

Cross-Laminated Timber Panels Produced from Low-Grade Yellow-Poplar Sorted by Structural Visual Grade

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Abstract

Low-grade yellow-poplar (*Liriodendron tulipifera*) graded No. 2 Common, and No. 3 Common (National Hardwood Lumber Association - NHLA rules) is mainly used by the industry to produce wood pallets. Cross-laminated timber (CLT) panels are options to diversify the usage and increase the value of this material. Therefore, the objective of this study was to produce CLT panels from a population of NHLA graded No. 2A, No. 2B, No. 3A, and No. 3B lumber and to evaluate whether the panel properties meet the bending criteria (major strength direction) and adhesive bond requirements listed for “V” type CLT in ANSI/APA PRG 320-2019 (2020) using Northeastern Lumber Association Manufacturers No. 2 and No. 3 in longitudinal and transverse layers, respectively. Ten panels were produced to evaluate the bond quality and mechanical properties. The bond test results showed average delamination under 5 percent and were more frequent in the central areas of the panel than in the outer panel areas. The results from testing showed that the calculated allowable stress-design bending-strength (major direction) value for the yellow-poplar CLT panels was 1,718 psi (11.84 MPa), which corresponds to a value 90 percent higher than V1 (900 psi, 6.20 MPa) layups. Modulus of elasticity (MOE; major direction) was comparable to V2 and V3, with an average MOE of 1.39 by 10⁶ psi (9,584 MPa). Based on these findings, the study indicated the potential for using low-grade yellow-poplar lumber to produce CLT panels. However, more research is needed to evaluate other mechanical properties in both the major and minor axis.

The Cross-Laminated Timber Handbook (Karacabeyli and Douglas 2013) describes the initial steps of panel making, including, but not limited to the following: lumber selection and grouping, surface cleaning, panel layout, and pressing. The handbook also highlights the factors of a successful production line: material quality and consistency in bonding parameters. The board quality is usually ensured by qualifying the lumber by visual structural grades or mechanically (Brandner 2013). The latter option is a more effective assessment because stress-rated boards provide MOE, which correlates well with bending strength (Ross 2015), an important property dictating usage.

The current North American cross-laminated timber (CLT) standard ANSI/APA PRG 320-2019 (2020) provides the strength requirements and test methods to evaluate a CLT panel layout. This qualification of panels ensures resistance in using these panels and considers the panel

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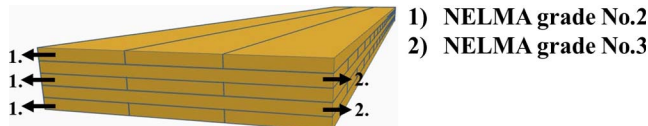


Figure 1.—Cross-laminated timber panel layup configuration based on boards' visual structural grade.

properties and reduction factors applied to timber in construction. Although, in this current version of the standard only softwoods and engineered wood products (laminated veneer lumber [LVL], laminated strand lumber, and oriented strand board) are presented as options for CLT production, limiting the usage of hardwoods. Yellow-poplar (*Liriodendron tulipifera*) has been previously evaluated and determined as having potential species for use in structural products, either as glulam beams (Moody et al. 1993) or CLT panels (Mohamadzadeh and Hindman 2015).

Bonding-wise, one of the challenges of gluing hardwoods is the wide range of porosity between species; their anatomy can facilitate or block adhesive penetration (Ross 2010). Additionally, hardwoods generally have dense wood with thicker cell walls and smaller lumens, further hampering adhesive penetration (Ross 2010). Compared with most hardwood species, yellow-poplar possesses a relatively low specific gravity of 0.43 (American Wood Council 2018). Hovanec (2015) tested the bonding condition of single-layer yellow-poplar samples bonded with resorcinol formaldehyde to simulate the production of CLT panels and found that the species produced adequately strong bonds to meet requirements from ANSI/APA PRG 320-2019 (2020).

This research aimed to evaluate full-scale CLT panels produced from low-grade (NHLA) yellow-poplar from the Appalachian region following visual structural grade layup methods—specifically, to use the visual grade recommendation for softwoods from ANSI/APA PRG 320-2019 (2020) to produce CLT panels and compare bending in major strength direction with standard “V” layups. Additionally, the CLT panels were evaluated for bond quality to characterize these panels according to ANSI/APA PRG 320-2019 (2020).

Materials and Methods

Low-grade yellow-poplar boards used in this research were from a population of 8,000 board-feet (18.9 m³) of kiln-dried, rough-cut yellow-poplar classified by NHLA (2014) rules as 2A Common and below, obtained from a mill in northern West Virginia. The target moisture content reported by the manufacturers was between 6 percent and 8 percent. The boards were surfaced on four sides (S4S) and regraded according to Northeastern Lumber Association Manufacturers (NELMA 2013) grades. The final dimension of each board was 6 inches wide, 0.75 inches thick, and 10 feet long (152 mm wide by 19 mm thick by 3,048 mm long). The selection of the boards to compose the panels was based on their structural visual grade, similar to ANSI/APA PRG 320-2019 (2020) recommendation for visual grades in softwoods. The boards used in the CLT panels (designated as YP) were as follows: NELMA No. 2 in longitudinal layers and NELMA No. 3 in transverse layers (Fig. 1).

