Material Testing

Production and Performance of Yellow-poplar CLT

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The present article explores the potential of hardwood lumber as a raw material for cross-laminated timber (CLT) production, addressing raw material diversity in mass timber construction. The authors demonstrate the commercial feasibility of manufacturing hardwood CLT panels using yellow-poplar lumber according to ANSI/APA PRG 320 standards using current sawmill setups and their mechanical performance. All panels were manufactured and tested following the ANSI/APA PRG 320 standards, and the data was provided for petitioning the inclusion of hardwood CLTs in the ANSI/APA PRG 320 for yellow-poplar lumber. Comparative analysis indicates significantly higher (1.22 to 13.33 times) strength values for 3-ply and 7-ply CLT than theoretical values obtained from the PRG 320 based standard shear analogy model. The results of this work provide a basis for the utilization of yellow poplar CLTs as a sustainable building material, thus potentially opening the door for new markets for underutilized hardwood species.

Keywords: *Hardwood Cross Laminated Timber, ANSI/APA PRG 320 standards, Yellow-poplar, Shear analogy tool, Mechanical Properties*

Introduction

Cross-laminated timber (CLT) has experienced rapid growth in the construction industry due to its sustainability and structural efficiency. The increasing demand for CLT has emphasized the necessity for diverse and sustainable raw materials, particularly with the rising import of structural-grade lumber in the US (Adhikari et al., 2023). Traditionally, CLT panels have been manufactured using softwood lumber, primarily due to its established supply chain and favorable processing characteristics (Hassler et al., 2024; Adhikari, 2020; Grasser, 2015). Recent research and demonstration projects in the United States explore the potential of utilizing hardwood lumber for CLT production, and the ample availability of hardwood logs in timberlands presents a promising alternative that can benefit both CLT mills and the hardwood industry (Grasser, 2015; Espinoza et al., 2018; Adhikari, 2020; Masoumi et al., 2024). This article examines using additional types of new raw materials for the CLT manufacturing industry by focusing on producing and testing APA custom-grade CLT panels from yellow-poplar (Liriodendron tulipifera) lumber.

The design values in the PRG 320 standard are derived from the Shear Analogy Method; therefore, the first step in standardizing hardwood lumber for CLT is to estimate the structural design values using the same model. Adhikari et al. (2023) developed a Shear Analogy Tool based on the PRG 320 standard to evaluate different wood species' performance on CLT structures and published the data for yellow-poplar lumber. The design values were derived using published mechanical properties and should be verified by testing commercially produced panels to validate that the observed design values fall within an acceptable range.

A secondary goal of this work was to utilize the mechanical test results of yellow-poplar Cross-Laminated Timber (CLT) to apply for a change request in the PRG 320 standard, aiming to include yellow-poplar as the first hardwood species certified for CLT manufacturing for structural use. The primary objectives of this article are, to measure the mechanical properties, and to validate them against the design values determined through the Shear Analogy method. This comparative analysis between commercially produced CLT test data and the Shear Analogy method is crucial for understanding the potential applications of yellow-poplar CLTs. Alignment with established industry standards is vital for successful commercialization. Therefore, this study has the following specific objectives:

1. Produce yellow-poplar CLT panels for structural applications in a commercial manufacturing facility.
2. Evaluate the mechanical strength properties of commercially produced yellow-poplar CLTs.
3. Compare the mechanical strength properties of yellow-poplar CLTs with design values calculated using the Shear analogy model.

Methodology

Lumber inventory

Yellow-poplar lumber was collected from 8 different hardwood sawmills and remanufactured into structural-grade hardwood lumber (SGHL) at Blue Ridge Lumber Millers Tavern, VA. All lumber was graded National Hardwood Lumber Association (NHLA) 2 Common and lower grades at the time of collection and

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regraded after dressing and trimming to the final dimension using structural grading rules for yellow-poplar lumber by a certified Northeastern Lumber Manufacturers Association (NELMA) grader. The corresponding NHLA grade of the lumber was also recorded after remanufacturing as SGHL. The lumber was sawn to 2x6 dimension for the CLT manufacturing process and graded as NO2, NO3, and the Economy (ECO) grade. The final inventory of the lumber is shown in Table 1. It was planned to use NO2 in the major direction and NO3 in the minor direction. However, due to a limited inventory of NO3 lumber, we agreed to use only NO2-grade structural lumber in both directions.

CLT manufacturing

The overall method adopted to produce YP CLTs is shown in Figure 1. Initially, some sample lumber was shipped to SmartLam USA, LLC, Dothan, Alabama, for face bond and mechanical property testing, and some sample panels were produced to evaluate and set the production parameters specific to YP. Nominal 2x6 No. 2 yellow-poplar lamella were used in the specimens' major and minor strength directions to manufacture four 3-ply and 7-ply CLT panels, two each for different orientations. Henkel Loctite HB X032 adhesive and Loctite PR 3105 Purbond primer were used for the finger joints of the lamella, whereas Henkel

Table 1. Lumber inventory supplied for CLT manufacturing.

