Evaluation of Low-Grade Yellow-Poplar (*Liriodendron tulipifera*) as Raw Material for Cross-Laminated Timber Panel Production

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Abstract

Utilization of low-grade yellow-poplar (*Liriodendron tulipifera*) lumber would provide for alternative structural lumber sources and promote the growth of cross-laminated timber (CLT) manufacturing facilities within the Appalachian Region. A significant amount of low-grade yellow-poplar lumber (i.e., National Hardwood Lumber Association [NHLA] No. 2A and Below Grade) is utilized for wood pallets. In practice, this material is not graded for structural purposes. Additionally, research on yellow-poplar for structural use has focused on grading lumber from a small population of selected logs, not by regrading NHLA lumber from manufacturing facilities. Therefore, the research's objective was to investigate the structural grades of a typical population of NHLA graded No. 2 and lower lumber and evaluate their potential to meet structural grades necessary for CLT panels. NHLA graded lumber was regraded and assigned to visual structural grades following Northeastern Lumber Manufacturers Association rules and evaluated for flatwise bending modulus of elasticity (MOE_b) by nondestructive proof loading. The results of the study indicated that 54.6 percent of the boards possessed a minimal structural visual grade required for CLT panels according to American National Standards Institutes/The Engineered Wood Association (ANSI/APA) PRG 320-2019 (2020). Splits were the most common limiting defect that downgraded boards to nonstructural grades. Also, 96.6 percent of the boards evaluated had a MOE_b above the required minimal board value of 1.2×10^6 psi (8,274 MPa) listed in ANSI/APA PRG 320-2019 (2020). The results of the study indicated that a majority of NHLA low-grade yellow-poplar, when regraded for structural purposes, meets or exceeds minimum lumber grade values necessary for use in CLT panel production.

Historically, there has been interest in using hardwoods in structural applications. The National Design Specification (NDS) for Wood Construction (American Wood Council 2018) published values for hardwoods in 1988, and since then, hardwood design values were available and certified for use (Green 2005). In the past, efforts were made to produce wood transportation structures (bridges), and by 2005, approximately 140 demonstrative hardwood bridges were constructed in 18 states (Wacker and Cesa 2020). Some of these demonstration bridges were made with yellow-poplar (*Liriodendron tulipifera*).

Yellow-poplar is an Appalachian hardwood that grows throughout the Appalachian region, a chain of mountains with >200,000 miles^2, which spreads over 13 American states (Pollard and Jacobsen 2011). The species has the most standing volume of timber in West Virginia (120 million m^3) and also presents a net growth-to-harvest ratio exceeding 3:1 with the greatest removal volume of 939,000 m^3/yr (Morin et al. 2017). Recent research into structural uses of yellow-poplar have included their use as glued-laminated timber (Glulam), truss cord members, general structural framing material (Green 2005), and more

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recently, for cross-laminated timber (CLT) panels. For example, Hernandez et al. (1996) evaluated the use of Glulam beams in bridge systems. The authors concluded that yellow-poplar could achieve the necessary mechanical requirements for bridges, but economic considerations, specifically the cost of the raw material, would be the deciding factor for future use as structural bridge components. Further research on structural grades for yellow-poplar were conducted by Moody et al. (1993) and Faust et al. (1990), but without considering NHLA low-grade lumber. Moody et al. (1993) concluded there was viability for yellow-poplar to meet glulam structural requirements, especially in cases where the outer layers did not contain edge knots present over more than one-sixth of board surface area and modulus of elasticity (MOE) was above 2.0 $\times 10^6$ psi (13,790 MPa). Pahl et al. (1992) conducted a study on NHLA low-grade lumber but did not consider the processing needed in CLT production. In all three studies, the authors found considerable numbers of boards meeting structural grades. Even with these studies, it has proven challenging for the hardwood industry to change grading methods without market incentives and/or guarantees.