Ten repetitions of five-layer CLT panels were produced. Each panel was 3.75 inches deep, 18 inches wide, and 120

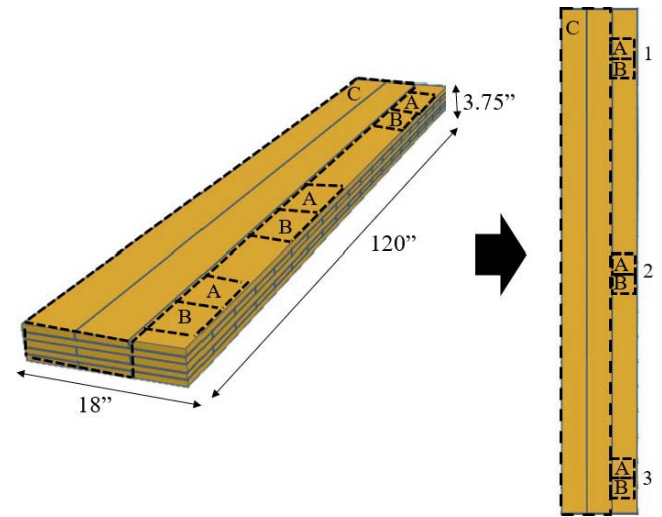


Figure 2.—Cross-laminated timber panel dimensions and specimens' layup. Where 1, 2, and 3 are the specimens' positions within a panel; A is the cyclic delamination specimens; B is the shear block specimens; C is the bending flatwise specimens.

inches long (95.25 mm by 457.2 mm by 3,048 mm). The panel size was chosen to fit the requirements of the mechanical tests from ANSI/APA PRG 320-2019 (2020). Specifically, the panel dimensions were selected to include bending flatwise following ASTM D198 (ASTM 2015). To ensure the panels' bond quality, shear block and cyclic delamination tests were conducted per ASTM D905 (ASTM 2010) and ASTM D1101 (ASTM 2013), respectively. To produce representative specimens from across the panel, the shear block and delamination specimens were taken from three different positions from the panel (from both ends and the middle). A representation of the panel's sampling positions is presented in Figure 2.

Panel production started by surfacing the two wide faces of the selected boards in a moulder. The surfaced boards were then transferred to a layup table for panel assembly. A Franklin Advantage EP-950 two-part adhesive (acrylic-based emulsion polymer isocyanate system, EPI and H-200, a diphenylmethane diisocyanate, MDI, hardener) was applied to each layer, creating four glue lines. The bonding and pressing parameters used to produce the CLT panels are presented in Table 1. The manufacturer's recommendations were slightly adjusted regarding pressure, adhesion rate, and press time to best meet the laboratory preparation environment and conditions. The adjustments are as follows.

Table 1.—Cross-laminated timber panel making parameters for full-length panels.

Parameter	Value
Adhesive spread rate	78 lbs./1,000 ft ² (384 g/m ²)
Resin:hardener	100:15 parts
Nominal pressure	231 psi (1.59 MPa)
Clamping time	6 h
Resting period*	12 h

* Resting period was the minimum period of time the panel remained in the press without moving.