NHLA grade	**SGHL Grade Lumber Pieces**			**Total**	
	NO 2	**NO 3**	**ECO**	**Count**	**Board Feet (BF)**
Select	280	0	0	280	2,024
1 COM	729	38	37	804	5,823
2 COM	1,358	258	68	1,684	12,143
3 COM	41	26	40	107	758
Total	**2,408**	**322**	**145**	**2,875**	**20,748**

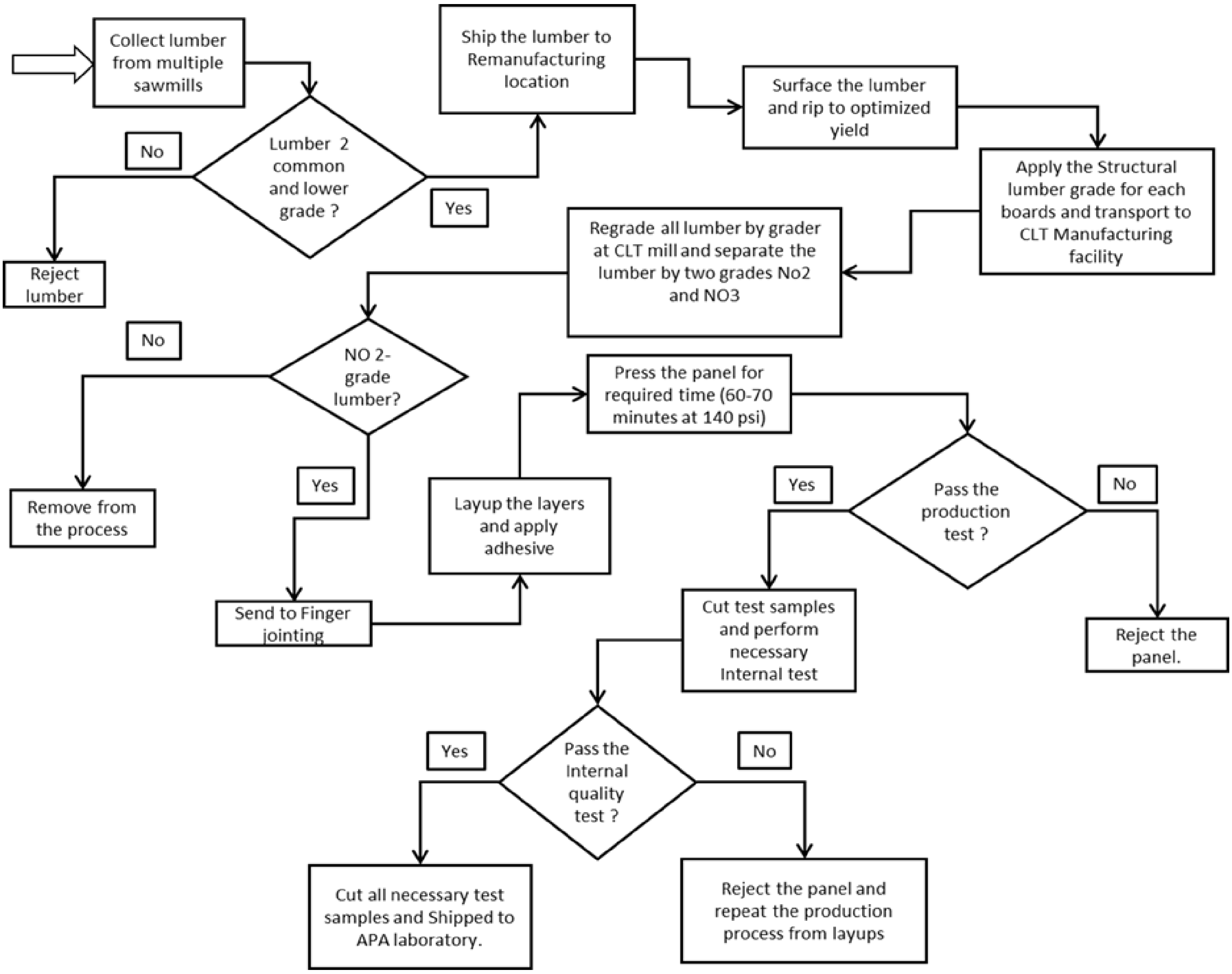

Figure 1. Overall Methodology of YP CLT production.

