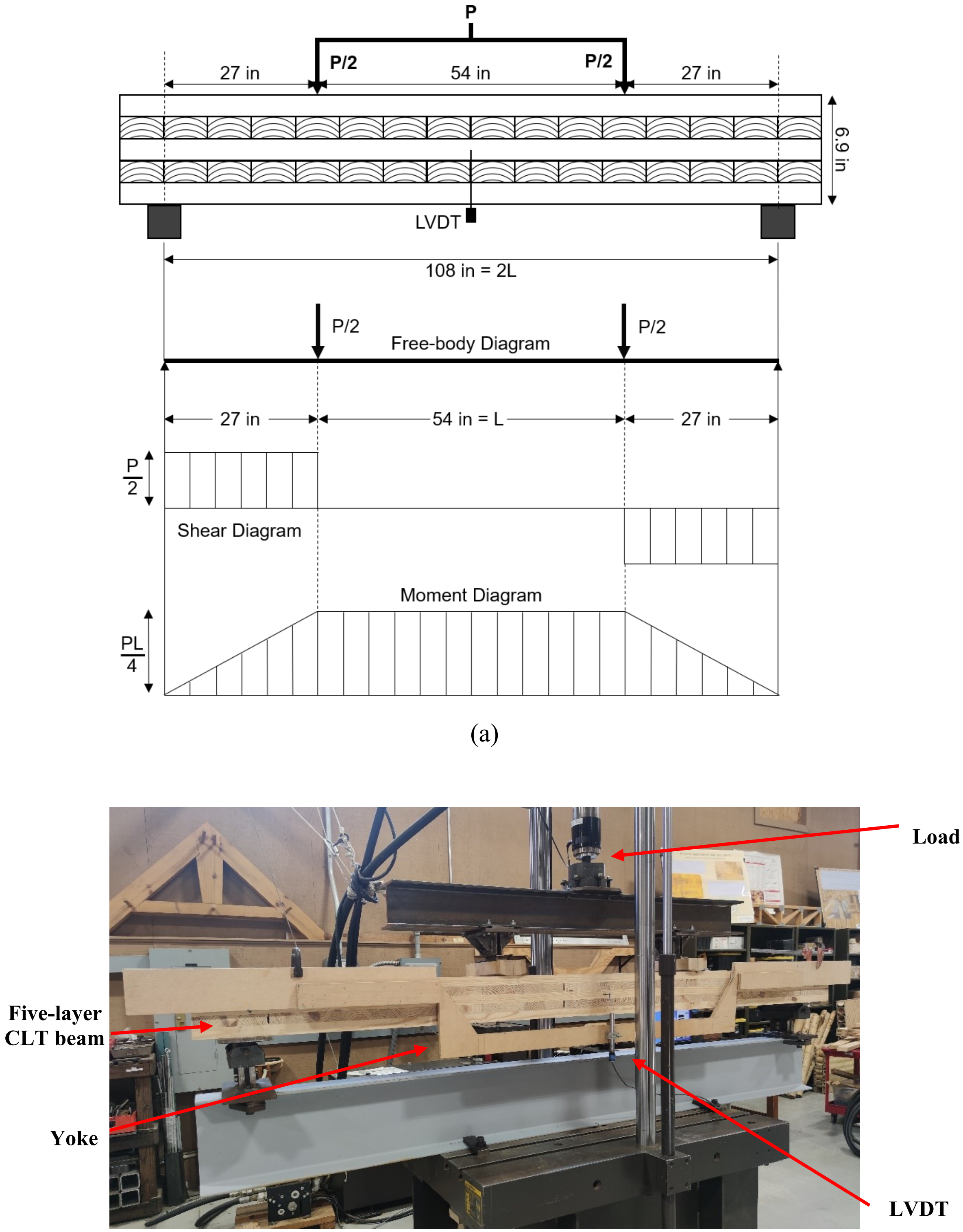
where P_{max} is the maximum load (lbf), S is section modulus (in.^{3}), L is the length of span in five-point test (in.), E is the modulus of elasticity (psi), I is the moment of inertia (in.^{4}), G is the shear modulus (psi), A is the cross sectional area (in.^{2}), K is the shape factor (5/6 for rectangular section), Y_{FP} is the inverse slope of load-deformation in five-point bending test (in/lbf), and Y_{QP} is the inverse slope of load deformation in four-point bending test.(in/lbf)



(a)

(b)

Figure 7. *a) Schematic with free-body, shear and moment diagrams, and b) Experimental setup of four-point bending test for three-layer CLT beams*



(a)

(b)

Figure 8. *a) Schematic with free-body, shear and moment diagrams, and b) Experimental setup of four-point bending test for five-layer CLT beams*

4.2.3. Moisture content and specific gravity measurements

For the measurements of moisture content and specific gravity, two 1 x 1 x 1.25 in. specimens were cut from each beam where no cracks or damages occurred after bending tests. Each layer of the specimens was cut from the bondlines to measure the moisture content of the lumber separately. Moisture content measurement was done using the oven-dry method laid out in ASTM D4442 (ASTM, 2020). The wet-weight of MC specimens were taken before drying in the oven. Then the specimens were placed in the oven set at 103 ± 2ºC and kept in the oven for 24 hrs. After this period, the weight change over a four-hour period being less than twice the sensitivity of the scale was monitored, and then the oven dry-weights of the specimens were measured. MC of the specimens was calculated according to the Eq. 4:

$$MC = \frac{wet\ weight - oven\ dry\ weight}{oven\ dry\ weight} * 100\% \quad (4)$$

Specific gravity was measured using the volume by immersion method in ASTM D2395 (ASTM, 2017). In this method, a container filled with water was placed on a balance, and using a sharp rod, each specimen taken out of the oven was submerged in a hot paraffin wax bath first and then in the water completely without any connection to the walls of the container. When the balance reached equilibrium, the readings on the balance were recorded and the SG of each specimen was calculated by dividing the dry weight of a specimen by the measure volume.

4.2.4. Shear test

ASTM D198 (ASTM, 2015) procedures were used for shear testing on 40 in. long undamaged sections cut from CLT beams previously tested for bending. Schematics and free-body, shear and moment diagrams of the three-layer and five-layer shear test samples are shown in Fig. 9. The width of the shear specimens from three-layer CLT beams was 12 in. with the span of 24 ¾ in, resulting in a span-to-depth ratio of 5.9:1 which falls within the recommended span-to-depth ratio of 5 – 6:1 in PRG-320 (ANSI/APA, 2019). However, due to the load approaching the 50,000 lbs. limit of the MTS universal testing machine, the width of the shear specimens from five-layer CLT beams was reduced to 9 in. with the span of 36 in. (Fig. 9). All specimens were loaded at the center point with a displacement rate of 0.07 in./min. Shear strength (V_s) calculations were made according to Eq. 5.