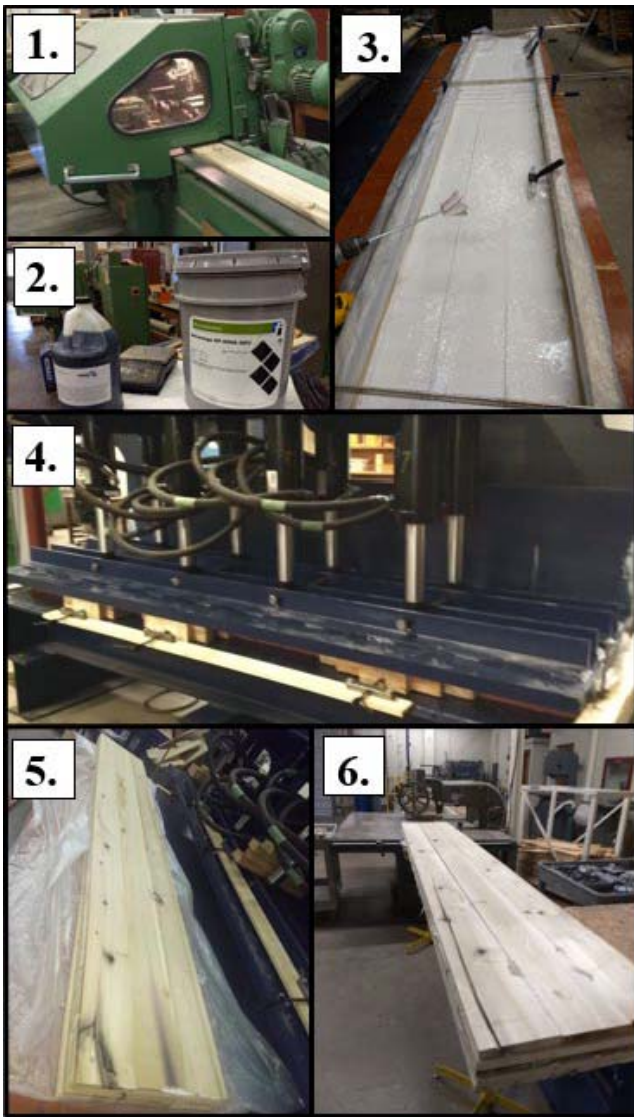


Figure 3.—A photographic composite containing the cross-laminated timber panel production steps. Where 1. Moulder used to surface the boards; 2. Adhesive and hardener used; 3. Adhesive application to each individual laminate; 4. Hydraulic plate press during panel pressing, with side restrictions; 5. Panel after being pressed outside the press; 6. The cross-laminated timber panels during processing to individual test specimens.

Each lamination was laid on the assembly table, and the adhesive mixture was weighed, applied, and spread by rubber rollers. To ensure proper adhesive application, 18 percent additional adhesive was used to compensate for the adhesive loss in tools and equipment (e.g., mixture pails, rollers, etc.) and the board equilibrium moisture content of 6 percent. The adhesive manufacturer recommended moisture content (MC) between 8 and 12 percent. Lumber with a lower MC would tend to absorb more adhesive during bonding, limiting the available adhesive to secure a bond between two faces. Therefore, additional adhesive was used to ensure a proper amount of adhesive at each interface.

After adhesive application, the panel was placed in a 3.5-inch (88.9-mm) -deep frame covered in plastic for easy

removal. The panel was then pressed using a specially designed hydraulic press. Lateral bracing was applied to both sides and ends to restrict the boards' movement during pressing and remove lateral gaps between boards in both directions. With the panel restricted inside a mold in the press, nominal pressure of 231 psi (1.59 MPa) was applied and held for 6 hours before release. Although the nominal pressure was higher than the adhesive product datasheet specification of 175 psi for hardwoods, additional pressure was applied to compensate for any pressure variation across the press plate and in lumber thickness throughout the panel. The pressing time was longer than the 1-hour recommendation from the adhesive manufacturer to compensate for the additional adhesive and to ensure complete drying, given the panel was wrapped in plastic. However, the additional curing time was not expected to impact the mechanical strength of the panel, rather necessary to ensure the best bonding possible given our limitations in equipment setup. The panels were left in the press for an additional 14 hours under no load before moving for further processing to ensure complete adhesive curing. An illustration of the CLT panel production method is presented in Figure 3.

After pressing and resting, the 10 CLT panels were processed into test specimens. One flatwise bending specimen, three shear block specimens, and three cyclic delamination specimens were prepared from each individual panel. The dimensions of the flatwise bending specimen were 3.75 inches thick by 12 inches wide by 120 inches long (95.25 mm by 304.8 mm by 3,048 mm), following ASTM D198 (ASTM 2015), and the failure modes were classified according to ASTM D143 (ASTM 2021). The bonding specimens were six blocks of 3.75 inches thick by 3 inches wide by 3 inches long (95.25 mm by 76.2 mm by 76.2 mm) following ASTM D905 (ASTM 2010). The full panel dimensions and the specimens' locations and sizes are presented in Figure 2.

To evaluate the prediction of bending properties, the theoretical effective bending stiffness (EI_{eff}) and the effective bending strength ($F_b S_{\text{eff}}$) of the panels were calculated based on formulas published in the CLT Handbook (Karacabeyli and Douglas 2013), using design values published in the National Design Specification - NDS (American Wood Council 2018) as shown in Equations 1, 2, and 3. The values of allowable stress design (ASD), modulus of elasticity (MOE), and bending strength (F_b) in bending were calculated according to ANSI/APA PRG 320-2019 (2020) and D2915 (ASTM 2016), as shown in Equations 4 and 5.

$$(EI)_{\text{eff},y} = \sum_{i=1}^n E_i \times b_y \times \frac{t_i^3}{12} + \sum_{i=1}^n E_i \times b_y \times t_i \times z_i^2 \quad (1)$$

$$S_{\text{eff}} = \frac{2EI_{\text{eff}}}{Eh} \quad (2)$$

$$F_b S_{\text{eff}} = \frac{0.85 \times F_b \times S_{\text{eff}}}{12} \quad (3)$$

where b_y is width of the panel for the parallel layer (inches); E_i is the average modulus of elasticity of i th layer (psi); t_i is the thickness of the i th layer (inches); z_i is the distance between the center point of the i th layer and the neutral axis (inches); h is the panel depth (inches); F_b is the board

Table 2.—Bending test results of the bending test for visually graded yellow-poplar (YP) test specimens.

