Cross-Laminated Timber Panels Produced by Low-Grade Yellow-Poplar Sorted by Nondestructive Evaluation

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Abstract

To manufacture and market a uniform and consistent product, the US lumber industry developed grading rules to classify their lumber. Visual grading is the most commonly applied grading system, although nondestructive evaluation (NDE) could be applied. Therefore, the objective of this research was to evaluate cross-laminated timber (CLT) panels produced from yellow-poplar (*Liriodendron tulipifera*) lumber sorted by NDE and compare their bending properties in the major direction to standard published panels by the American National Standards Institutes/The Engineered Wood Association (ANSI/APA) PRG 320-2019. Ten panels were produced with dimensions of 3.75 inches thick by 18 inches wide by 120 inches long. Flatwise bending, shear block, and cyclic delamination tests were performed following ANSI/APA PRG 320-2019. The results of the bending tests indicated that the calculated characteristic values using NDE-sorted lumber resulted in a 19 percent higher bending strength (F_b) than published values in ANSI/APA PRG 320-2019 for stress-rated lumber (E1 and E4) and 35 percent higher than visually graded yellow-poplar CLT panels reported by Azambuja et al. However, the modulus of elasticity (MOE) values (1.56 by 10^6 psi) were lower than those listed for E1 and E4 type panels. The adhesive evaluation showed delamination in some samples located in the outer areas of the panel, indicating that proper adhesion is possible with improvements in the panel production process used in the research. Overall, the results suggest potential opportunities to utilize yellow- poplar lumber that does not meet a visual structural grade category under Northeastern Lumber Association Manufacturers' rules by classifying and sorting the lumber according to static MOE (MOE_s) values assessed using NDE.

Visual grading was developed to ensure the quality of commercialized lumber. The Northeastern Lumber Association Manufacturers (NELMA 2013) grading rules are the standard methods used for yellow-poplar (*Liriodendron tulipifera*) lumber when graded for structural purposes according to a national design specification (American Wood Council 2018). Mohamadzadeh and Hindman (2015) tested two yellow-poplar cross-laminated timber (CLT) panel layouts with the same National Hardwood Lumber Association (NHLA) visual grade (No. 2 Common) but different defect presence to find higher bending properties in the panels produced with boards with fewer defects, proving the importance of defect sorting. Another way to evaluate lumber is using nondestructive evaluation (NDE) techniques, including mechanical tests (e.g., proof loading) that do not damage the lumber. In particular, NDE via proof loading allows calculating a board's static modulus of elasticity (MOE_s). Visual classification of the board can be a good predictor of wood properties, and is cost effective. However, when designing tall wood structures such as CLTs, NDEs can provide additional insurance to the architectural designs. When comparing visual grading and machine rating the lumber, machine stress rating identifies and quantifies a

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direct measurement of mechanical properties (Green et al. 1993).

Based on data from Azambuja et al. (2022), the distribution of MOEs from a population of low-grade yellow-poplar showed the potential of increasing panel mechanical properties, such as bending stiffness (MOE), by sorting boards based on NDE; this methodology was one of the paper's final recommendations. Sorting boards by their MOE in outer layers is common in glue-laminated (glulam) beams. Janowiak et al. (1997) sorted boards in the making of red maple (*Acer rubrum*) glulam beams and were able to improve the bending strength and MOE of the beams by dividing the beam into the outer and core sections and placing stress-rated boards with higher MOE and defect size in the outer section of the beam. Sorting based on NDE to ensure the mechanical properties of composites was tested by Cunha and Matos (2011). The authors tested glulam beams comprising two groups: randomly selected and boards sorted by dynamic MOE (MOE_d) as determined by NDE using a Metriguard stress wave timer. The research results concluded that the bending properties differed statistically between groups, suggesting the efficiency of MOE_d sorting of the boards. Moody et al. (1993) produced yellow-poplar glulam beams by selectively placing boards based on their MOE_s in the outer layers of the beams. These results suggest that selecting and sorting yellow-poplar boards by their MOE improved the sorting methods of glulam beams. Hernandez et al. (1997) added glass-fiber plastic to reinforce yellow-poplar glulam beams. They found that layup reinforced in the two bottom layers increased the bending stiffness, while reinforcement in the two outer layers increased bending strength. Similar sorting could also be used to increase the mechanical properties of CLT panels.