Loctite HB X202 adhesive and Loctite PR 3105 Purbond primer were used for the face joints of the lamella. A uniform pressure of 140 psi was applied while producing the test panels, and one test panel was manufactured at a time. An APA auditor witnessed the manufacturing process.

Test and data collection.

Description of the Testing facility and specimen

Face bond tests were conducted at the SmartLam facility in Dothan, Alabama, in September 2021 and witnessed by an APA auditor following the PRG-320 standards. Mechanical property tests were completed at the APA Research Center in Tacoma, Washington, in October and November 2021.

After manufacturing, all panels were left in the open environment for more than 24 hours to cure the adhesive. Each panel was evaluated for and passed the manufacturing facility's prequalification test before specimens for mechanical testing were prepared. Block shear and delamination tests are the prequalification tests conducted at the mill facility in Dothan, Alabama, and witnessed by an APA auditor during preparation and testing. All specimens tested in the APA laboratory were produced, wrapped, and protected for moisture conditioning after curing. These specimens were transported in protected wrap from Dothan, Alabama, and evaluated at the Engineered Wood Association (APA) facility in Tacoma, Washington, under as-received moisture conditions.

Block Shear: Block shear tests on test specimens were completed at the Dothan facility, following the guidelines in section 8.2.5 of the ANSI/APA PRG 320 standard. Two glue lines for 3-ply CLTs were evaluated for the 6 different samples, 3 each for both longitudinal and transverse orientation of layups, whereas six different glue lines were evaluated by obtaining 3 samples from each longitudinal and transverse orientation of layups for 7-ply CLTs.

Delamination: Face bond delamination of the panels was evaluated following the guidelines in 8.2 of ANSI/APA PRG 320 with the moisture cycling standard specified in section 8.2.6 of ANSI/APA PRG 320. Three test samples were obtained from both longitudinal and transverse orientation of layups, and a total of six different samples were evaluated for eight bond lines from two glue lines for 3-ply CLTs, whereas 24 bond lines from six different glue lines were evaluated for the 7-ply CLTs.

Mechanical Properties: Four different mechanical properties, Flatwise Bending Moment (F_b,S)$_{eff}$) Flatwise Bending Stiffness ((EI)$_{eff}$), Flatwise Shear Stiffness (GA_{eff}) and Flatwise Shear (V_s) commonly known as the rolling share of CLT panels, were evaluated following ANSI/APA PRG 320 guidelines and procedure. For each layup combination, 10 test specimens were produced for 3-ply and 7-ply CLTs and tested following the guidelines presented in the standard.

The Flatwise Shear Stiffness test was completed based on section 8.5.4 of ANSI/APA PRG 320 following the principles of Sections 45 through 52 and Appendix X4 of ASTM D198. The center-point loading test was completed per sections 45 through 52 of ASTM D198. Tests were conducted on the same specimens with four different span-to-depth ratios, as shown in Table 2.

Equation One

$$G = \frac{6}{5\Theta}.$$

Where,

G = shear modulus (psi) and

Θ = slope of linear regression between $(h/L)^2$ and 1/MOE

Based on the E_{true} and G determined from the tests, E_{app} was calculated using Equation 2 for the third-point load configuration, i.e., a = L/3 and L = 18h.

Equation Two

$$E_{app} = G(3L^2 - 4a^2)E_{true}/[G(3L^2 - 4a^2) + 2.4\ E_{te}h^2$$

Where,

G = shear modulus (psi)
L = 18h (in.),
a =L/3 (in.),
E_{true} = true modulus of elasticity (psi), and
h = specimen thickness (in.).

Then, E_{true} / E_{app} can be evaluated to determine $GA_{effective}$.

The flatwise bending test was conducted according to sections 8.5.3 of ANSI/APA PRG 320, 4 through 12 of ASTM D198, and 8 of ASTM D476. The targeted time to failure was about 5 minutes, and load points were located within ±1/8 in. The details of test samples for flatwise bending tests with third-point loading are shown in Table 3

Table 2. Span-to-depth ratios for 3-Ply and 7-Ply CLTs for Flatwise Shear Stiffness test.

Test ID	Layups			
	3-Ply		7-Ply	
	L/h	(h/L) 2	L/h	(h/L) 2
1	5.6	0.0322	5.5	0.0330
2	6.5	0.0233	6.5	0.0233
3	8.5	0.0139	8.5	0.0138
4	**20.1**	**0.0025**	**20.1**	**0.0025**

Table 3. Test Sample Specification for flatwise bending and flatwise shear capacity test.