Specimen ID	Ultimate load		F_b		MOE ^a		Failure mode
	lbs	kN	psi	Mpa	10 ⁶ psi	Mpa	
YP-1	6,675	29.7	4,609	31.8	1.40	9,637	Simple Tension
YP-2	7,478	33.3	5,162	35.6	1.27	8,780	Simple tension
YP-3	6,352	28.3	4,390	30.3	1.47	10,141	Simple tension
YP-4	6,718	29.9	4,562	31.5	1.37	9,455	Simple tension
YP-5	8,154	36.3	5,606	38.7	1.33	9,195	Simple tension
YP-6	9,848	43.8	7,028	48.5	1.47	10,119	Splintering tension + Simple tension
YP-7	9,660	43.0	6,702	46.2	1.31	9,054	Cross-grain tension + Simple tension
YP-8	9,139	40.7	5,797	40.0	1.28	8,822	Splintering tension
YP-9	9,139	40.7	6,190	42.7	1.40	9,619	Simple tension
YP-10	9,791	43.6	6,828	47.1	1.55	10,680	Splintering tension
Mean	8,295	36.9	5,687	39.2	1.39	9,550	
Minimum	6,352	28.0	4,390	30.3	1.27	8,780	
Maximum	9,848	44.0	7,028	48.5	1.55	10,680	
5th percentile	6,497	28.9	4,467	30.8	1.27	8,799	
ST.DEV. ^b	1,395	6.20	988	6.81	0.09	621	
COV (%) ^c		17		17		6	

^a MOE is modulus of elasticity. 1,000,000 psi = 6,895 MPa.

^b ST.DEV. is the standard deviation.

^c COV is the coefficient of variance.

bending strength (psi); E is the board elasticity (psi); and S_{eff} is the effective section modulus (in³)

$$PTL = x - (s \times K) \quad (4)$$

$$F_b = PTL/2.1 \quad (5)$$

where PTL is Parametric Tolerance Limit (psi); x is the population mean (psi); s is population standard deviation (psi); K is the tabulated K factor; and F_b is the characteristic bending strength.

A Digital Image Correlation (DIC) system also was used to evaluate strain development and investigate potential failure mechanisms. This system consisted of two fast-speed cameras being used by Aramis software (version 8) to record the specimen stress-strain during the bending test. The CLT panel was coated with a layer of white background paint and then black speckles were applied in a stochastic pattern. The stochastic speckle pattern helps the camera system to distinguish the material's surface. The software tracks the spatial distance between the black speckles during loading. The images also were used to investigate layer effects and defects in the panels to strain development. The software used for data management was Microsoft Excel 365, and statistical analyses were conducted in Program RStudio (version 3.6.3).

Results and Discussion

Bending results

Table 2 shows the results from third-point bending tests of the CLT specimens. The failure type elicited from the panels helped elucidate potential issues resulting from the cyclic delamination results, which did not occur. The F_b has a coefficient of variance (COV; 17%) that was slightly higher than the recommended COV of 15 percent from PRG 320-2019 (ANSI/APA 2020). However, this variation was accounted for when calculating the parametric tolerance limit (PTL) and the associated ASD design values. This variation could result from the board selection process and

randomized placement in the panel, as compared with selective placement. The boards were selected from a set of visually graded lumber previously reported to have a considerable range of MOE for yellow-poplar boards (Azambuja et al. 2022). This range of boards' mechanical properties could have affected the variation in mechanical properties of the CLT panels. Additionally, prior research on layered composites reported that visually graded veneer resulted in LVL panels with higher COV than observed when using nondestructively sorted veneer (Sharp 1985).

Figure 4 and Figure 5 show examples of the DIC system results. The analyses compared specimens with high and low bending results and compression and tension strain during testing. The results indicated an expected behavior during testing that the strain (tension and compression) built up in the outer areas of the panel. Also, the DIC analysis showed that YP-2 and YP-3, which had lower MOE and F_b results, had noticeable preliminary failures before the final major failure. In higher strength CLT panels (e.g., YP-10 and YP-6), the DIC analysis indicated that these panels better resisted the forces (i.e., lower strain) until the final major failure. The strain map images showed no evidence of bondline failure during the test, and layer effects were only visible after failure followed the grain orientation.

The theoretical and experimental bending strength and bending stiffness are shown in Table 3. The calculated and experimental values differ because of the more conservative nature of theoretical values. These theoretical values were calculated based on the thickness of the produced panels and

Table 3.—The theoretical and experimental results from the yellow-poplar cross-laminated timber panels.

Bending properties ^a	Theoretical value	Experimental value
EI_{eff} (10 ⁶ lbf-in ² /ft of width)	54.7	73.3
$F_b S_{\text{eff}}$ (lbf-ft/ft of width)	1,113	4,026.56

^a EI_{eff} is effective bending stiffness, and $F_b S_{\text{eff}}$ is effective bending strength.