Therefore, this research aimed to produce and test CLT panels produced using solely low-grade yellow-poplar (NHLA 2A and below, and NELMA Below Grade [B.G.]) sorted based on NDE.

Material and Methods

A summary of the methodology is presented in Figure 1. The boards used in this study were from a population of yellow-poplar graded NHLA No. 2A, No. 2B, No. 3A, and No.

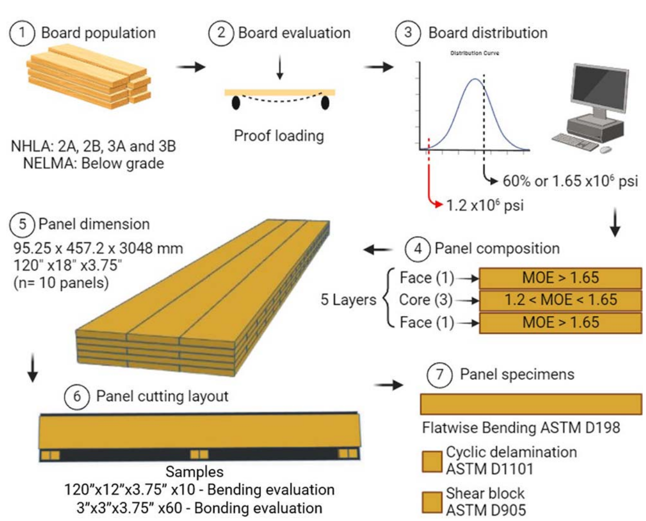

Figure 1.—Summary of the methods used in this research.

3B, based on NHLA (2014). Additionally, the boards used for the panel production were graded NELMA B.G., meaning boards that did not achieve any visual structural grade according to NELMA rules. These B.G. boards were sorted based on their MOE_s obtained by nondestructive proof-loading evaluations performed previously. The five-layer panels were made from boards that had MOE_s above 1.65 by 10^6 psi in the two outside layers, and boards with MOE_s between 1.2 by $10^6$and 1.65 by 10^6 psi (8,273 and 11,376 MPa) were used in the three inner layers of the panel. This range of MOE_s values was selected because the 1.65 by 10^6 value was about the top 40 percent of the B.G. boards, and 1.2 by 10^6 psi was the minimal stiffness requirement of the American National Standards Institutes/The Engineered Wood Association (ANSI/APA) PRG 320-2019 (ANSI/APA 2020). The choice of using the top 40 percent was made to study the possibility of using all the boards available in the population, except for boards with MOE_s below 1.2 by 10^6 psi, to produce five-layer CLT panels. This research CLT panel set composition was labeled Y.P. and is presented in Figure 1 (4).

The panel production started by surfacing two wide sides of the selected boards, which were laid on an assembly table for adhesive application prior to pressing. The adhesive used was Franklin Advantage EP-950, a two-part adhesive (acrylic-based emulsion polymer isocyanate system, EPI and H-200, a diphenylmethane diisocyanate, MDI, hardener). Details of the parameters used are presented in Table 1.