$$V_S = \frac{P_{max}L}{2} \quad (5)$$

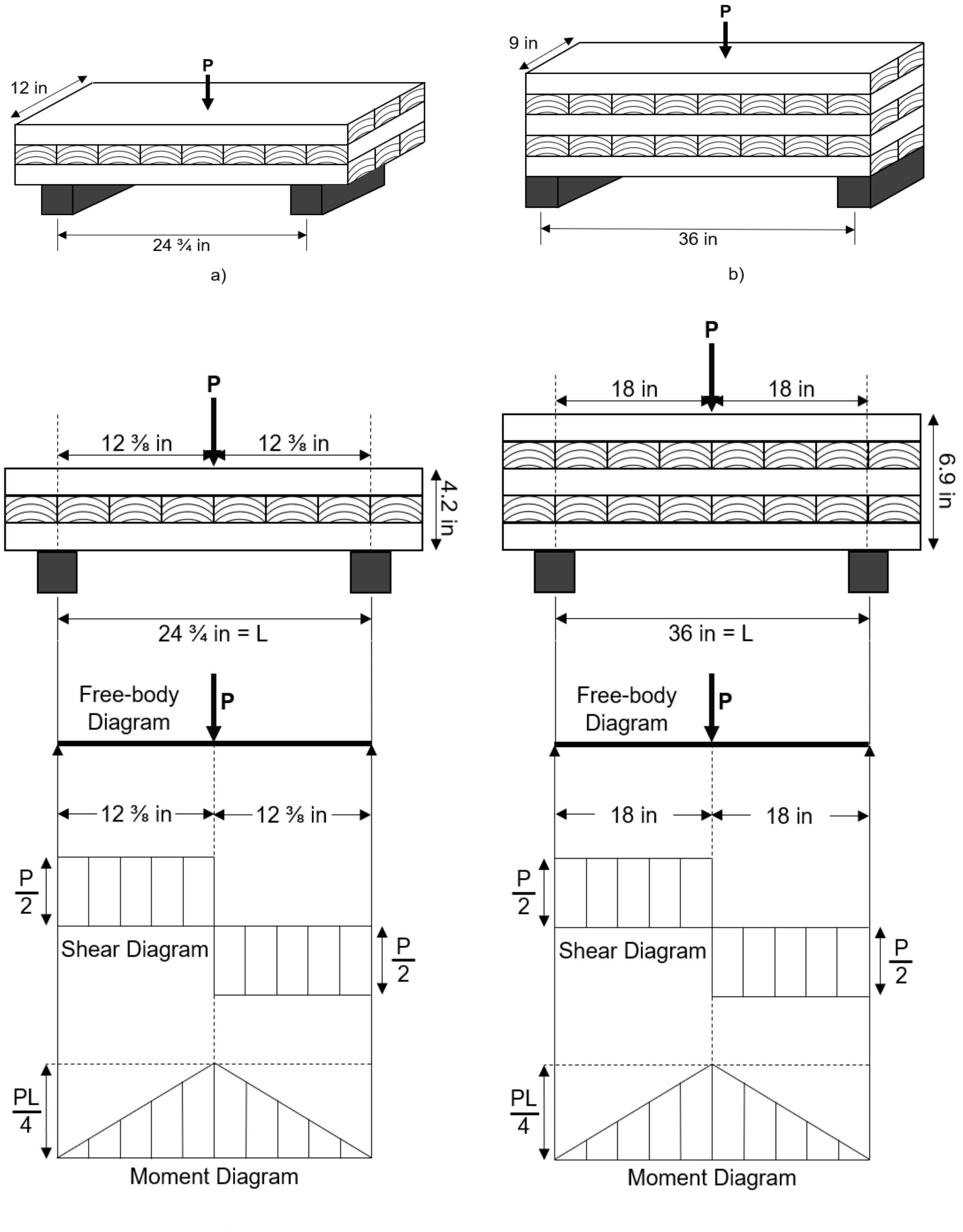


Figure 9. *Schematics and free-body, shear, and moment diagrams of shear specimens a) Three-layer specimen, b) Five-layer specimen*

4.2.5. Resistance to shear by compression loading

The resistance to shear by compression loading test was done applying a shear force to the bondline of specimens that were cut from the beams after bending tests. AITC T107 (AITC, 2007b) states that the load is applied parallel to the grain of the specimen in the resistance to shear by compression loading test. Since the CLT has cross laminations between all bondlines, the geometry of the specimens needs to be specified for the uniformity of the test (Hindman & Bouldin, 2015). Test specimens were cut as a two stair-step with the parallel to the grain lamination being upright and the notch being on the other lamination (Fig. 10). One specimen was cut for each bondline, yielding 92 and 176 test specimens for three-layer and five-layer CLTs, respectively. Testing was conducted according to ASTM D905 (ASTM, 2013) and the average shear area of the specimens measured approximately 2.00 in. by 1.75 in.. The displacement rate was 0.024 in./min and all specimens were loaded until they failed. The maximum load and percent wood failure measured using a 2x2 transparent sheet divided into 64 squares were recorded. Maximum shear stress for each specimen (F_v) was calculated according to Eq. 6.

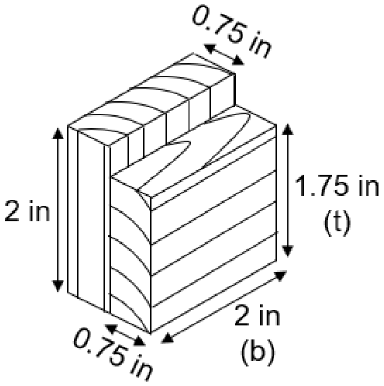


Figure 10. *The geometry of resistance to shear by compression loading test specimen*

$$F_V = \frac{P_{max}}{bt} \quad (6)$$

4.2.6. Resistance to delamination

The resistance to delamination test was conducted to measure the bond durability in accelerated cyclic aging condition (vacuum/pressure-soak/drying) based on AITC T110 (AITC, 2007a). Similar to AITC T107, AITC T110 also describes the test method assuming all laminations are in the same direction. For the best adaptation of this method to CLT, the bondline lengths were measured from all four sides of the specimens. The specimens in size of 3 x 3 x 4.2 in. for each three-layer CLT, a total of 46 specimens, and 3 x 3 x 6.9 in. for each five-layer CLT, a total of 41 specimens, were cut from the undamaged section of the beams previously tested for bending. All specimens were weighed, and the lengths of bondlines were measured from all faces and recorded. To conduct the delamination test, the specimens were transported to Wood Science and Technology Program at West Virginia University. For cyclic exposure, the specimens were submerged into water and placed in the autoclave. The cycle included the application of a vacuum of 25 in. of Hg for 30 mins followed by the application of pressure of 75 psi for 2 hours to the specimens in the autoclave and the drying the specimens in a drying oven at 160ºF for at least 24 hours until they weighted at least 10% above of their original weights.

The Poisson's effect, which describes the tendency of a material to shrink or expand in perpendicular directions when stretched or compressed, caused the laminations of the specimens to lose their original shape and deform in an hourglass-like fashion, so that the bondlines became curved rather than straight (Fig. 11). Additionally, the length of the exposed bondlines increased due to radial and tangential swelling of each lamina during the autoclave procedure. When the specimens reached at or below the desired weight percentage, final bondline measurements were taken from all four faces for each bondline and separations between laminations on the bondlines were inspected using a feeler gauge. All separations were marked with a marker and the length of delaminations were measured with a caliper. Delamination percentages of each specimen were calculated based on the ratio of delamination length to original bondline length as shown in Eq 7.

$$\%\,Delamination = \frac{Length\ of\ delamination}{Total\ bond\ length} \qquad (7)$$