Mechanical properties of yellow-poplar are published in the National Design Specifications (NDS; American Wood Council 2018). Using these values, Beagley et al. (2014) calculated that a CLT panel made from yellow-poplar grade No. 3 (Northeastern Lumber Manufacturers Association [NELMA]) would exceed ANSI/APA PRG 320-2019 (ANSI/APA 2020) requirements for strength and stiffness. Early research on using yellow-poplar for CLTs investigated NHLA graded lumber, rather than structural grades. Mohamadzadeh and Hindman (2015) produced and tested CLT panels using NHLA graded No. 2 common (a mix of 2A and 2B) yellow-poplar. The results of their research concluded that bending stiffness and strength surpassed the design values for CLT made from softwoods, specifically the two strongest grades where the layout is based solely in visual grade and species—ANSI/APA PRG 320-2019 grades V1 and V2. Although their results were promising, they did not analyze structurally graded lumber. Visual appearance grade lumber was used, so the CLT panels could have had higher grades of structural lumber present and there was no way to know or replicate these panels from a structural standpoint. As such, to consider using low-grade NHLA graded hardwoods in CLT panel manufacturing, research is needed to evaluate the amount and types of structural-grade lumber present in traditionally graded hardwood lumber available in the market—specifically, the amount of NELMA No. 3 and above present in NHLA No. 2 and below—and further, by nondestructive evaluation, to measure and assess their mechanical properties (modulus of elasticity or MOE_b).

Commonly, yellow-poplar lumber is marketed according to National Hardwood Lumber Association (NHLA) grading rules (NHLA 2014) and sold as commodity lumber with varying prices by grade. For example, the Hardwood Market Report from March 2021 (American Hardwood Export Council 2020) lists the higher grades—FAS and No. 1 Common—at around 95 percent and 25 percent higher than the price of No. 2A Common, respectively, for dried 4/4 thickness yellow-poplar lumber. NHLA grades 2B, 3A, and 3B do not generally have published values in this report for dried lumber because they have less market interest. However, these low-grade materials will most likely have lower prices than grade 2A. These NHLA grades—2A Common, 2B Common, 3A Common, and 3B Common—are generally termed ''low-grade'' because they represent the lower end of the grading rules and are mostly used by the wooden pallet and container industry. Therefore, low-grade yellow-poplar lumber is commercially available and has a relatively low cost, making this species a good candidate to be used as raw material in CLT (cross-laminated timber) panels or other engineered structural products. To be used in CLT panels, however, structural lumber must be assigned a structural visual grade of at least No. 3. A well-known structural visual grading agency for yellow-poplar, as per the American Wood Council, National Design Specification (2018), is the Northeastern Lumber Manufacturers Association (NELMA 2013). Visual grading classifies boards into grades according to defect position and board size based on strength-limiting defects.

Low-quality hardwoods, based on appearance grade, are intended for nonstructural markets; so issues with using yellow-poplar lumber for CLT panels are directly related to the markets being served and the associated grading requirements, which do not reflect mechanical properties of the boards. Appearance-grade hardwood lumber is typically produced in random widths and random lengths, with a target thickness that is oversized to account for shrinkage during drying. Hardwood lumber is produced in various rough thicknesses (e.g., 8/4, 6/4, 5/4, 4/4, etc.), but a majority of produced hardwood lumber is processed for use as pallet stock, especially when looking at grades No. 2A/2B and below. A majority of CLT panel manufacturers in North America are using nominal 2-in-thick (5.1-cm) softwood lumber, but using thinner laminates is not uncommon. However, for hardwood CLT markets to emerge using the current manufacturing and grading practices, there is a need to evaluate how the current hardwood grading system is related to structural grading systems, and how to homogenize the raw material dimensions to be used as structural elements.

This study was designed to categorize kiln-dried, 4/4-thick (2.54-cm), NHLA No. 2A, 2B, 3A, and 3B yellow-poplar lumber into appropriate structural grades in both original unsurfaced form and after processing to a standard size suitable for use in CLT panels. Analyses included detailing the structurally graded lumber by NHLA grade, investigating the effects of processing into standard widths and thicknesses on the final grade, evaluating the use of proof loading as an alternative to visual grading, and calculating a relative economic value for each NHLA grade according to their structural properties.