Layup	Orientation/ Test Types	Flatwise bending		Flatwise shear
		L (in.)	a (in.)	L (in.)
3-ply	Longitudinal	120	40	24
	Transverse	75	25	24
7-ply	Longitudinal	288	96	54
	Transverse	174	58	54

Based on the theory of elasticity, the bending moment (FbS) and apparent and effective bending stiffness (EI) were calculated using the following equations:

Equation Three

$$F_bS = \left(\frac{P_{ult}}{2}a + \frac{wL^2}{8}\right)\frac{1}{12}(lbf - ft)\ X\ \frac{12}{b}(\frac{in}{in.ft})$$

Equation Four

$$(EI)_{app} = \frac{\theta a(3\mathrm{L}^2 - 4\mathrm{a}^2)}{48}\frac{1}{12}(lbf - in.^2)\ X\ \frac{12}{b}(\frac{in}{in.ft})$$

Equation Five

$$(EI)_{eff} = \frac{(EI)_{app}}{1 - \frac{K_s(EI)_{app}}{(GA)_{eff}L^2}}$$

Equation Six

$$V_s = \left(\frac{P_{ult}}{2}\right)(lbf)\ X\ \frac{12}{b}(\frac{in}{in.ft})$$

Where,

Vs. = interlaminar shear capacity (lbf/ft),

P_{ult} = ultimate total load (lbf), and

b = measured specimen width (in.).

Comparing the Design Value with PRG 320 Derived using SAM-CLT Tool

Finally, the design value based on the ANSI/APA PRG 320 methodology was calculated using the SAM-CLT tool (Adhikari et al., 2023) and compared to (lower tolerance limit (LTL)) / 2.1 for FbS and Vs and the mean value for EI. LTL was calculated using Equation 7, assuming the observed results are normally distributed. As the test sample size is 10, the value of k, 2.104, was calculated.

Where,

$(\mathrm{EI})_{\mathrm{app}}$ = apparent bending stiffness (lbf-in^2/ft),

$(\mathrm{EI})_{\mathrm{eff}}$ = effective bending stiffness (lbf-in^2/ft),

$(\mathrm{GA})_{\mathrm{eff}}$ = evaluated effective shear stiffness (lbf/ft),

$\mathrm{F_bS}$ = bending moment (lbf-ft/ft),

$\mathrm{K_s}$ = 11.27 (shear deformation adjustment factor based on third-point load),

P_{ult} = ultimate total load (lbf),

a = distance between the reaction point to the nearest loading point (in.),

b = measured specimen width (in.),

L = test span (in.),

w = measured specimen weight (lbf/in.), and

θ = Slope of load vs. deflection plot below the proportional limit

Flatwise Shear Capacity was conducted under sections 8.5.4 of ANSI/APA PRG 320, 4 through 12 of ASTM D198, and 7 of ASTM D4761. The bearing length was 4 inches and 6 inches for 3-ply and 7-ply CLT, respectively, and all specimens were cut to length with no overhangs. The test sample was loaded, so the targeted time to failure was about 5 minutes. Based on the theory of elasticity, the interlaminar shear capacity (Vs) was calculated using Equation 6.

Equation Seven

$$LTL = Mean * (1 - \frac{k}{cov})$$

Results and Discussion

Moisture Content of the test samples

The distribution of the moisture content for all test samples at the time of mechanical testing was summarized in Figure 2.