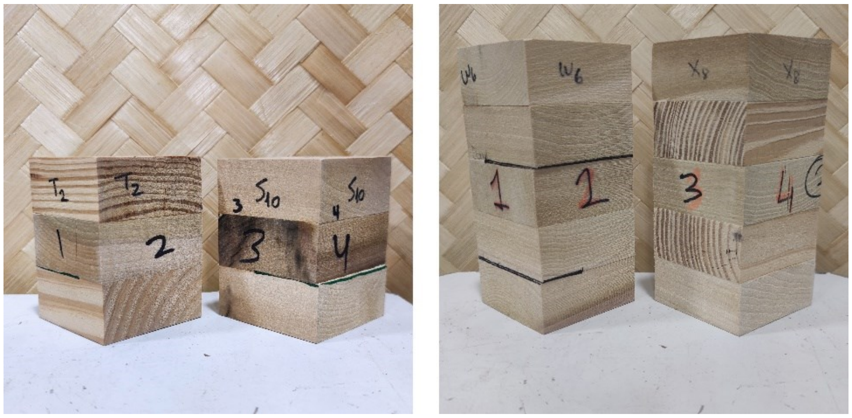


Figure 11. *Delamination specimens*

5. RESULTS and DISCUSSION

5.1. Bending and Shear Tests

5.1.1. Bending and shear test results of three-layer CLTs

The average and coefficient of variations[1] (COV), which is the dispersion of the data set relative to its mean, of the bending strength, bending stiffness, shear stiffness, and shear strength values from the three-layer CLT groups are shown in Table 3. The SSS group had the greatest average bending strength value with 17,633 lbf-ft/ft and the difference between the SYS group, which had the lowest average bending strength, was 49.6%. This was followed by the YYY group with a difference of 25.9%. Differences in bending strength between the SSS and other groups can be associated with high COV, which indicates there was great variability within each group.

Table 3. *Average bending and shear test results of three-layer CLTs*

Groups	F_bS lbf-ft/ft	EI 10^6 lbf-in^2/ft	GA 10^6 lbf/ft	V_s lbf/ft
SSS	17633 ^{a} (8.2%)	123 ^{a} (13.6%)	1.65 (45.7%)	14488 ^{a} (15.9%)
YYY	14006 $^{b, c}$ (18.6%)	95 ^{b} (8.2%)	2.26 (25.0%)	10617 ^{b} (13.3%)
SYS	11785 ^{c} (19.0%)	102 ^{b} (11.8%)	1.53 (44.0%)	10243 ^{b} (17.8%)
YSY	15206 $^{a, b}$ (27.1%)	105 ^{b} (11.3%)	2.21 (44.9%)	12516 $^{a, b}$ (12.8%)

Note: Coefficient of variation (COV) values are given in parentheses.
The superscript letters represent the difference between the groups from Tukey's HSD test.

The SSS group also had the greatest value in average bending stiffness among all groups. In comparison between the groups consisting of yellow-poplar species, the YSY group had the maximum value with 105*10^6 lbf-in^2/ft. The difference between the YSY group and the SYS group was only about 3%. The YYY group, on the other hand, had the minimum value with 95*10^6 lbf-in^2/ft.

Groups containing at least two southern pine species in layers, the SSS and SYS groups, showed similar average shear stiffness values. The SYS group had the lowest average shear stiffness value with 1.53*10^6 lbf/ft and the SSS group was 7.8% greater than this value. A similar trend was observed in groups with at least two yellow-poplar species in their layers, such as the YYY and YSY groups. The average shear stiffness value of the YYY group was 2.26*10^6 lbf/ft and this was the greatest value among all groups.

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[1] The degree of variability in a set of data relative to its mean, expressed in %.

Similar to bending strength and bending stiffness, the SSS group had the greatest average shear strength value with 14,488 lbf/ft. This was followed by the YSY group with 12,516 lbf/ft. The average shear strength values of the YYY group and the SYS group were close to each other, but the SYS group had the lowest average shear strength value with 10,243 lbf/ft.

A set of one-way analysis of variance (ANOVA) tests were conducted to compare the bending strength, bending stiffness, shear stiffness and shear strength values of three-layer CLT groups. Comparison of p-values from the ANOVA test ($\alpha = 0.05$) showed significant differences for all properties except shear stiffness. The Tukey's Honestly Significant Difference (HSD) test was also conducted for all data with a p-value less than alpha (α) and the results are shown in superscript letters in Table 3. The bending strength (F_bS) values of SSS and SYS groups were greater and less than the other groups, respectively; however, the differences were not statistically significant. The bending stiffness (EI) values of YYY, SYS and YSY groups were not significantly different, however, the EI value of SSS group was significantly greater than others. The ANOVA test conducted for the shear stiffness (GA) values showed that the p-value of this property (0.061) was greater than the alpha, and therefore the Tukey's HSD test was not applied. Shear strength (V_s) values showed a similar trend with the EI values, except that the superscript letter "b" was also present in addition to the letter "a" in the YSY group.

Four failure modes were observed in the inspection made of both three-layer and five-layer CLT beams following the four-point bending test. A bending failure which occurred on the tension side (bottom) of the beam is shown in Fig. 12, marked (a). The wood fibers elongated and reached their maximum capacity, resulting in bending failure in the forms of cracking, splitting, or complete rupture of the wood.

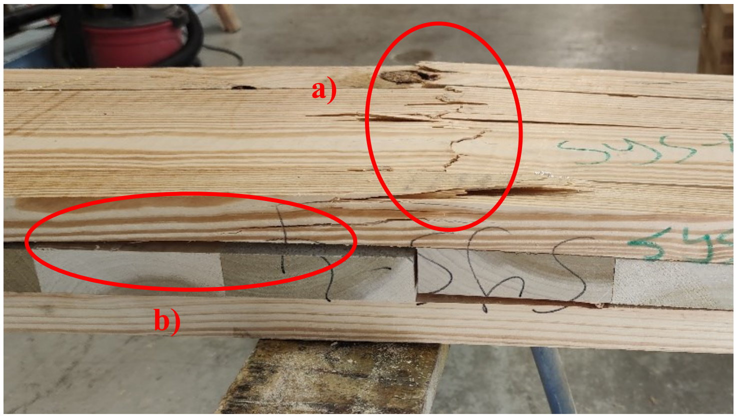


Figure 12. *Examples of (a) Bending failure, and (b) Glue failure of tested CLT beams*

Glue failure was the second most observed failure and it occurred when the glue used to bond layers of CLT failed to maintain its integrity. Failure at glue line, shown in Fig. 12 as well, marked (b), were caused by the shear forces internal to beam due to the applied load.

Shear failure in the beams occurred when the internal stresses caused by the applied load exceeded the shear parallel-to-grain strength of the wood laminations. This resulted in shearing to the nearest end surface of the beams, as shown in Fig. 13.

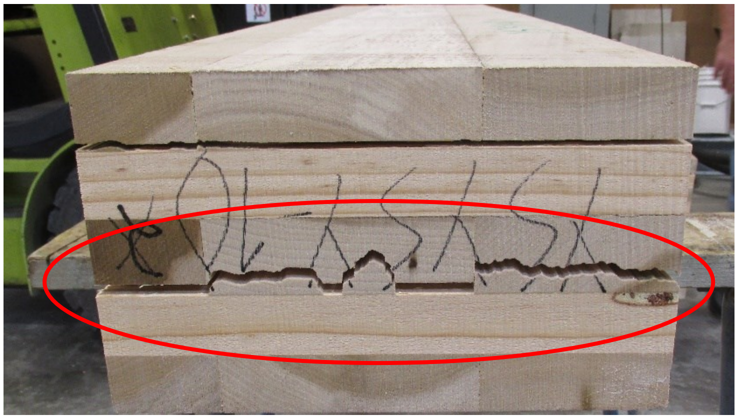


Figure 13. *Example of shear failure of tested CLT beams*

Rolling shear generally occurred in the beams near the supports or along the connection lines of two layers due to the shear stress acting on the radial-tangential plane perpendicular to the fiber direction. The vertical and horizontal shear forces acting on the cross-section of the material under the effect of rolling shear are shown in Figure 14. In the example in Fig. 15, the failure included glue failure near the end of the beam, becoming rolling shear across one of the cross-layers, and then glue failure at the next glue line.