Material and Methods

The focus population was low-grade yellow-poplar lumber typically used in industrial applications such as wooden pallets and graded by NHLA rules. Initially, 8,000 board-feet (18.9 m^3) of kiln-dried, rough-cut yellow-poplar classified as NHLA 2A and below were obtained from a mill in northern West Virginia. The boards were kiln-dried to a target moisture content that ranged between 6 percent and 8 percent. Although hardwood lumber is usually sold in random widths and multiple fixed lengths, a specific board dimension was available through a local sawmill, with the average dimensions of 6.88 inches wide $\times$ 1.06 inches thick $\times$ 121.2 inches long (17.47 $\times$ 2.69 $\times$ 308 cm). Initially the boards were numbered, measured, and graded to NHLA and

NELMA visual grades. Regarding NELMA grading, the material was 1 inch (2.54 cm) in thickness, so they were categorized as Stress Rated Boards. As such, the NELMA grading was performed following rules within the Structural Light Framing/Structural Joists and Planks classification as per NELMA requirements. The grades were assigned by professional graders, with certification from their respective Associations.

The boards were then surfaced on both sides and sent through a gang rip saw to achieve the final dimension of 6 inches wide × 7/8 inch thick × 121 inches long (15.24 cm × 2.23 cm × 307 cm). After this dimensioning of the boards, the same professional graders regraded the boards. During this second grading, the determinant defect that limited the board from achieving a higher NELMA grade was recorded.

The boards were then taken to the West Virginia University research laboratories where they were tested nondestructively to determine the flatwise bending modulus of elasticity (MOE_b) using a center-point loading configuration over a span of 88 inches (221 cm). The span selected was 100 times the average board thickness, span-to-depth in accordance to ASTM D3737 (2012). The boards were evaluated flatwise to better simulate the stresses of a board in a CLT panel used as a floor or roof type panel, where bending properties are more relevant.

Each board was deflected at the center for 3 inches (7.62 cm), and through this loading, the applied force and deflection were measured and recorded. MOE_b was calculated in accordance with Equation 1. A summary of the methods is presented in Figure 1 and the grade requirements are provided in Table 1a and b.

$$\mathrm{MOE_b} = \frac{M \times L^3}{48I} \quad (1)$$

where MOE_b is modulus of elastic in bending flatwise in pounds/square inch (psi), M is the slope of the load deflection curve (lbs/in), L is the test span in inches, and I is the moment of inertia (inches).

Generally, commodity prices for yellow-poplar structural grades are not available. Therefore, to provide an estimate value, in terms of structural grades, to each of the low NHLA grades used in this research, a Total Relative Worth (TRW) was calculated. The TRW was calculated using the ratio between cell frequency and row frequency, and the ratio of the relative strength and relative price, as presented in equation 2, used by Pahl et al. (1992).

$$\mathrm{TRW} = \sum_{SS}^{BG} \frac{Cellfrequency}{Rowfrequency} \times \frac{Relativestrength}{Relativeprice} \times 1,000 \quad (2)$$

where BG is Below Grade and SS is Select Structural.

The relative strength (SR) of the NELMA grades was calculated based on values provided by ASTM D245-06 (2019) that provide values for strength-reducing factors for defect-free, straight-grain material when developing various grades of visually graded structural lumber. There are no SRs available for the proof-loading scenario, so SRs used in the MOE_b grading scenario were chosen based on the range of elasticity found in the boards. The current available price of the NHLA grade according to Hardwood Market Report of March 2021 was used to define Relative Price.

Some of the boards could not be measured through nondestructive evaluation because of uneven shape caused by defect (wane, split and/or holes), so that 55 boards were excluded from the proof loading. Also, boards with an NHLA grade above 2A (FAS, 1F, and 1C) were excluded from the research because they were out of the study scope. As a result, 1,192 boards were evaluated in nondestructive tests. The distribution of NHLA and NELMA grades before and after processing were tested using a paired chi-square test. The MOE_b data were analyzed using an analysis of variance (ANOVA) test and the averages were differentiated using a Tukey honestly significant difference (HSD) test. These statistical tests were conducted with a confidence level of 5 percent ($\alpha = 0.05$).