Ten repetitions of five-layer panels were produced with dimensions of 3.75 inches deep, 18 inches wide, and 120 inches long (95.25 mm by 457.2 mm by 3,048 mm). From each panel, specimens were prepared and tested, including one flatwise bending following American Society for Testing and Materials (ASTM) D198 (ASTM 2015), three shear blocks following ASTM D905 (ASTM 2010), and three cyclic delamination following ASTM D1101 (ASTM 2013). The bond evaluation specimens were taken from three positions (both ends and center) to assess the panel production, hence the three specimens from each panel. Additionally, the theoretical effective bending stiffness (EI_{eff}) and the effective bending strength (F_bS_{eff}) of the panels were calculated based on formulas published in the *CLT Handbook* (Karacabeyli and Gagnon 2019). Additionally, to evaluate the effects of sorting and the panel composition the results were compared to Azambuja et al. (2023), since the research used similar methods, only differing in the boards' structural visual grade. The author used boards graded No. 2 and No. 3 in accordance to NELMA visual grades. Finally, the software used for data management was Microsoft Excel 365, and statistical analyses were conducted using RStudio (version 3.6.3).

This study was a follow-up from Azambuja et al. (2023), and additional information regarding the methodology can be found in Azambuja (2022) and Azambuja et al. (2022).

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

Adhesive spread rate	78 lb/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[a]	12 h

[a] Resting period was the minimum period of time the panel remained in the press without moving.

Table 2.—Results of the bending evaluations performed in layup Y.P.[a]

Specimen ID	Ultimate load		F_b		MOE		Failure mode
	lb	kN	psi	Mpa	10^6 psi[b]	Mpa	
YP-1	10,154	45.2	6,988	48.18	1.65	11,376	Splintering tension
YP-2	8,298	36.9	5,760	39.71	1.42	9,791	Splintering + simple tension
YP-3	10,055	44.7	7,080	48.81	1.71	11,790	Simple tension
YP-4	10,432	46.4	7,126	49.13	1.37	9,446	Simple tension
YP-5	7,992	35.6	5,590	38.54	1.47	10,135	Cross-grain tension
YP-6	8,369	37.2	5,713	39.39	1.50	10,342	Cross-grain tension
YP-7	10,287	45.8	7,213	49.73	1.66	11,445	Simple tension
YP-8	9,737	43.3	7,113	49.04	1.52	10,480	Simple tension
YP-9	8,659	38.5	6,062	41.80	1.59	10,963	Simple tension
YP-10	11,733	52.2	8,176	56.37	1.71	11,790	Simple tension
Mean	9,572	42.6	6,682	46.07	1.56	10,756	
Minimum	7,992	36.0	5,590	38.54	1.37	9,446	
Maximum	11,733	52.0	8,176	56.37	1.71	11,790	
5th percentile	8,130	36.2	5,645	38.92	1.39	9,601	
SD	1,198	5.33	851	5.87	0.12	838	
COV (%)	13		13		8		

[a] Y.P. = yellow-poplar layup repetitions; lb = pounds; kN = kilonewton; psi = pounds per square inches; MPa = megapascals; F_b = bending strength; MOE = modulus of elasticity; SD = standard deviation; COV = the coefficient of variance.
[b] 1,000,000 psi = 6895 MPa.

Results and Discussion

Bending results

Table 2 presents the results from the third point flatwise bending in the major direction. The table shows the results of the ultimate load, the F_b, the MOE, and the failure modes from testing.

The average MOE and F_b results of Y.P. were higher than Azambuja et al. (2023) reported, specifically 12 percent and 17 percent higher for average MOE and average F_b, respectively. The differences between the two layups were their board's MOE_s and NELMA grades, as Azambuja et al. (2023) utilized No 2 and No 3 NELMA-graded lumber. Based solely on the NELMA grade, CLT panels using B.G. lumber would generally be expected to be lower in strength and stiffness than those using No. 2 and No. 3 lumber. However, these results were not the case for this study. The ability of B.G. lumber to produce CLT panels with higher strength and stiffness was due to the defect presented in this population and the composite panel configuration. Azambuja et al. (2022) reported the defects found in low-grade yellow-poplar (NHLA 2A, 2B, 3A, and 3B) and reported that the most common defect was knots, followed by splits. However, the distribution of defects from B.G. lumber consisted of 43 percent of splits, 24 percent of knots, 11 percent of shake, 10 percent of wane, and 12 percent of other defects. Specifically, for these 10 panels and considering the cut layout presented in Figure 1, 40 boards composed the two outer layers of the set of panels, and their defect distribution was 50 percent splits, 20 percent knots, 20 percent shakes, 5 percent wane, and 5 percent slope of grain. This defect characterization could explain the mechanical differences between these layups. Based on these results, it is interesting to review structural visual grades when boards are used to produce CLT panels since boards with splits as their limiting defect could be used in CLT production.