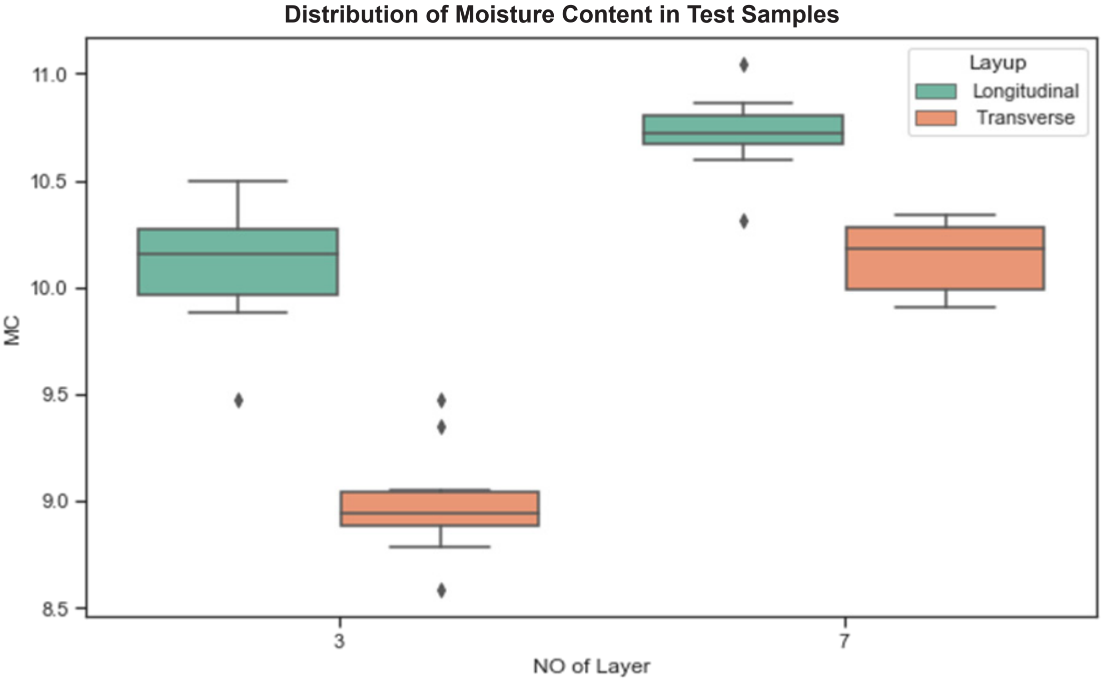

Figure 2. Moisture content distribution for all test samples during mechanical testing.

The moisture content shows minimal variation between the two-layer configurations. For 3 layers, the mean is 9.54%, with a standard deviation of 0.63. The minimum and maximum values are 8.58% and 10.49%, respectively. For 7 layers, the mean is slightly higher at 10.43%, with a smaller standard deviation of 0.34. The minimum and maximum values are 9.91% and 11.05%, respectively. As the test specimens' moisture content is less than 15% and has minimal standard deviation, there will not be a significant difference in the panels' performance for all measured MCs of each specimen. Also, the observed minimum MC for all test samples is higher than 8%, which satisfied the ANSI/APA PRG 320 requirement for the mechanical test according to section 8.5.2.

Block Shear

From the observed data for the glue line wood failure, the 3-layered CLT consistently exhibits an average wood failure of 99 %, with minimal variation (std = 1.94), while the 7-layered CLT had a lower average mean wood failure percentage of 88 with a higher standard deviation of 19.8 %. For the specimen wood failure percentage, the average for all glue lines from each test specimen is the same as for both 3 and 7-layered CLTs, but the standard deviation drops to 1.23 and 9.06, respectively. Based on the observed result, the average wood failure for 3-ply and 7-ply YP CLTs met the requirements of ANSI/APA PRG 320, greater than the minimum required 80% or more, as specified in section 8.3. The observed distribution of the Wood failure of the block shear test by glue lines, specimen, and overall average are presented in Figure 3.

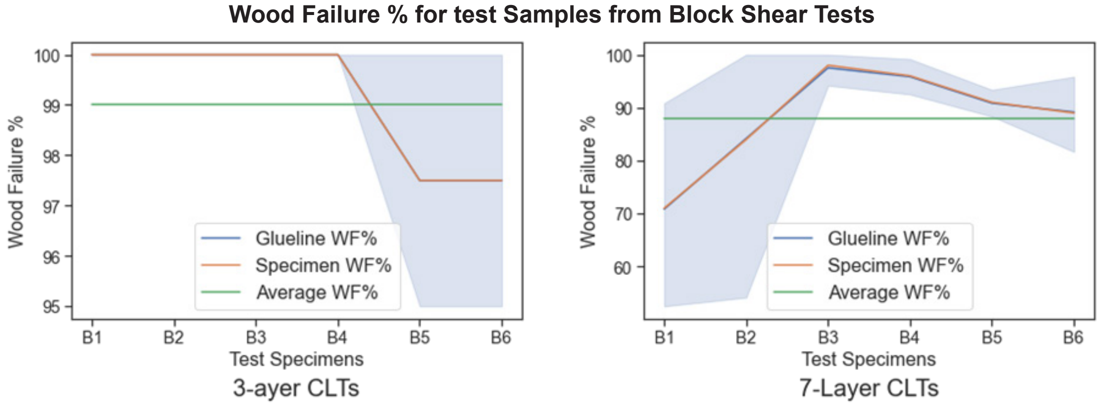

Figure 2. Block shear test percentage of the wood failure.

Delamination test

The ANSI/APA PRG 320 standard specifies that delamination should be less than 5%. The results on all test samples show no delamination in the 3-ply or 7-ply CLT samples. Thus, the delamination levels in both cases meet the minimum requirements set by the ANSI/APA PRG 320 standard, as specified in section 8.2.6.