Results

The study was divided into four separate sections that address different aspects related to regrading and classifying NHLA lumber for structural grades. The first section details changes in grade resulting from processing of kiln-dried, 4/4 (2.54-cm), yellow-poplar lumber into uniform dimensions for structural purposes. The second section details the NELMA grades (visual structural grades) for the low-grade lumber processed into uniform dimensions of 6 inches wide by 7/8 inch thick by 121 inches long (15.24 cm × 1.905 cm × 307 cm) and used to produce CLT panels. The third section examines the mechanical properties of processed NHLA low-grade lumber according to their visual grades in the context of required values needed for producing CLT panels. Finally, the fourth section presents the relative worth of each NHLA grade according to their structural capabilities, in NELMA grades and MOE_b values.

Effects of processing low-grade yellow-poplar for structural purposes

The number of boards assigned to each grade in both systems before and after processing is presented in Figure 2. As shown in Figure 2, no data were collected for No. 3 NELMA graded boards before processing. During this part of the analysis, there was miscommunication regarding the grades that needed to be evaluated; therefore, boards that were found to be visually graded below a No. 2 grade were grouped into the Below Grade (BG) category. However, when the lumber was graded after processing, the No. 3 NELMA grade was also determined so that final grade limiting defects could be determined for every possible grade. As a result, a direct comparison between NELMA grades before and after processing could not be determined. Processing produced an average 12.7 percent reduction in width and a 5.8 percent reduction in depth, leading to a significant change in grade based on chi-square test results. After processing, the No. 3 and the Below-Grade boards were grouped to allow a more direct comparison, and even then, the test showed a statistical difference ($\chi^2 = 116.409$, P value <0.0001).

Table 2 details the percentage change in NELMA grade from each of the starting grades the boards were assigned, presumably resulting from surfacing. When comparing the NELMA grade of a board before and after processing, the result could be divided into two categories: boards graded Select Structural and Below Grade before processing were more likely to remain in the same grade afterward; boards graded No. 1 and No. 2 changed grade more randomly, with