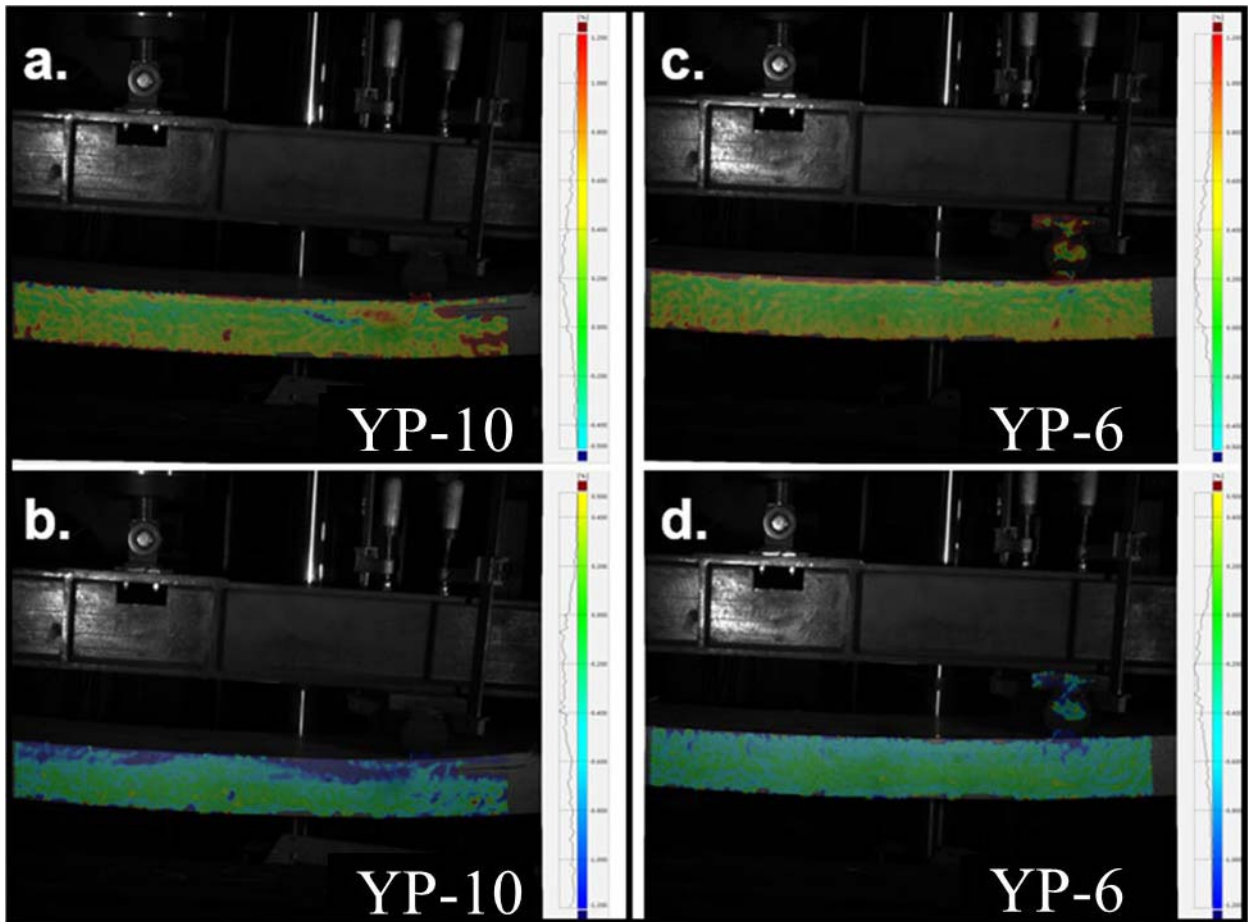


Figure 4.—The frame captured by the digital image correlation system prior to major panel failure. (a) YP-10 panel in tensile strain; (b) YP-10 panel in compressive strain; (c) YP-6 panel in tensile strain; (d) YP-6 in compressive strain.

compared with panels having a similar thickness. These research panels had a thickness of 3.75 inches, so the comparison with ANSI/APA PRG 320-2019 (2020) was done using the produced panel’s F_b and E .

Table 4 compares the visual layups from ANSI/APA PRG 320-2019 (2020) and the characteristic values from the set of panels made from yellow-poplar visually graded in this research. The average moisture content of the panels was 6.2 percent. When the panel properties were adjusted from 6.2 percent to 12 percent moisture content using

ASTM D-1990 (ASTM 2019), the MOE was reduced by 8.3 percent to 1.27 by 106 psi (8,687 MPa), while F_b remained the same. The sawmill dried the yellow-poplar boards to a target MC of 6 percent to 8 percent. This target MC was used by the local industry to meet the equilibrium MC of the region, which was corroborated by the final board and panel equilibrium moisture content. Therefore, the resulting mechanical properties found in this study would be expected to represent general CLT panel manufacturing in this region.

Table 4.—Comparison between the calculated allowable stress design reference design value tested layup and ANSI/APA PRG 320-2019 (2020) published values.

Layups	F_b (psi)	MOE (10^6 psi) ^a	Longitudinal layers	Transverse layers
YP* ^b	1,718	1.39	No. 2 Yellow-poplar (YP)	No. 3 YP
V1	900	1.6	No. 2 Douglas fir Larch (DL)	No. 3 DL
V1(N)	850	1.6	No. 2 Douglas Fir–Larch North	No. 3 DL North
V2	875	1.4	No. 1–2 Spruce–pine–fir (SPF)	No. 3 SPF
V3	750	1.4	No. 2 Southern Pine	No. 3 SP
V4	775	1.1	No. 2 SPF South	No. 3 SPF South
V5	850	1.3	No. 2 Hem–fir (HF)	No. 3 HF

^a MOE is modulus of elasticity.