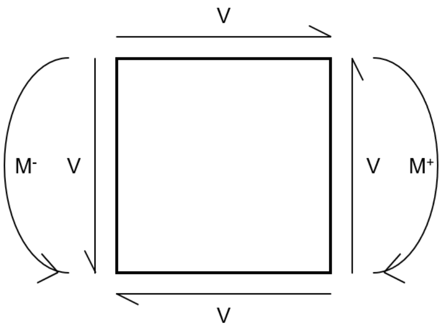


Figure 14. *Shear forces during rolling shear*

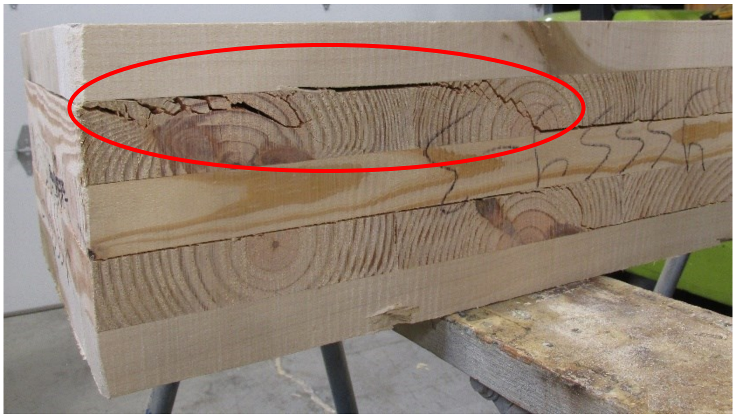


Figure 15. *Example of rolling shear failure of tested CLT beams*

Failure modes in the three-layer beams from four-point bending test were investigated and shown in Table 4. In the SSS group, one shear failure was observed, and rolling shear and bending failure were commonly observed failures. While 75.0% of the beams showed bending failure in this group, bending failure and rolling shear were observed together in 9 of these beams, and glue failure was observed nearly in half of the beams in this group. Shear, glue, and bending failures were more frequent, although all failure modes were observed in the YYY group. While 70.0% of the beams in the YYY group showed a combination of at least two of these failure modes, only 20.0% of them had all of these failures. In SYS group, glue failure was observed in all specimens and 90.0% of the beams in this group exhibited shear failure at the ends. No instances of shear failure were observed in the YSY group while all specimens in this group had glue failure, and some individual samples exhibited breakings at knots and rolling shear.

Table 4. *Distribution of failure modes for three-layer CLT groups*

Groups	***Bending failure***	***Glue failure***	***Shear failure***	***Rolling shear***
SSS	75.0%	43.8%	6.25%	81.3%
YYY	70.0%	60.0%	60.0%	20.0%
SYS	40.0%	100%	90.0%	10.0%
YSY	40.0%	100%	0%	40.0%

Note: All beams showed multiple failures, so the percentage of beams does not sum to 100%.

Generally, southern pine has higher MOE and MOR values than yellow-poplar, indicating greater stiffness and strength. With this information, the three-layer CLT groups with southern pine in their major axis direction would be expected to have greater strength and stiffness values compared to the yellow-poplar beams; however, the SYS group showed very low strength and stiffness values, which seems contrary to this trend. The order of the species in the layups seemed irrelevant to strength and stiffness values of the CLT beams tested. The YYY group had moderate strength and stiffness values compared to other groups. However, the bending strength, bending stiffness, and shear strength values of the group having southern pine in its minor axis direction (the YSY group) increased. In terms of failure modes, the SYS and YSY groups showing relatively low bending failure compared to other groups may indicate quality control issues with CLT panels.

5.1.2. Bending and shear test results of five-layer CLTs

The average bending strength, bending stiffness, shear stiffness, and shear strength values from tested five-layer CLTs are shown in Table 5. The greatest average bending strength value was from the YSYSY group with 38,006 lbf-ft/ft. The groups consisting of only single species (the SSSSS and YYYYY groups) had the lowest average bending strength values with 29,947 and 27,550 lbf-ft/ft, respectively. The difference between the group with the greatest average bending strength and the YYYYY was 38.0%.

Table 5. *Average bending and shear test results of five-layer CLTs*

Groups	F_bS lbf-ft/ft	EI 10^6 lbf-in^2/ft	GA 10^6 lbf/ft	V_s lbf/ft
SSSSS	29947 ^{c} (10.3%)	351 ^{b} (6.7%)	3.58 $^{a, b}$ (31.5%)	16852 (11.1%)
YYYYY	27550 ^{c} (20.0%)	363 ^{b} (12.0%)	4.04 $^{a, b}$ (16.4%)	16930 (17.3%)
YSYSY	38006 ^{a} (5.8%)	409 ^{a} (4.7%)	4.25 ^{a} (13.7%)	19339 (14.8%)
SYYYS	35574 $^{a, b}$ (12.0%)	361 ^{b} (11.4%)	4.83 ^{a} (38.3%)	19790 (22.8%)
YSSSY	30314 $^{b, c}$ (22.5%)	381 $^{a, b}$ (8.5%)	2.53 ^{b} (31.5%)	15734 (12.5%)

Note: Coefficient of variation (COV) values are given in parentheses.
The superscript letters represent the difference between the groups from Tukey's HSD test.

The greatest average bending stiffness value was also obtained in the YSYSY group with $409*10^6$ lbf-in^2/ft. The fact that the YSYSY group had the greatest bending strength and bending stiffness can be attributed to the low COV within the group for both properties. The lowest value for average bending stiffness was $351*10^6$ lbf-in^2/ft in the SSSSS group. The SSSSS group was followed by the SYYYS group with $361*10^6$ lbf-in^2/ft and the difference with the YYYYY group was only 0.5%.

The groups with yellow-poplar and southern pine in their core layers (the SYYYS and YSSSY groups) had the greatest and lowest average shear stiffness values with $4.83*10^6$ lbf/ft and $2.53*10^6$ lbf/ft, respectively. After the SYYYS group, the average shear stiffness values of the groups consisting of at least three layers of yellow-poplar species were followed by YSYSY and YYYYY with $4.25*10^6$ lbf/ft and $4.04*10^6$ lbf/ft, respectively.

The SYYYS group had the greatest average shear strength value, followed by the YSYSY group with a difference of only 2%; however, the YSSSY group was the lowest average shear strength value with 15,734 lbf/ft. The average shear stiffness value of the YYYYY group was greater than that of the SSSSS group; however, the average values of these groups were very close to each other with a difference of 0.5%.

A set of one-way analysis of variance (ANOVA) tests were conducted to compare the bending strength, bending stiffness, shear stiffness and shear strength values of five-layer CLT groups. Comparison of p-values from the ANOVA test ($\alpha = 0.05$) showed significant differences in bending strength, bending stiffness and shear stiffness. However, there was only weak evidence for significance in shear strength even though the p-value of that (0.0355) was smaller than alpha of 0.05. The results of Tukey's Honestly Significant Difference (HSD) test are shown in Table 5, where superscript letters indicate significant differences between groups. The bending stiffness (EI) and shear stiffness (GA) properties only showed the letters of “a” and “b” which indicates that the values were within a close range. The SSSSS and YYYYY groups shared the same superscript letters in all properties. For the shear strength values (V_s), the Tukey's HSD test was unable to detect significant differences between the groups, as the standard errors of the differences between the averages of the shear strength values were great.