Mechanical properties of the CLTs

Flatwise Shear Stiffness (GA_{eff})

To determine the flatwise shear stiffness, samples were tested, data was collected as specified in the methodology, and data was synthesized to plot a linear equation graph between (h/L)2 and 1/MOE. From the linear regression plot between (h/L)2 and 1/ MOE, the Slope of the line was utilized to calculate the shear modulus G for each test sample group. The regression plot for each test group sample is presented in Figure 4. Etrue was then calculated as the reciprocal of the Intercept of the regression line for each test sample group. The value of G was calculated using Equation 1. Here, preset is a sample calculation or GA_{eff} for 7-ply transverse layup CLTs,

The average thickness of the CLTs (h) = 9.6inches
The average width of the CLTs (w) =12 inches
Area (A) =115.2 Square inches

The linear equation connecting the average of all test values at a different thickness-to-length ratio is y= 23.42X+1.9016, the Slope (θ) = 23.42 and Intercept = 1.90. Thus, E_{true} = 1/Intercept = 0.526x10^6 psi and G=6/5ϴ so G= (6/ 5*23.42), which gives G = 0.051 x10^6 psi - Thus using Equation 2 E_{app} can be determined for L= 18 h = 172.80 and a= L/3 = 57.60, so E_{app} = 0.511X 10^6 psi.

Knowing G, A, Etrue, and E_{app}, all other required parameters can be determined for further calculation. Thus, data are summarized with other determined values based on the E_{true} and G and presented in Table 4 for all CLT layups.

Table 4. Summary of Yellow-poplar CLT flatwise shear modulus test results.

Layup	Orientation	E_{true} (10^6 psi)	G (psi)	E_{app} (10^6 psi)	E_{true}/ G	E_{true}/ E_{app}	$(GA)_{eff',f.}$ (10^6)	PRG 320-derived (10^6)
3-ply	Longitudinal	1.515	53,651	1.400	28.2	1.082	2.66	0.49
	Transverse	0.101	131,901	0.100	0.8	1.002	0.49	0.49
7-ply	Longitudinal	1.085	51,957	1.023	20.9	1.061	6.53	1.5
	Transverse	0.526	51,217	0.511	10.3	1.030	6.0	1.5

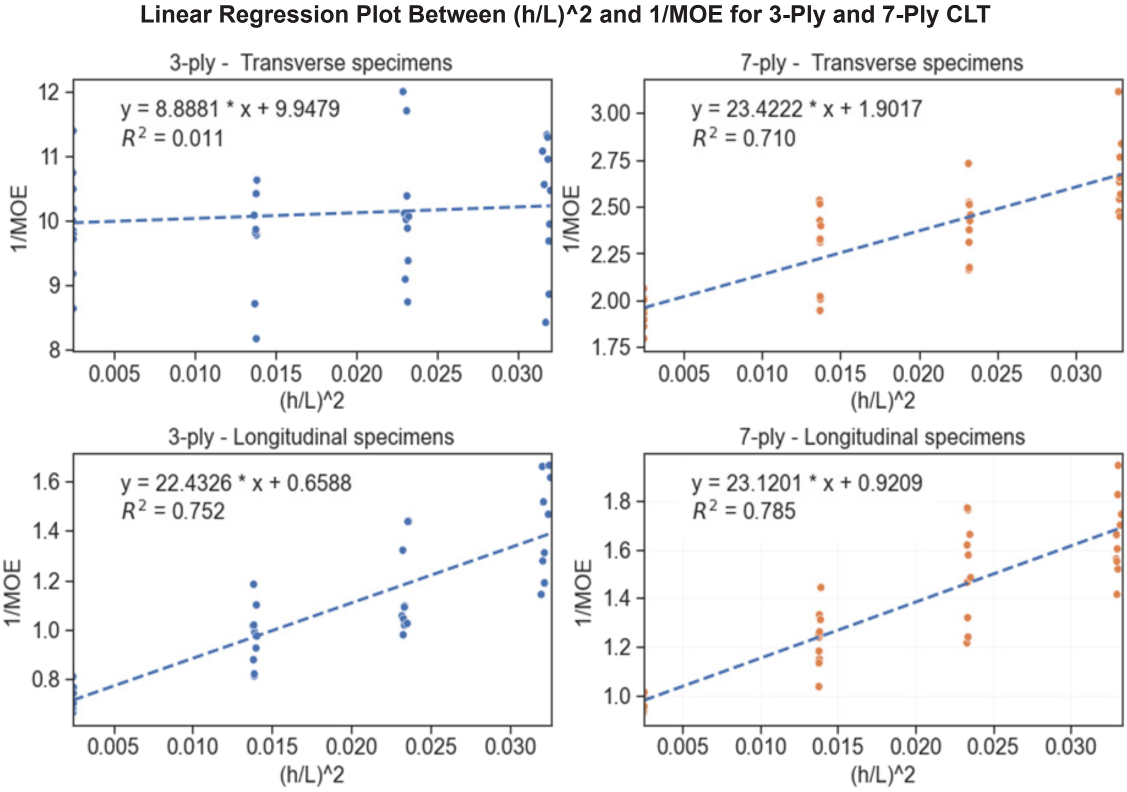

Figure 4. Linear regression plot between (h/L)2 and 1/MOE.