^b *YP is the research in this study.

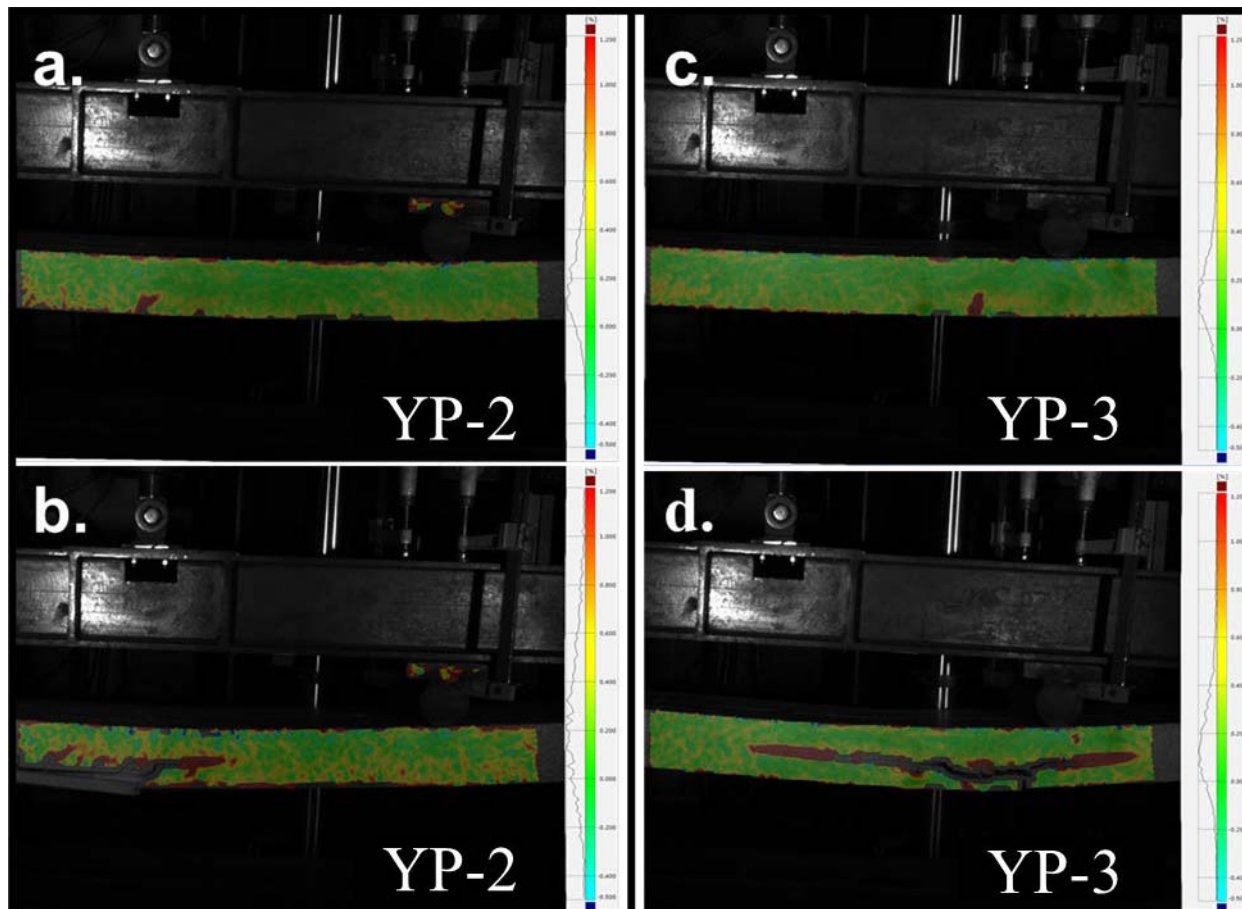


Figure 5.—Frames from the digital image correlation system. (a) YP-2 panel in tension strain a frame after first partial failure; (b) YP-2 panel in tension strain a frame after major failure; (c) YP-3 panel in tension strain a frame after first partial failure; (d) YP-3 in tension strain a frame after a major failure.

In comparison, the F_b values of 1,718 psi (11.8 MPa) from yellow-poplar panels presented values 90.9 percent higher than the strongest visual layups in ANSI/APA PRG 320-2019 (2020). The MOE of 1.39 by 10^6 psi (9,584 MPa) matched or surpassed the ASD values from V2, V3, V4, and V5. These panel test results are similar to those of Mohamadzadeh and Hindman (2015). Testing yellow-poplar CLT panels, the authors encountered bending strength above the V1 layup minimums of ANSI/APA PRG 320-2012 (2012), which was the current standard at the time of their research. They also presented a promising bending stiffness result. However, their bending methods were made with smaller span specimens and not per the standard; therefore, they recommended testing the panels according to the ANSI/APA PRG 320-2019 (2020) specifications to ensure their results.