Failure modes in the five-layer beams from four-point bending were investigated and the distribution of rolling shear, glue failure, shear failure and bending failure was shown in Table 6. While all failure modes were observed in at least half of the specimens from the SSSSS group, bending failure was observed in all specimens of that group. At least two different failure modes in addition to bending failure were observed in 70.0% of the beams in this group. Bending failure was the most common failure mode observed in the YYYYY group, and rolling shear, which was observed in only one beam, was the least common failure mode. In the YSYSY group, all failure modes were encountered in at least four beams out of 10. Shear failure occurred in 80% of the beams in the YSYSY group and each beam showed at least two failure modes at the same time. The SYYYS group was the only CLT groups which exhibited bending failure in all beams. Other failures were also observed. The YSSSY group was the second group of which all beams exhibited one failure mode after the SYYYS group, and the first group in which glue failure was observed in all beams.

Table 6. *Distribution of failure modes for five-layer CLT groups*

Groups	***Bending failure***	***Glue failure***	***Shear failure***	***Rolling shear***
SSSSS	100%	60.0%	50.0%	70.0%
YYYYY	85.7%	57.1%	42.9%	14.3%
YSYSY	50.0%	40.0%	80.0%	60.0%
SYYYS	100%	40.0%	30.0%	40.0%
YSSSY	71.4%	100%	42.9%	42.9%

Note: All beams showed multiple failures, so the percentage of beams does not sum to 100%.

The YSYSY group, which consisted of five-layer CLT with yellow-poplar in the major axis direction and southern pine in the minor axis direction (the YSYSY group), exhibited the greatest bending properties while ranking second in shear properties. The groups that consist of southern pine and yellow-poplar used together in major axis directions (the SYYYS and YSSSY groups) showed good bending and shear properties. When all groups are considered, the groups with more yellow-poplar exhibited slightly better bending and shear properties than the groups with more southern pine. This indicates that southern pine and yellow-poplar exhibited very similar strength and stiffness properties to each other.

5.2. Moisture Content and Specific Gravity Results

5.2.1. Moisture content and specific gravity results of three-layer CLTs

The average moisture content and specific gravity of each three-layer CLT group by species are listed in Table 7. Average moisture contents of southern pine species in the test groups ranged from 11.9% to 13.4% while that of yellow-poplar species in the test groups varied very narrowly between 10.8% and 10.9%. For southern pine species in the three-layer CLT groups, the SSS group with the lowest average moisture content and the YSY group with the largest average moisture content, in contrast, had the highest COV value, 10.2%, and the lowest COV value, 5.64%, respectively. The COV value of yellow-poplar in the groups varied from 4.61% to 8.06%.

Table 7. *Average moisture content and specific gravity values of three-layer CLTs*

Groups	Moisture Content, % (COV)		Specific Gravity, kg/m^3 (COV)	
	SP	YP	SP	YP
SSS	11.9% (10.2%)	- (-)	0.505 (12.4%)	- (-)
YYY	- (-)	10.8% (6.32%)	- (-)	0.493 (11.3%)
SYS	12.8 % (6.25%)	10.9% (8.06%)	0.539 (7.98%)	0.479 (16.0%)
YSY	13.4% (5.64%)	10.9% (4.61%)	0.517 (8.00%)	0.483 (7.35%)
PRG-320	12 ± 3%		0.55[a]	0.43[b]

[a, b] According to national design specification in wood construction (NDS) (AWC, 2018), specific gravities of southern pine and yellow-poplar species are 0.55 and 0.43, respectively.

The average specific gravities of southern pine species in the three-layer CLT groups were between 0.505 and 0.539, which was about -2% to -8% less than the value of 0.55 specified in *National Design Specification for Wood Construction* (NDS) (AWC, 2018). However, the average specific gravities of yellow-poplar species in the groups were between 0.483 and 0.493 and this range was about 12 to 15% greater than the value of 0.43 stated for yellow-poplar in the NDS (AWC, 2018). Similar to the COV values in the MC results, the southern pine species in the SSS group had the lowest SG value and the greatest COV at 12.4%, and the SYS group had the greatest SG value and the lowest COV at 7.98%. The range of COV values of yellow-poplar species in the groups was slightly greater, ranging from 7.35% to 16.0%.

The moisture contents of both species in all three-layer CLT groups were within the 12 ± 3% value required for CLT production in PRG-320 (ANSI/APA, 2019). The COV values for both species were relatively low which indicated no major difference was observed among moisture contents. Although the specific gravity of yellow-poplar species was greater and that of southern pine species was less than the corresponding values in the NDS, which can be associated with the relatively great COV values, there was no abnormal specific gravity value observed among the CLT groups.

5.2.2. Moisture content and specific gravity results of five-layer CLTs

The average moisture content and specific gravity regarding to five-layer CLT group by species are listed in Table 8. The average moisture content of southern pine species in the groups ranged from 11.3% to 13.5%. Similar to the moisture content of the yellow-poplar species in the three-layer CLTs, the yellow-poplar species in the five-layer CLTs varied from 11.1% to 11.3%. The SSSSS and YYYYY groups showed the highest COV value in southern pine and yellow-poplar species with 8.36% and 6.83%, respectively, while the YSSSY group showed the lowest COV values for both species with 4.30% for southern pine and 3.15% for yellow-poplar species.

Table 8. *Average moisture content and specific gravity values of five-layer CLTs*

Groups	Moisture Content, % (COV)		Specific Gravity, kg/m^3 (COV)	
	SP	**YP**	**SP**	**YP**
SSSSS	12.9% (8.36%)	- (-)	0.509 (14.5%)	- (-)
YYYYY	- (-)	11.1% (6.83%)	- (-)	0.488 (10.1%)
YSYSY	13.2% (7.11%)	11.3% (4.43%)	0.591 (13.3%)	0.492 (4.91%)
SYYYS	11.3% (6.36%)	11.1% (4.16%)	0.536 (7.40%)	0.493 (8.73%)
YSSSY	13.5% (4.30%)	11.1% (3.15%)	0.519 (9.67%)	0.487 (6.83%)
PRG-320	12 ± 3%		0.55[a]	0.43[b]

[a, b] According to the National Design Specification in wood construction (AWC, 2018), specific gravities of southern pine and yellow-poplar species are 0.55 and 0.43, respectively.

The specific gravities of southern pine species were between 2.5% and 7.5% lower than the 0.55 value specified in the NDS (AWC, 2018) in all five-layered CLT groups, except the YSYSY group, while the YSYSY group was 7.5% higher. The specific gravities of yellow-poplar species in all five-layer CLT groups were about 0.490, and 14% greater than the value of 0.43 given for yellow-poplar in NDS (AWC, 2018). The SSSSS group showed the greatest COV value for southern pine species with 14.5% and the YYYYY groups had the greatest COV value for yellow poplar species with 10.1%. The YSSSY group showed the lowest COV value for southern pine species with 9.67%, while the YSYSY group exhibited the lowest COV for yellow-poplar species with 4.91%.