A comparison between the bending results coefficient of variances of this research and Azambuja et al. (2023) is presented in Figures 2 and 3. The values ranged approximately from 3,000 psi (20.7 MPa) and 9,000 psi (62 MPa) in bending strength and 1.2 by 10^6 psi (8,274 MPa) and 1.9 by 10^6 psi (13,100 MPa) in bending stiffness. The comparison shows a higher variance in strength and a lower variance in stiffness compared to the other research. This variance could

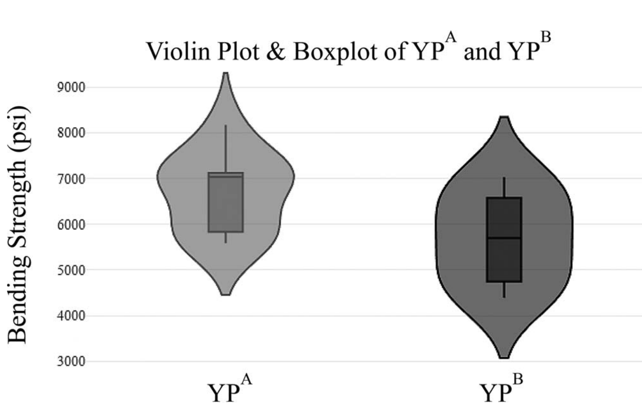

Figure 2.—Panel's bending strength (F_b) distribution and comparison of the present research layup (YP^A) and Azambuja et al. (2023) layup (YP^B).

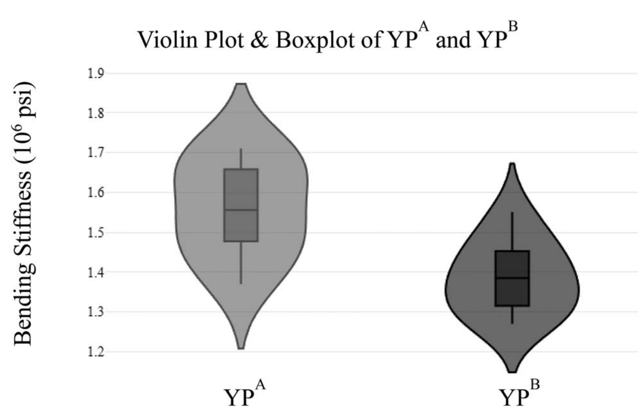

Figure 3.—Panel's bending stiffness (MOE) distribution and comparison of the present research layup (YP^A) and Azambuja et al. (2023) layup (YP^B).

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)	69.2	82.26
F_bS_{eff} (lbf-ft/ft of width)	n/a	5240

[a] lbf-in2/ft of width = pounds per square inch per feet of width; EI_{eff} = effective bending stiffness; F_bS_{eff} = effective bending strength.

be explained by the differences in board selection between the two studies, nondestructive testing and visual structural grade.

The theoretical effective bending stiffness and bending strength and experimental results are shown in Table 3. The theoretical bending strength was not calculated as there are no published F_b values for NELMA B.G. lumber. The difference between calculated and experimental values is due to, among other reasons, the safety coefficients that are applied to the theoretical values and theoretical calculations, minimizing the effect of minor direction forces.