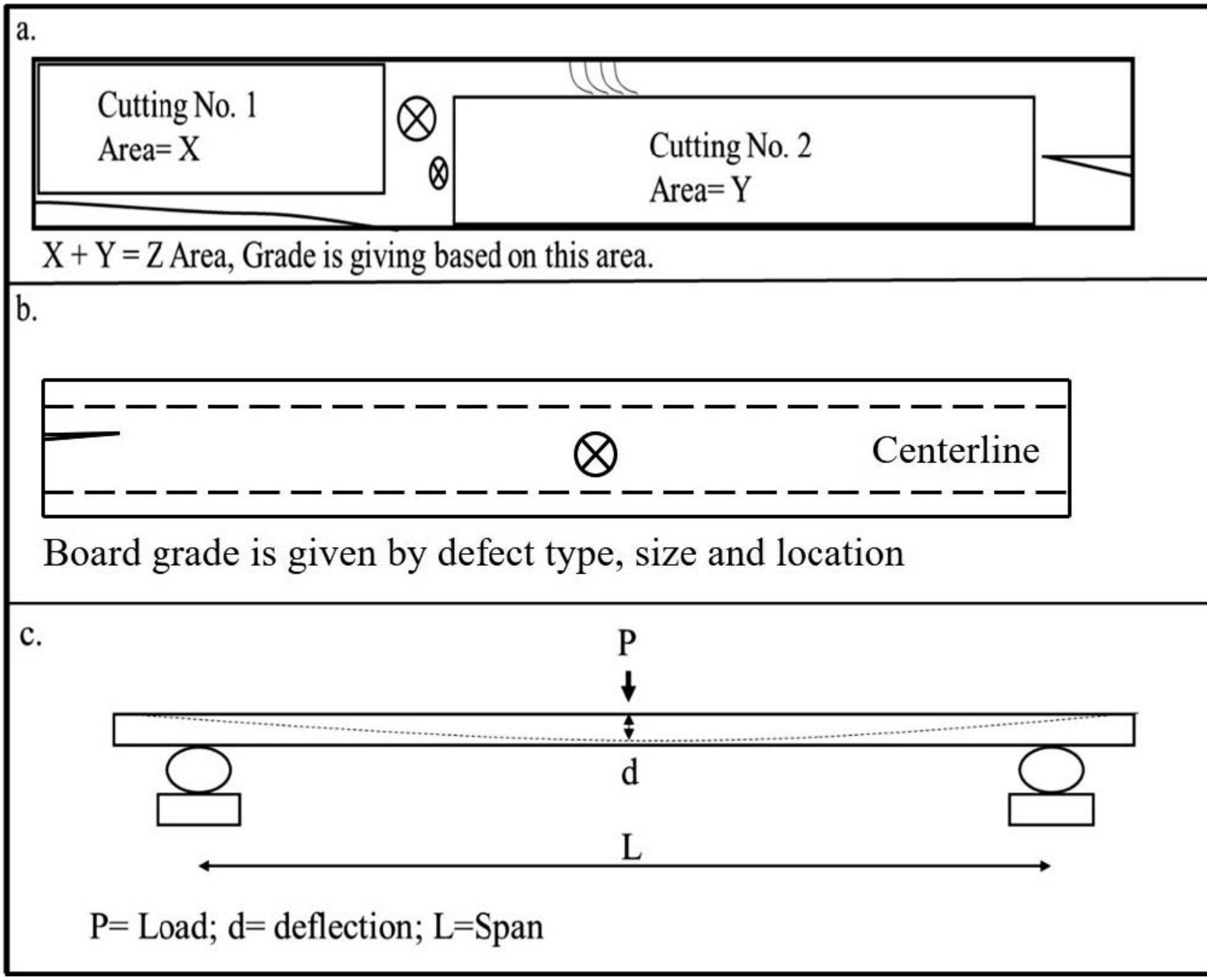


Figure 1.—Illustration of the board classification methods performed in this research where (a) National Hardwood Lumber Association (NHLA) visual grade; (b) Northeastern Lumber Manufacturers Association (NELMA) visual grade; (c) nondestructive test.

no discernable pattern of grade change. Grade changes in grades No. 1 and No. 2 after surfacing on all four sides (S4S) were hypothetically influenced by the presence of defects in the smaller boards. For example, an edge defect removed through processing can improve the grade; or a defect that remains after processing (S4S) becomes more significant in these smaller boards, potentially leading to lower assigned grades. On the other hand, boards that were initially graded as Selected Structural most likely do not have any significant defects; therefore, the processing

Table 1a.—Visual grading rule requirements: Minimum yield requirements of National Hardwood Lumber Association (NHLA) grade.

Grade	Yield (%)[a]
FAS	83.3
1F	83.3
1C	66.6
2A	50.0
2B	50.0[2]
3A	33.3
3B	25.0

[a] Yield is the amount of clear face cuttings that can be obtained from a board where 1F presents a better wide face that meets FAS requirements and opposite face at least meets 1C requirements, Grade 2A requires clear cuttings, and Grade 2B accepts sound cuttings.

Table 1b.—Visual grading rule requirements: Northeastern Lumber Manufacturers Association requirements for knots and splits for 6-inch-wide (15.24-cm) boards.

	Knots in wide face[a]			
Grade	At edge	Centerline	Unsound	Splits[a]
SS	1.125''	1.875''	1''	6''
No. 1	1.5''	2.25''	1.25	6''
No. 2	1.875''	2.875''	1.5''	9''
No. 3	2.75''	3.75''	2''	20''

[a] Maximum defect size accepted in each respective grade in inches. More information about the grading methods can be found in the respective rule books.