Figure 5 presents the distribution of the results for each test specimen for flatwise bending capacity, effective bending stiffness, and flatwise shear capacity with third-point loading, summarizes them in Table 5, and discusses them in subsequent paragraphs.

Flatwise Bending Moment ($(F_b,S)_{eff}$)

A total of 10 samples were tested for each layup sample group, and bending moments were calculated. Equation 3. For three-layer layups, the longitudinal bending moment (FbS) was in a range of 11,050 to 19,926 with a standard deviation of 2735, while transverse bending moment values ranged from 2,538 to 4,553 with a standard deviation of 667. For the seven-layer longitudinal layups, bending moments values were distributed from 40,700 to 60,483 SD of 5752, and transverse layups strength values were distributed from 32,678 to 48,878 with SD of 5054.

Flatwise Bending Stiffness ($(EI)_{eff}$)

Effective bending stiffness (EI)eff evaluated using Equation 5 after evaluating (EI)app using Equation 4. The test values for three-layer longitudinal layers ranged from 100 to 124 with an SD of 6.63, whereas the transverse layers test values were from 5.66 to 8.19 with an SD of 0.78. Seven-layer layups of test panels exhibit a wider range and are distributed between 925 and 1,083 with an SD of 46 for longitudinal layups and 411 and 501 with an SD of 31 for transverse specimens.

Flatwise Shear (V_s)

For the flatwise shear of each test, specimens were evaluated using Equation 6 for all test groups. For the three-layer test panels in the longitudinal direction, the test values ranged from 10,153 to 15,865 with a higher SD of 1847, whereas transverse layup samples produced test values ranging from 3,281 to 6,556 with an SD of 1144. Seven-layer test samples with longitudinal layups test values spread from 23,295 to 36,536 with an SD of 3618, and transverse test samples values were distributed from 20,521 to 27,412 with an SD of 2956. The predicted design value based on the ANSI/APA PRG 320 methodology calculated using the SAM-CLT tool (Adhikari et al., 2023) was also included in Table 5.

Comparing the Design Value with PRG 320 Derived using SAM-CLT Tool

The test data of the 3-ply and 7-ply CLT types showed significantly higher values when compared with PRG 320-derived data for all mechanical properties evaluated, as presented in Table 4 and Table 5. For the 3-ply layer, flatwise bending moment test values at parallel and perpendicular layups are 2.92 and 4.38 times higher, whereas flatwise bending stiffness test values were approximately 1.27 and 2.06 times higher, respectively. Flatwise Shear for parallel and perpendicular layups exceeded PRG 320 derived data by 3.2 and 2.41 times, whereas flatwise shear stiffness test data were 5.43 and 13.33 times higher, respectively. Similar trends were found for the 7-ply layer, with test data consistently surpassing PRG 320 derived data across all mechanical properties evaluated. Flatwise bending moment values are 2.67 and 3.14 times higher for the test values, whereas flatwise bending stiffness test values are approximately 1.22 and 1.37 times higher for parallel and perpendicular layups, respectively. Flatwise shear for parallel and perpendicular layups exceeded PRG 320 derived data by 3.11 and 3.31 times, whereas flatwise shear stiffness test data were 4.0 and 3.93 times higher

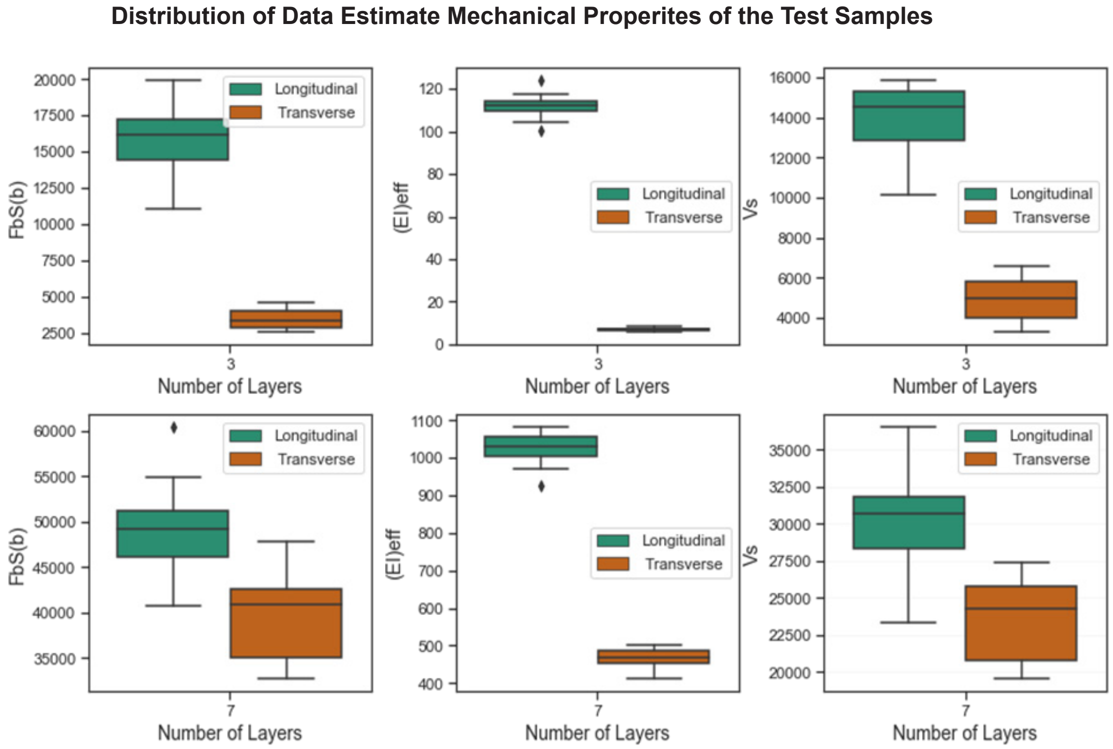
Distribution of Data Estimate Mechanical Properites of the Test Samples