The moisture contents of both species in all five-layer CLT groups were within the 12 ± 3% value required for CLT production in PRG-320 (ANSI/APA, 2019). The COV values for both species were relatively low which indicated no major difference was observed among moisture contents. The specific gravity values of the five-layer CLT groups showed very similar results to that of the three-layer CLT groups. This indicated that there was no significantly different value in the specific gravity values of this group.

5.3. Resistance to Shear by Compression Loading Test

The wood failure and the resistance to shear by compression loading strength measured from three-layer and five-layer CLTs and the comparison of wood failure with ANSI A190.1 (ANSI, 2022) are given in Table 9 and Table 10, respectively. The wood failures in the resistance to shear by compression loading test of all three-layer and five-layer CLT beams were less than the minimum acceptable wood failure value for evaluation given as 80% in ANSI A190.1 (ANSI, 2022), and were ranging from 18.7 to 69.3%.

Table 9. *The results of wood failure and bond line shear strength of three-layer CLT beams and the comparison with ANSI A 190.1 values*

Groups	Wood failure, % (COV)	Bondline shear, psi (COV)
SSS	58.1% (49.7%)	423 (25.3%)
YYY	44.7% (77.1%)	399 (23.7%)
SYS	37.9% (97.9%)	306 (40.1%)
YSY	18.7% (48.2%)	401 (18.2%)
ANSI A190.1	≥ 80%	

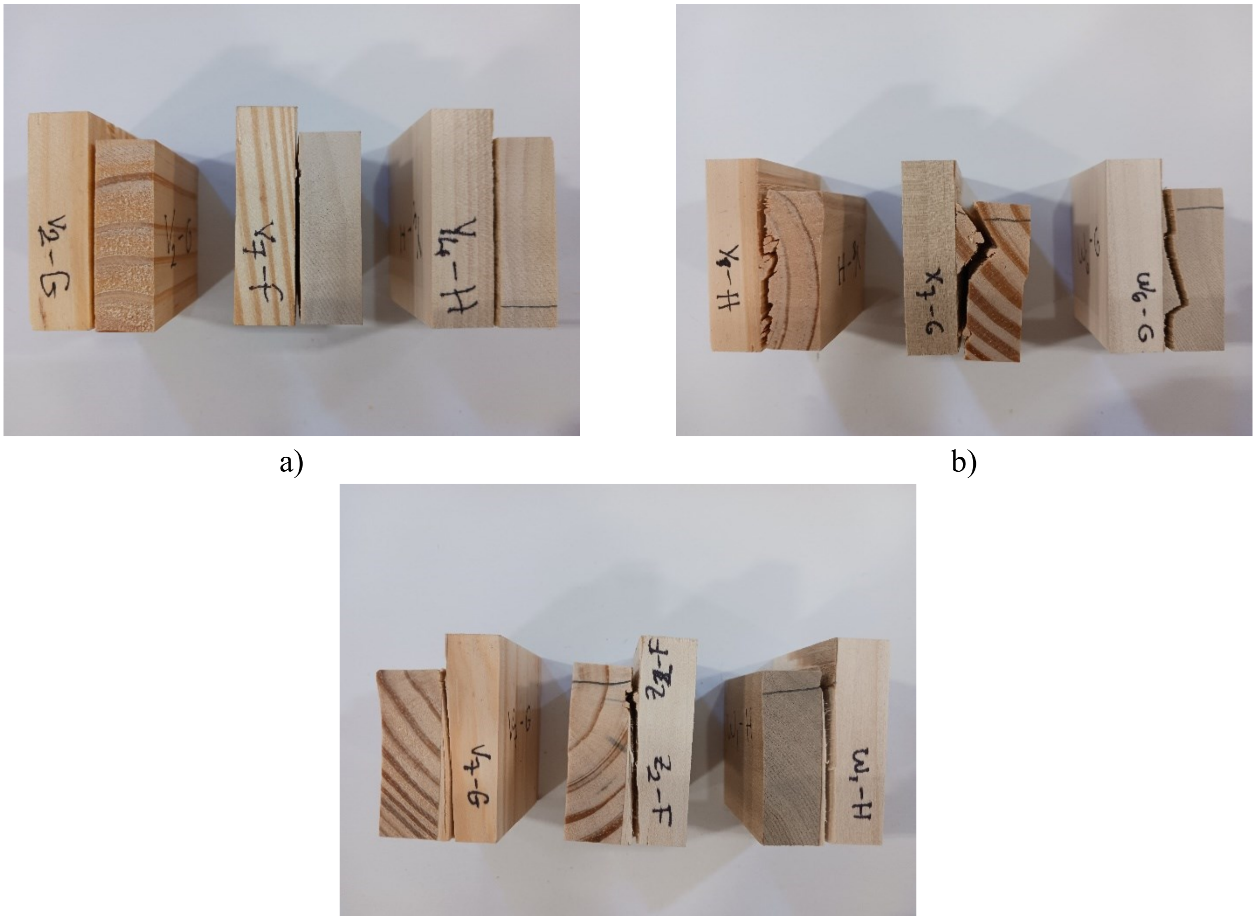
In three-layer CLTs, the groups consisting of only one species (the SSS and YYY groups exhibited greater average wood failure values. The average wood failure value of the group with southern pine in the major axis direction (the SYS group), aside from the SSS group, was greater than the group with yellow-poplar in this axis direction (the YSY group). The YSY group showed the lowest average wood failure values among all CLT groups. A similar trend was observed in the five-layer CLT groups, where groups consisting of only one species (the SSSSS and YYYYY groups) exhibited greater average wood failure values. This was followed by the groups with yellow-poplar and southern pine in their core layers (the YSSSY and SYYYS groups) with wood failure of 57.7% and 53.1%, respectively. The YSYSY group had the lowest average wood failure values.

Table 10. *The results of wood failure and bond line shear strength of five-layer CLT beams and the comparison with ANSI A 190.1 values*

Groups	Wood failure, % (COV)	Bondline shear, psi (COV)
SSSSS	69.3% (15.5%)	419 (15.6%)
YYYYY	66.0% (37.2%)	423 (16.3%)
YSYSY	35.2% (53.2%)	463 (26.6%)
SYYYS	53.1% (43.9%)	383 (16.5%)
YSSSY	57.7% (28.1%)	335 (15.8%)
ANSI A190.1	≥ 80%	

The low wood failure percentage of the three-layer CLT beams was inversely proportional to the number of beams on which glue failure was observed after the bending tests. The highest wood failure value of the SSS group can be attributed to having the lowest glue failure, as shown in Table 4. Similarly, the reason for the YSY group having the lowest wood failure could be due to the observation of glue failure in all specimens of that group. According to Table 4, glue failure was observed in all specimens of the SYS group; however, some individual specimens in this group (high COV value) resulted in a greater wood failure percentage than the YSY group. The average bondline shear strength values applied to the specimens cut from five-layer beams were greater than that applied to specimens cut from three-layer beams which resulted in greater average wood failure values in the five-layer groups compared to the three-layer groups. However, in five-layer CLT groups, a correlation between average wood failure values and glue failure percentages, as shown in Table 6, could not be established as it was done for the three-layer CLT groups.