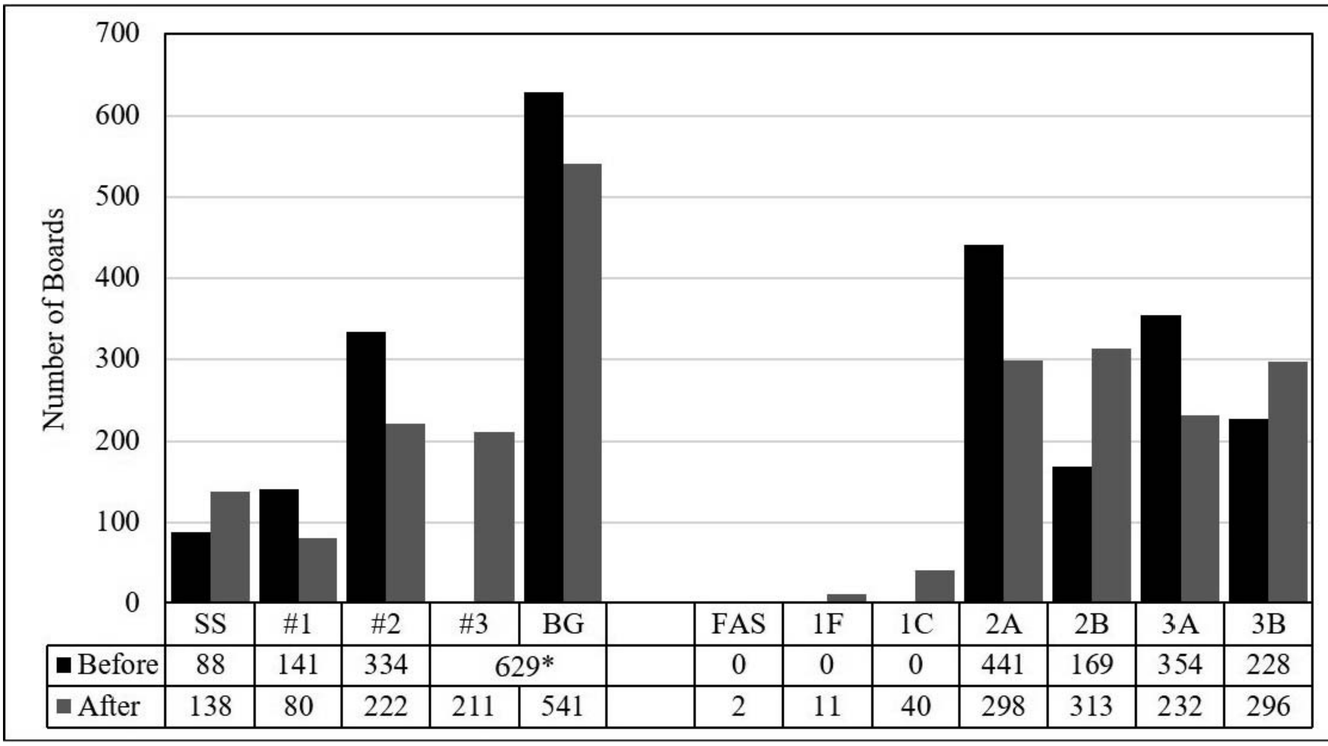


*Figure 2. —Number of boards before and after processing. * Where Northeastern Lumber Manufacturers Association (NELMA) grade No. 3 was not assigned to boards before processing.*

should theoretically not affect the initially assigned grade. Similarly, boards initially classified as Below Grade most likely had several or large defects that were unaffected by processing (S4S) and maintained their initially assigned grades.

Table 3 summarizes the major defect that resulted in board downgrading in accordance with NELMA rules. The most common defects in grades No.1, No.2, and No.3 were knots, while in Below Grade the most common defect was splits. A board when used in a CLT panel will mostly be used flatwise and is expected to be glued to an adjacent layer, minimizing the effects of a split. Given this layup pattern, larger splits, which were responsible for placing a board into a nonstructural grade by NELMA rules, may not play as much of a significant role when placed into a CLT panel. More research, however, is needed to evaluate the use of Below-Grade lumber with splits as the limiting defect in CLT panels.