Table 4 shows the calculated characteristic value results. Results from Azambuja et al. (2023) and ANSI/APA PRG 320-2019 (2020) are compared. The data comparison showed that values from the current layup (Y.P.) were 19 percent greater than the highest F_b value in ANSI/APA PRG 320-2019 (2020). The MOE values from the Y.P. panels were only below the layups E1 and E4.

Mohamadzadeh and Hindman (2015) found that the presence of the defect would decrease the bending strength of panels from the same NHLA visual grade. Although considering that Azambuja et al. (2023) had better visual grades than the tested in this research, this indicates that sorting by MOE_s can override the defects differences between NELMA No. 2 and B.G.

Moody et al. (1993) used a similar sorting system to produce yellow-poplar glulam beams with outermost layers with a MOE of 2.0 by 10^6 psi. This value of MOE is above the values used in this research, which is 1.65 by 10^6 psi (11,376 MPa), indicating the potential for improving the yellow-poplar panels' composition of this research.

Table 5.—Results of cyclic delamination test for layup Y.P.[a]

I.D.	Mean (%)	Minimum (%)	Maximum (%)	SD (%)
1.1	22[b]	0	68	31
1.2	2	0	7	4
1.3	7[b]	0	14	8
2.1	16[b]	0	31	14
2.2	1	0	5	2
2.3	15[b]	0	48	23
3.1	0	0	0	0
3.2	0	0	2	1
3.3	0	0	0	0
4.1	6[b]	0	22	11
4.2	0	0	0	0
4.3	1	0	5	3
5.1	9[b]	0	25	12
5.2	0	0	0	0
5.3	12[b]	0	49	24
6.1	1	0	2	1
6.2	0	0	0	0
6.3	4	0	16	8
7.1	9[b]	0	34	16
7.2	4	0	17	9
7.3	1	0	6	3
8.1	0	0	0	0
8.2	0	0	0	0
8.3	4	0	11	5
9.1	1	0	3	2
9.2	7[b]	0	27	14
9.3	0	0	0	0
10.1	1	0	2	1
10.2	0	0	0	0
10.3	24[b]	0	60	27

[a] Y.P. = yellow-poplar layup.
[b] Specimens did not achieve the minimum 5 percent delamination failure.

In this current study, B.G. lumber with high MOE values was placed in the outer layers. This sorting method likely resulted in CLT panels with higher strength and stiffness. The results are similar to those of Hernandez et al. (1997), who reported that increasing the resistance (via fiber-reinforcement) of the outer layers of glue-laminated, yellow-poplar beams improved bending strength and stiffness, showing the potential of reinforcing outer panel layers. Finally, the NDE showed

Table 4.—Characteristic values of tested layup, prior layup, and the published standard layups.

Layups	F_b[a](psi)	MOE (10^6 psi)	Longitudinal layers	Transverse layers
YP^A[b]	*2,329*	*1.56*	*B.G.; E > 1.65e*[b]	*B.G.; 1.2e > E > 1.65e*
YP^B[b]	*1,718*	*1.39*	*No. 2 Yellow-poplar*	*No. 3 Yellow-poplar*
V1	900	1.60	No. 2 DFL	No. 3 DFL
V1(N)	850	1.60	No. 2 DFL North	No. 3 DFL North
V2	875	1.40	No. 1-2 SPF	No. 3 SPF
V3	750	1.40	No. 2 S.P.	No. 3 S.P.
V4	775	1.10	No. 2 SPF South	No. 3 SPF South
V5	850	1.30	No. 2 H.F.	No. 3 H.F.
E1	1,950	1.70	1950f-1.7E SPF	No. 3 SPF
E2	1,650	1.50	1650f-1.5E DL	No. 3 DL
E3	1,200	1.20	1200f-1.2E ENWS	No. 3 ENWS
E4	1,950	1.70	1950f-1.7E S.P.	No. 3 S.P.
E5	1,650	1.50	1650f-1.5E H.F.	No. 3 H.F.