The three failure modes were observed in the specimens and are shown in the Fig. 15. The failures included adhesive failure (Fig. 15a), rolling shear (Fig. 15b), and shear parallel to grain (Fig. 15c). Both rolling shear and shear parallel to grain are considered as wood failures in resistance to shear by compression loading test, since the failures occurred in wood fibers according to AITC T107 (2007b).



a) b)

c)

Figure 16. *Failure modes in resistance to shear by compression loading test (left: SP-SP, middle: SP-YP, right:SP-YP) a) adhesive failure, b) rolling shear and c) shear parallel-to-grain*

5.4. Resistance to Delamination

The resistance to delamination values of three-layer and five-layer CLTs are given in Table 11. According to AITC T110 (2007a), bondline delamination should not exceed 5% for softwoods and 8% for hardwoods. The average delamination for three-layer CLTs ranged from 16.7 to 44.1%. Among the two groups with yellow-poplar in the major axis direction, the YSY group showed the greatest average face delamination with 16.7%, while the YYY group had the lowest average face delamination with 44.1%. The YSY group was followed by the groups having southern pine in their major axis direction, the SSS and SYS groups, with differences of -23.7% and -49.5%, respectively. In the five-layer CLTs, as in the three-layer CLTs, the greatest average face delamination was obtained by the YSYSY group with 6.74%, followed by the SSSSS group with 9.36%. The SYYYS group showed the lowest average face delamination with 23.5%.

Table 11. The results of face delamination of three-layer and five-layer CLTs and comparison with AITC T110 values

Groups	Face delamination (%)	Groups	Face delamination (%)
SSS	21.9% (111%)	**SSSSS**	9.36% (120%)
YYY	44.1% (61.7%)	**YYYYY**	16.7% (77.8%)
SYS	33.1% (96.1%)	**YSYSY**	6.74% (121%)
YSY	16.7% (137%)	**SYYYS**	23.5% (57.5%)
		YSSSY	14.1% (77.7%)
AITC T110	< 5% for SW < 8% for HW		< 5% for SW < 8% for HW

In both three-layer and five-layer CLTs, the groups with yellow-poplar in the minor axis direction showed lower face delamination compared to the groups with southern pine in this axis direction. Even though the average face delamination of the five-layer CLTs were greater than the three-layer CLTs, the average face delamination values regarding five-layer CLT groups, except YSYSY group, still did not meet the criteria given in the standard. The average delamination value of YSYSY group exceeded the value given for softwoods, however, it was within the allowable range for hardwoods. Observation of glue failures in all CLT groups, except some individual beams, resulted in excessive face delamination.

5.5. Shear Analogy Method Results and Comparison with Allowable Values

The shear analogy (Kreuzinger, 1999) method, as adopted in the US CLT Handbook (Karacabeyli & Douglas, 2013), was applied to predict the bending and shear properties using the NDS values (AWC, 2018) shown in Table 12. The allowable bending strength, bending stiffness, shear stiffness and shear strength values and the values calculated by the shear analogy method of three-layer and five-layer CLTs with their differences were given in Table 13 and Table 14, respectively.

Table 12. NDS values for both Southern pine and Yellow-poplar

Species	F_b (psi)	F_v (psi)	MOE (psi)
Southern pine	1,000	175	1,400,000
Yellow-poplar	700	145	1,300,000

All values calculated using the shear analogy method were less than the ASD-adjusted experimental values for three-layer CLT groups. The comparison of the values obtained from the shear analogy method to the ASD-adjusted experimental values showed that the greatest difference in bending strength (F_bS) and bending stiffness (EI) properties occurred in the SSS group with 203% and 29.5%, respectively. Although the ASD-adjusted values of the SYS group for each property were greater than the shear analogy method values, the differences between them were the lowest among the other groups. The YSY group showed the greatest difference in the shear strength (V_s) values with 160% and the second greatest difference in the shear stiffness (GA) values with 325% when compared to the values obtained from the shear analogy.

Table 13. *Shear analogy and ASD-adjusted bending, and shear test results of three-layer CLTs and their differences*

Groups		F_bS (lbf-ft/ft)	EI (10^6 lbf-in^2/ft)	GA (10^6 lbf/ft)	V_s (lbf/ft)
SSS	***Theo.***	2320	95	0.53	1820
	Exp.	7034	123	1.65	4709
	Diff.	203%	29.5%	211%	159%
YYY	***Theo.***	1630	88	0.49	1490
	Exp.	3707	95	2.26	3326
	Diff.	127%	7.95%	361%	123%
SYS	***Theo.***	2320	95	0.49	1820
	Exp.	3263	102	1.53	2917
	Diff.	40.6%	7.37%	212%	60.3%
YSY	***Theo.***	1630	88	0.52	1490
	Exp.	2926	105	2.21	4157
	Diff.	79.5%	19.3%	325%	179%

Note: Theoretical, experimental (ASD-adjusted) values, and their difference were abbreviated as "*Theo.*", "*Exp.*" and "*Diff.*", respectively.
% Difference = [(Experimental Value – Theoretical Value) / Theoretical Value] x100

For five-layer CLT groups, all values calculated using the shear analogy method, except the bending stiffness (EI) values of the SSSSS and SYYYS groups, were less than the ASD-adjusted experimental values. The shear analogy values of the SSSSS and SYYYS groups for bending stiffness (EI) were 3.42% and 0.55% greater than the ASD-adjusted experimental values, respectively. The differences of YSYSY group for bending strength (F_bS), bending stiffness (EI) and shear strength (V_s) properties were the greatest when the values obtained from the shear analogy method was compared to the ASD-adjusted experimental values. The SYYYS group showed the greatest difference in the shear stiffness (*GA*) values with 393%, while having the lowest difference in the shear strength (V_s) values with 46.4%.

Table 14. *Shear analogy and ASD-adjusted bending, and shear test results of five-layer CLTs and their differences*

Groups		F_bS (lbf-ft/ft)	EI (10^6 lbf-in^2/ft)	GA (10^6 lbf/ft)	V_s (lbf/ft)
SSSSS	***Theo.***	5350	363	1.10	3025
	Exp.	11171	351	3.58	6143
	Diff.	109%	-3.31%	225%	103%
YYYYY	***Theo.***	3750	337	0.98	2480
	Exp.	6591	363	4.04	4490
	Diff.	75.8%	7.72%	312%	81.0%
YSYSY	***Theo.***	3750	338	1.00	2480
	Exp.	15044	409	4.25	6061
	Diff.	301%	21.0%	325%	144%
SYYYS	***Theo.***	5350	363	0.98	3025
	Exp.	11993	361	4.83	4684
	Diff.	124%	-0.55%	393%	54.8%
YSSSY	***Theo.***	3750	338	1.00	2480
	Exp.	6867	381	2.53	5132
	Diff.	83.1%	12.7%	153%	107%

Note: Theoretical, experimental (ASD-adjusted) values, and their difference were abbreviated as "*Theo.*", "*Exp.*" and "*Diff.*", respectively.
% Difference = [(Experimental Value – Theoretical Value) / Theoretical Value] x100

5.6. Comparison of Allowable Values with Grade V3 from PRG-320

The comparison of allowable bending strength (F_bS), bending stiffness (*EI*), shear stiffness (*GA*), and allowable shear strength (V_s) values from the three-layer CLTs with Grade V3 in PRG-320 is shown in Table 15. The highest difference percentage in bending strength was between the SSS group and the Grade V3 with 304%, while the lowest difference percentage was between the YSY group and V3 with 68%. The difference in bending stiffness was the lowest among other properties for three-layer CLT beams. For bending stiffness, percent difference results varied from 0% to 29%. For shear stiffness, the YYY group showed the greater difference with 361%, and the SYS group the lowest with 212%. Similarly for shear strength, the SYS group showed the lowest value with 159%, while the SSS group yielded the greatest value with 159%.