Figure 5. Distribution of the test data.

than derived data. These observations validate that the derived values can be used confidently for structural application in the future design of the CLTs using yellow-poplar lumber.

Table 5. Summary of mechanical test results for yellow-poplar CLTs.

Layers		N	Mean	Maximum	Minimum	COV	LTL normal distribution	LTL/k	PRG 320-derived
3-ply	$(F_bS)_{\mathrm{eff},0}$	10	15731	19926	11050	0.17	9977	4751	1630
	$(EI)_{\mathrm{eff},0}$	10	112	124	100	0.06	112	112	88
	$(F_bS)_{\mathrm{eff},90}$	10	3427	4553	2538	0.20	2023	963	220
	$(EI)_{\mathrm{eff},90}$	10	7.00	8.20	5.70	0.11	7	7	3.40
	$(V_s)_0$	10	13907	15864	10153	0.13	10021	4772	1490
	$(V_s)_{90}$	10	4908	6556	3281	0.23	2501	1191	495
7-ply	$(F_bS)_{\mathrm{eff},0}$	10	49257	60483	40750	0.12	37114	17673	6625
	$(EI)_{\mathrm{eff},0}$	10	1023	1083	925	0.05	1023	1023	836
	$(F_bS)_{\mathrm{eff},90}$	10	39681	47878	32678	0.13	29047	13832	4400
	$(EI)_{\mathrm{eff},90}$	10	463	501	411	0.07	463	463	337
	$(V_s)_0$	10	30346	36536	23296	0.12	22734	10826	3475
	$(V_s)_{90}$	10	23459	27412	19521	0.13	17238	8209	2480

Conclusions

Our study results confirm that manufacturing yellow-poplar CLT panels on a commercial scale requires no additional investments depending upon the existing setup of the mills in the US. Based on current practice, mills producing any CLTs can manufacture yellow-poplar CLTs commercially with minimal technological adjustments, such as glue type, pressing force, and press time. Our study was completed at a higher press force of 140 psi for 60 minutes using Henkel Loctite HB X032 adhesive and Loctite PR 3105 Purbond primer. These panels, made with No. 2 yellow-poplar wood in major and minor directions, were tested for 3-ply and 7-ply panels and evaluated and compared to meet the ANSI/APA PRG 320 standard requirements. The observed results explain that these panels met the requirements for block shear and delamination set by the PRG 320 standard, and for mechanical properties, all test samples exceed the theoretical design values significantly, showing their exceptional strength and reliability for structural application. The observed results from this study were utilized to apply for a change in PRG 320 to include yellow-poplar lumber as the first hardwood species. As of August 2024, this proposal is in the final voting stage for inclusion in the new version of the standard, which is set to be published by December 2024 and will include the VH1 grade, identifying it as a visually graded hardwood CLT grade.

This study also finds that yellow-poplar cross-laminated timber panels are strong and suitable for structural application. Moreover, this study provides valuable insights into the strength properties of yellow-poplar CLTs, helping architects, engineers, and builders understand their potential better. Looking ahead, the continued growth in the mass timber sector in the US and the use of yellow-pollar CLT panels in structural applications can lead to more eco-friendly and innovative building solutions, shaping the future of sustainable construction. Commercial acceptance of the hardwood species in mass timber construction eventually helps remove more wood from the forest as most hardwood species are now not harvested significantly due to a lack of market. This research team believes the results will have positive implications and help open a new hardwood lumber market as sustainable raw materials for the CLT industry.

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