[a] Y.P. = yellow-poplar layup; F_b = bending strength; MOE = modulus of elasticity; B.G. = below grade; DFL = douglas-fir–larch; SPF = spruce-pine-fir; S.P. = outhern pine; H.F. = hemlock–fir; ENWS = eastern, northern, and western softwoods.
[b] *YP^A* is the current research; *YP^B* results from Azambuja et al. (2023); e is $\times 10^6$ psi.

Table 6.—Results of the shear block test for the layup Y.P.[a]

ID	Shear strength (psi)				Shear strength (MPa)				Wood failure (%)			
	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD
1.1	566	487	713	101	3.9	3.4	4.9	0.7	100	100	100	0
1.2	771	568	1258	327	5.3	3.9	8.7	2.3	100	100	100	0
1.3	705	247	1010	354	4.9	1.7	7.0	2.4	81	35	100	31
2.1	677	571	790	90	4.7	3.9	5.4	0.6	99	95	100	3
2.2	552	452	635	76	3.8	3.1	4.4	0.5	89	75	100	13
2.3	648	377	933	228	4.5	2.6	6.4	1.6	85	45	100	27
3.1	939	667	1268	252	6.5	4.6	8.7	1.7	98	95	100	3
3.2	954	709	1234	244	6.6	4.9	8.5	1.7	98	95	100	3
3.3	645	341	767	205	4.4	2.4	5.3	1.4	98	95	100	3
4.1	674	576	788	97	4.6	4.0	5.4	0.7	98	95	100	3
4.2	754	632	952	139	5.2	4.4	6.6	1.0	99	95	100	3
4.3	733	653	781	57	5.1	4.5	5.4	0.4	100	100	100	0
5.1	558	350	700	154	3.8	2.4	4.8	1.1	100	100	100	0
5.2	712	478	994	226	4.9	3.3	6.9	1.6	100	100	100	0
5.3	711	560	850	120	4.9	3.9	5.9	0.8	100	100	100	0
6.1	800	489	1141	269	5.5	3.4	7.9	1.9	100	100	100	0
6.2	646	560	750	96	4.5	3.9	5.2	0.7	100	100	100	0
6.3	760	587	938	147	5.2	4.0	6.5	1.0	98	95	100	3
7.1	802	688	948	108	5.5	4.7	6.5	0.7	98	95	100	3
7.2	935	683	1120	183	6.4	4.7	7.7	1.3	100	100	100	0
7.3	555	318	673	162	3.8	2.2	4.6	1.1	100	100	100	0
8.1	559	509	610	46	3.9	3.5	4.2	0.3	100	100	100	0
8.2	919	616	1070	206	6.3	4.2	7.4	1.4	98	95	100	3
8.3	415	203	623	190	2.9	1.4	4.3	1.3	69	20	100	37
9.1	733	677	757	38	5.1	4.7	5.2	0.3	100	100	100	0
9.2	444	383	473	41	3.1	2.6	3.3	0.3	95	90	100	4
9.3	777	662	962	134	5.4	4.6	6.6	0.9	100	100	100	0
10.1	607	508	716	105	4.2	3.5	4.9	0.7	100	100	100	0
10.2	742	628	827	83	5.1	4.3	5.7	0.6	99	95	100	3
10.3	698	652	758	52	4.8	4.5	5.2	0.4	95	94	97	1
Min	415	203	473	38	2.9	1.4	3.3	0.3	69	20	97	0
Max	954	709	1268	354	6.6	4.9	8.7	2.4	100	100	100	37
COV%	19	26	24	56	19.4	26.4	23.6	56.0	7	22	1	0
Overall Mean	700	528	868	151	4.8	3.6	6.0	1.0	97	90	100	4.8

[a] Y.P. = yellow-poplar layup; Min = minimum; Max = maximum; COV% = the coefficient of variance as a percentage.

more potential for use on grading boards than structural visual grading.