Table 15. *The comparison of bending and shear test results of three-layer CLTs with the Grade V3 in PRG-320*

	% Differences with Grade V3[a]			
Groups	F_bS	EI	GA	V_s
SSS	304%	29%	237%	159%
YYY	113%	0%	361%	83%
SYS	88%	7%	212%	60%
YSY	68%	11%	351%	128%

[a] % Difference = [(Average Group Value - Grade V3) / Grade V3] x100

The comparison of allowable bending strength (F_bS), bending stiffness (EI), shear stiffness (GA), and allowable shear strength (V_s) values from tested five-layer CLTs with Grade V3 from PRG-320 (ANSI/APA, 2019) is shown in Table 16. The YSYSY group with 276% had the highest allowable bending strength among the five-layer CLT groups. The YYYYY group still had a greater bending strength than the Grade V3 standard, with the smallest difference of 65%. Bending stiffness values ranged from -3% to 13% difference over Grade V3 from PRG-320. The bending stiffness values of the SSSSS and SYYYS groups were less than Grade V3, while that of the YSYSY and YSSSY groups exceeded the required value for Grade V3. The YYYYY group only met the requirement for Grade V3 with 0% difference. Shear stiffness and shear strength values showed a consistent trend across all the groups. The shear stiffness and shear strength of all groups were significantly greater than the Grade V3 from PRG-320, with differences ranging from 158% to 393% for shear stiffness, and 48% to 103% for shear strength.

Table 16. *The comparison of bending and shear test results of five-layer CLTs with the Grade V3 in PRG-320*

	% Differences with Grade V3[a]			
Groups	F_bS	EI	GA	V_s
SSSSS	179%	-3%	265%	103%
YYYYY	65%	0%	312%	48%
YSYSY	276%	13%	334%	100%
SYYYS	200%	-1%	393%	55%
YSSSY	72%	5%	158%	70%

[a] % Difference = [(Average Group Value - Grade V3) / Grade V3] x100

The allowable bending strength and shear strength, and shear stiffness values of all tested three-layer and five-layer CLT groups were greater than the Grade V3 values from PRG-320 (ANSI/APA, 2019). When compared for bending stiffness, the values of the SSSSS and SYYYS groups fell below the Grade V3 values, whereas all three-layered CLT groups and the YYYYY, YSYSY, and YSSSY groups from five-layered CLTs either met or exceeded the Grade V3 values from PRG-320 (ANSI/APA, 2019).

6. CONCLUSION

6.1. Conclusion

The goal of this study was to evaluate the mechanical properties of hybrid CLT produced using various lay-ups of softwood and hardwood lumbers in major and minor directions. Future projections indicating an increase in the demand for CLT may lead to a potential shortage of softwood, causing a challenge to the domestic supply in the US, as the current standard, ANSI/APA PRG-320 (2019), only allows for softwood species to be used in the production of CLT. The incorporation of hardwood species in the production of CLT alongside with softwood species can solve this problem, as well as increase the value of underutilized hardwood species in the US. In this context, the efforts to modify the PRG-320 standard to include hardwoods are currently in progress.

In this study, No.2 2 x 6 southern pine and 6/4 No.2 Better yellow-poplar were used for the manufacturing CLT panels in three-layer and five-layer with nine different layup options. CLT panel was assembled in a cold press with a press pressure of 90 psi using a one-component polyurethane adhesive. Each panel was cut into seven CLT beams, and had approximately 12 in. of width and 120 in. of length. The actual depths for three-layer and five-layer CLTs were 4.2 in. and 6.9 in., respectively. All specimens were subjected to four-point, five-point bending tests and shear test, and the data were analyzed using equations specified in Eq. 1, 2 and 3 to obtain bending and shear properties. Other mechanical tests such as resistance to shear by compression loading and resistance to delamination test were also conducted.

The greatest average bending strength with 17,633 lbf-ft/ft, bending stiffness with $123*10^6$ lbf-in^2/ft and shear strength with 14,488 lbf/ft was observed in the SSS group, while the YYY group had greatest average shear stiffness with $2.26*10^6$ lbf/ft for three-layer CLT groups. The YSYSY group showed the greatest average bending strength with 38,006 lbf-ft/ft and bending stiffness with $409*10^6$ lbf-in^2/ft while the greatest shear stiffness with $4.83*10^6$ lbf/ft and shear strength with 19,790 lbf/ft was observed in the SYYYS group. These results indicated that having either southern pine or yellow-poplar in the major axis direction did not affect the bending and shear values obtained from five-point and four-point bending tests. The most common failure types for both three-layer and five-layer CLT groups after bending tests were glue failure and bending failure. Glue failure was more prominent for three-layer CLTs, while bending failure was more common for five-layer groups.

The average moisture contents of southern pine and yellow-poplar species for both three-layer and five-layer CLT groups were within the range of 12% ± 3 given in the standard (ANSI/APA, 2019). The specific gravity of southern pine ranged between 0.505 and 0.591 in all groups, and except for the YSYSY group, all average specific gravity values were below the value (0.55) provided by NDS (AWC, 2018) for southern pine. The range of specific gravity of yellow-poplar was narrow and between 0.479 to 0.493. The average specific gravity of yellow-poplar in all groups was below the value (0.43) given by NDS (AWC, 2018) for yellow-poplar. Both moisture content and specific gravity of southern pine and yellow-poplar were consistent through the study.

Even though the wood failure values in groups consisting of a single species for both three-layer and five-layer CLTs were much greater than other groups; the wood failure values of all groups were below the value of 80% given in the AITC A190.1 standard. The type of the glue and the selection of inappropriate adhesion process parameters may have affected the strength of the bond in the resistance to shear by compression loading test. Overall, the five-layer CLTs required greater amount of force to obtain shear at bondline compared to three-layer CLTs.

The face delamination test was conducted according to AITC T110 (2007a), which allows a maximum face delamination of 5% for softwoods and 8% for hardwoods. Even though the YSY group exhibited the best face delamination percentage among the three-layer CLTs with 16.7%, it did not meet the required value set by the standard. In fact, only the YSYSY group with 6.74% among all CLT groups was below the maximum value allowed by the standard for hardwoods; however, it was still above the value of 5% given in the standard for softwoods.

In conclusion, after the examinations done on the CLT beams to see which type of failure mode was developed following the four-point bending tests, the effects of glue failure were observed in all mechanical tests conducted throughout this study. Apart from this, southern pine and yellow-poplar species exhibited similar performance in terms of strength and stiffness.

6.2. Limitation of Work

- It is important to note that the findings of this study are limited to the specific species used, with southern pine representing the softwood species and yellow-poplar representing the hardwood species, and therefore may not generalize to other hardwood or softwood species.
- It should also be noted that a single production setting including same adhesive and pressure parameters was used for all CLT beams in this study, where CLT beams made of single species or manufactured as hybrid may require different settings.
- Only the values given for the major axis direction were used in calculating shear analogy values, and comparing allowable bending and shear strengths to PRG-320 values, and the behavior of the beams in the minor axis direction was not fully evaluated.

6.3. Recommendations for Future Work

- To fully understand the performance and behavior of CLT beams, similar experiments on CLT beams manufactured using other hardwood and softwood species could be conducted.
- It could be investigated to use different manufacturing settings depending on the species from which the CLT is produced to optimize the production process and potentially improve the performance of CLT beams.
- For a more comprehensive understanding of the performance of CLT beams under different loading conditions, it is important to take into account the values provided for both the major and minor axis directions in the calculations.

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