Based on the bending strength and stiffness results, yellow-poplar NELMA No. 2 and No. 3 lumber placed in the longitudinal and transverse layers, respectively, has the potential to be used in the production of CLT panels. Additional mechanical properties listed in ANSI/APA PRG 320 need to be evaluated to evaluate the potential of yellow-poplar fully. There also exists the potential to improve CLT properties when using yellow-poplar lumber. According to Azambuja et al. (2022), the population of low-grade yellow-poplar lumber had more

potential to be classified based on their nondestructive evaluation values than on visual structural grades. Specifically, laying up CLT panels using yellow-poplar lumber based on nondestructively evaluated MOE values and specialized layer configuration can potentially improve a CLT panel's MOE.

Bonding evaluation

According to ANSI/APA PRG 320-2019 (2020), “The delamination of all bond lines in each specimen shall not exceed 5%.” The results from cyclic delamination testing on specimens taken from the 10 panels can be found in Table 5. This research indicated that delamination was greater than an average of 5 percent in 9 out of 10 panels. Instances of high delamination failures occurred more frequently in positions 1 and 3. Specifically, the number of specimens with delamination above 5 percent was 6 in position 1, 2 in position 2, and 5 in position 3. Additionally, the average delamination of positions 1, 2, and 3 was 9.6 percent, 1.8 percent, and 6.0 percent, respectively. These results indicated that delamination was higher in the outer areas of the panels in comparison with central areas. Although the one-way Analysis of Variance (ANOVA) test showed no statistical difference between positions 1, 2, and 3 (P value = 0.063, $n = 30$). Regarding shear block testing,

Table 5.—Results of cyclic delamination test for layup yellow-poplar.

ID	Mean (%) ^a	Min. (%)	Max. (%)	St. Dev. (%)
1.1	1.3	0.0	5.2	2.6
1.2	0.0	0.0	0.0	0.0
1.3	12.8*	0.0	31.4	13.3
2.1	25.0*	0.0	50.0	28.9
2.2	1.5	0.0	5.8	2.9
2.3	6.6*	0.0	13.7	7.7
3.1	6.9*	0.0	16.0	7.0
3.2	0.0	0.0	0.0	0.0
3.3	1.3	0.0	5.2	2.6
4.1	7.3*	0.0	11.5	5.2
4.2	0.0	0.0	0.0	0.0
4.3	5.2*	0.0	16.4	7.7
5.1	11.7*	0.0	33.9	16.0
5.2	0.0	0.0	0.0	0.0
5.3	2.0	0.0	8.2	4.1
6.1	5.0	0.0	20.1	10.1
6.2	5.4*	0.0	21.6	10.8
6.3	0.7	0.0	3.0	1.5
7.1	12.0*	0.0	30.1	14.7
7.2	0.0	0.0	0.0	0.0
7.3	0.0	0.0	0.0	0.0
8.1	0.0	0.0	0.0	0.0
8.2	2.6	0.0	10.2	5.1
8.3	9.2*	0.0	36.9	18.4
9.1	26.3*	2.2	50.0	23.9
9.2	6.8*	0.0	27.3	13.7
9.3	21.8*	0.0	61.8	27.8
10.1	0.0	0.0	0.0	0.0
10.2	2.3	0.0	9.1	4.5
10.3	0.0	0.0	0.0	0.0

^a * represents specimens that did not achieve the minimum 5 percent delamination failure.

the yellow-poplar CLT shear block results exceeded the requirements in ANSI/APA PRG 320-2019 (2020). Shear block testing resulted in average shear strength of 741 psi (5.1 MPa), as shown in Table 6. The specimens had an average percentage of wood failure of 95 percent. Also, 95.8 percent of the specimens had at least 60 percent wood failure.

Given the laboratory layup process, factors such as lumber thickness variation, applied pressure, pressure variation throughout the panel, and adhesive application could result in specimens showing higher delamination. Regarding lumber thickness variation, prior to lumber surfacing, new moulder blades were installed. The moulder was set up to meet the tolerances specified by ANSI/APA PRG 320-2019 (2020) such that lumber thickness did not exceed a variation of 0.008 inches (0.2 mm) across the width and/or 0.012 inches (0.3 mm) across the length of the board. Also, if board thickness variation was the main issue for poor cyclic delamination results, poor results would be expected throughout the panel, not just in the board's outer areas.

The most likely issue causing poor cyclic delamination near the ends was the uneven pressure due to the press system itself. Specifically, given the hydraulic ram placement in the press, the pressure at the outer ends of the panel was not as even and, thus, as high as that found within the

center panel region. This limitation of the laboratory press would be easily overcome within industrial setups where presses were designed to ensure pressure uniformity throughout the panel. Therefore, any delamination issue when using yellow-poplar lumber is expected to be minimal. For example, Hovanec (2015) tested different grain orientations and layer thicknesses in the production of yellow-poplar CLT panels. The highest average delamination found was 3.7 percent.