Bonding evaluations

Table 5 shows the results from cyclic delamination of the 10 panels. Seven out of the 10 panels presented delamination above 5 percent. Delamination above 5 percent was more frequently found in the outer areas of the panel. Ten out of 30 tested samples showed delamination above 5 percent, with one specimen from position 2, at the center of the panel. The average delamination of the positions was 6.4, 1.5, and 6.8 percent for positions 1, 2, and 3, respectively. The analysis of variance test showed no statistical difference between the positions 1, 2, and 3 ($P = 0.14$).

As expected, similar results were found by Azambuja et al. (2023), given both studies used the same methods and equipment. Some panels presented delamination into the ends, probably due to uneven pressure during the pressing of the panels. With the same delamination results and manufacturing parameters, such as the adhesive application, spread rate, and nominal pressure, it is safe to affirm that the bonding of the two sets of panels was similar. Therefore, there is no evidence that the change of board visual grade due to a defect affects the bonding delamination of the panel according to bond quality tests from ANSI/APA PRG 320-2019 (2020).

Table 6 shows the results of the shear block tests. The average percentage of wood failure in all the samples was 97 percent, above the standard requirement of 80 percent, and 95 percent of the samples presented wood failure of at least 74.5 percent, above the standard requirement of 60 percent. These results indicated that the glue bond quality based on shear block evaluation was satisfactory, contrary to the cyclic delamination evaluation.

The bonding parameters were based on product specifications and preliminary small-scale tests. In the preliminary samples, the results meet ANSI/APA PRG 320-2019 (2020) requirements. Even using the same parameters, the results of the full-scale panels did not meet the requirements, which can be attributed to laboratory limitations, which could be resolved in industrial production.

Summary and Conclusion

In this study, yellow-poplar boards graded NELMA B.G., mainly due to splits and boards not rated for minimum structural use requirements, were used to produce CLT panels. The boards that composed the panels were selected by their static MOE, and those with higher values (top 40%) within the population were placed in the outer two layers of the CLT panels.

The results of cyclic delamination showed delamination above the 5 percent requirement from ANSI/APA PRG 320-2019 (2020) in 10 out of 30 samples, mainly in the outer areas of the panel (9 out of 10 samples with delamination over 5%). The shear-block tests showed a result of an average wood failure of 97 percent in all the samples and a fifth percentile of 74.5 percent. These results highlight the stringency parameters in panel production and the severity of bond line evaluation of cyclic delamination and shear block. No bending specimen presented bonding failure, eliminating the possible influence of the bonding issues in bending results. The results of flatwise bending in the major direction showed an average of F_b of 6,682 psi (46.07 MPa) and MOE of 1.56 by10^6 psi (10,756 MPa) for the 10 CLT panels tested. The calculated Allowable Stress Design (ASD) reference design values results indicated that sorting the boards according to MOE_s with outer layers with at least 1.65 by 10^6 psi (11,376 MPa)and core of at least 1.2 by 10^6 psi (8,273 MPa) can produce CLT panels that exceed listed F_b ASD values from all stress-rated layups (E) and MOE only lower than E1 and E4 from ANSI/APA PRG 320-2019 (2020).

The results from this study indicate that NELMA B.G. lumber downgraded due mainly to end splits has the potential to be used in the production of CLT panels if sorted by nondestructive MOE_s. Specifically, the selection of boards based on nondestructive tests appeared to be more feasible than solely using NELMA visual grades.

Based on these findings, NDE and board sorting can allow material that would otherwise be rejected to be used in CLT production. This option is viable because of this type of panel configuration, where adjacent layers can minimize the board's individual defects. However, the majority of the B.G. lumber used in this research consisted of end splits as the limiting factor. More research is needed to see if similar findings occur when the limiting defect of B.G. lumber is another defect type (e.g., knots).

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