Conclusion

This research evaluated the potential of producing CLT panels using yellow-poplar, NELMA No. 2 and No. 3 grades placed in the longitudinal and transverse layers, respectively. The lumber came from a population of NHLA yellow-poplar considered low-grade that was regraded to NELMA visual grade standards. Flatwise bending test results showed an average F_b of 5,687 psi (39.2 MPa) and an average MOE of 1.39 by 106 psi (9,550 MPa) in the major strength direction. The calculated ASD reference design values results indicated that using NELMA Grade No. 2 and No. 3 in the longitudinal and transverse layers, respectively, can produce CLT panels that exceed listed F_b ASD values for all visual (V) type CLT panel layups presented in ANSI/APA PRG 320-2019 (2020). Results of cyclic delamination tests showed delamination above 5 percent in 9 out of 10 panels or 13 of the 30 specimens tested. Yet delamination of over 5 percent was primarily found in the outer areas of the panels, indicating manufacturing issues, most likely uneven press pressure. The shear block specimens results exceeded the requirements set in ANSI/APA PRG 320-2019. Specifically, the shear blocks had an average wood failure of 80 percent, and 95.8 percent of specimens possessed an average wood failure above 60 percent. Additionally, the mechanical tests did not show bonding failures, including in the DIC system evaluation, indicating that bending flatwise was not affected by the bonding.

Given these results, low-grade yellow-poplar shows potential for use in the production of CLT panels. Specifically, using low-grade yellow-poplar in high-end engineered wood products, such as CLT panels, provides opportunities to add significant value to yellow-poplar grown in the Appalachian Region of the United States. However, additional investigation is needed to evaluate other properties and to assess the suitability of NELMA Grade No. 2 and No. 3 yellow-poplar lumber in longitudinal and transverse layers within CLT panels. Knowledge related to these additional properties would assist in the commercialization of this product and provide data needed for yellow-poplar as a potential lumber species in ANSI/APA PRG 320-2019 (2020).

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Table 6.—Results of the shear block test for the layup yellow-poplar. Min. is the minimum, Max. is the maximum, COV% is the coefficient of variance in percent, and SD is the standard deviation.

ID	Shear strength (psi)				Shear strength (MPa)				Wood failure (%)			
	Mean	Min.	Max.	SD	Mean	Min.	Max.	SD	Mean	Min.	Max.	SD
1.1	834	687	889	98	5.75	4.74	6.13	0.68	94	90	95	3
1.2	695	450	878	183	4.79	3.10	6.05	1.26	100	100	100	0
1.3	759	710	852	63	5.23	4.90	5.87	0.43	98	90	100	5
2.1	877	685	1,107	221	6.05	4.72	7.63	1.52	99	95	100	3
2.2	911	800	1,139	159	6.28	5.52	7.85	1.10	100	100	100	0
2.3	899	699	1,032	154	6.20	4.82	7.12	1.06	96	90	100	5
3.1	399	152	650	226	2.75	1.05	4.48	1.56	64	20	100	42
3.2	553	409	677	110	3.81	2.82	4.67	0.76	78	10	100	45
3.3	740	566	938	163	5.10	3.90	6.47	1.12	96	95	100	3
4.1	736	567	917	145	5.07	3.91	6.32	1.00	80	40	95	27
4.2	699	575	906	144	4.82	3.96	6.25	0.99	99	95	100	3
4.3	788	579	1,170	262	5.43	3.99	8.07	1.81	99	95	100	3
5.1	525	346	720	158	3.62	2.39	4.96	1.09	95	95	95	0
5.2	545	400	639	115	3.76	2.76	4.41	0.79	98	95	100	3
5.3	808	693	924	97	5.57	4.78	6.37	0.67	99	95	100	3
6.1	869	669	994	152	5.99	4.61	6.85	1.05	99	95	100	3
6.2	677	589	864	130	4.67	4.06	5.96	0.90	99	95	100	3
6.3	628	550	704	86	4.33	3.79	4.85	0.59	100	100	100	0
7.1	717	555	866	129	4.94	3.83	5.97	0.89	100	100	100	0
7.2	664	500	862	167	4.58	3.45	5.94	1.15	100	100	100	0
7.3	755	605	930	168	5.21	4.17	6.41	1.16	98	95	100	3
8.1	764	503	987	220	5.27	3.47	6.81	1.52	79	25	100	36
8.2	869	590	1,034	200	5.99	4.07	7.13	1.38	99	95	100	3
8.3	766	378	1,221	370	5.28	2.61	8.42	2.55	98	90	100	5
9.1	1,050	627	1,445	342	7.24	4.32	9.96	2.36	100	100	100	0
9.2	823	672	994	133	5.67	4.63	6.85	0.92	100	100	100	0
9.3	699	468	902	183	4.82	3.23	6.22	1.26	95	90	100	6
10.1	731	379	1,059	352	5.04	2.61	7.30	2.43	98	90	100	5
10.2	750	571	911	140	5.17	3.94	6.28	0.97	100	100	100	0
10.3	695	516	811	141	4.79	3.56	5.59	0.97	100	100	100	0
Min	399	152	639	63	2.75	1.05	4.41	0.43	64	10	95	399
Max	1050	800	1445	370	7.24	5.52	9.96	2.55	100	100	100	1050
COV%	18	25	19	43	18	25	19	43	9	30	2	18
Total Mean	741	550	934	174	5.11	3.79	6.44	1.20	95	86	100	7

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