Most of the observed defects, such as knots, shake, wane, and slope of grain, are inherent in boards following manufacture at the sawmill, while splits and cracks are more commonly associated with handling and processing of the boards. In fact, Lamb (1992) indicates that splits and cracks are associated with four factors: wood characteristics, processing, drying, and handling.

There was no conclusive way to fully understand changes caused by handling and processing the boards during the research without tracking every single board and what evolved from processing (S4S) the board. In this study, the primary objective was to estimate a final NELMA grade after processing (S4S) NHLA low-grade lumber. However, to fully evaluate changes that occurred during processing and handling, future research should focus on analysis through imaging the boards before and after handling and processing.

Table 2.—Distribution in percentages of each of the original Northeastern Lumber Manufacturers Association (NELMA) grades after processing.

	Percent per NELMA grade after processing				
Starting NELMA grade	SS	No. 1	No. 2	No. 3	BG
SS N = 88	61.4	8.0	14.8	4.4	11.4
No. 1 N = 141	29.1	21.3	27.0	12.1	10.5
No. 2 N = 334	8.4	11.1	35.2	21.0	24.3
No. 3 & BG N = 629	2.4	1.0	8.3	19.1	69.2

Table 3.—Percentages of limiting defects keeping boards from achieving a higher grade.

	Percent defects per Northeastern Lumber Manufacturers Association (NELMA) GRADE (%)				
Defect type	No. 1 ($n = 80$)	No. 2 ($n = 222$)	No. 3 ($n = 211$)	BG ($n = 541$)	Total (1.054[a])
Knot	84	76	62	24	47
Splits	4	14	21	43	29
Slope of grain	1	2	5	4	4
Decay	3	0	0	5	3
Shake	3	3	4	11	7
Wane	3	2	6	10	7
Bow	1	0	0	0	0
Other defects	1	3	2	3	3

[a] This total number of boards did not include 138 boards that were graded Select Structural and did not have a limiting factor.

NELMA distribution of low-grade yellow-poplar

To determine the potential use of low-grade yellow-poplar appearance lumber in structural applications (e.g., CLT), the NHLA grade of the kiln-dried, 4/4 (2.54-cm), unsurfaced lumber (before processing) was compared with the final NELMA grade after S4S processing for standard thickness and width, which is necessary for CLT production. The results of this analysis are presented in Table 4.

Based on ANSI/APA PRG 320-2019 (2020), a softwood board should achieve at least a structural visual grade No. 3 grade to be used in the production of CLT panels. From the researched population of NHLA low-grade yellow-poplar, 54.6 percent were graded above the standard requirements for CLT manufacturing specifications. The percentages of boards that achieve structural grade (at least No. 3) within their NHLA grades were 2A (64.4%), 2B (66.3%), 3A (52.3%), and 3B (30.7%). The grade 3B, with 69 percent of boards grading out as Below Grade, presented the least amount of yield when used as structural material, based on NELMA rules; therefore, lumber within this grade is least likely to result in a significant amount usable structural lumber based on NELMA criteria.

Table 5 compares the current results with those by Pahl et al. (1992) and Faust (1990) for NHLA 2A and below lumber. The authors evaluated the NELMA grade of boards from different sources of yellow-poplar. Comparison with data provided by Pahl et al. (1992) and Faust (1990) suggest that the distinct grades results can be justified by the difference in material and methods.

Pahl et al. (1992) used similar methods of grading, and NELMA rules for structural joist and planks, whereas Faust (1990) used grading rules from the Southern Pine Inspection Bureau. In both studies, even with different visual grading methods, the majority of NHLA No. 2 and No. 3 common yellow-poplar met the minimum requirements for structural purposes. Pahl et al. (1992), which had the lowest percentage of Below Grade dried material between studies, air-dried material under roof over 12.5 months to a moisture content (MC) under 19 percent; while Faust (1990) and current research used a dry kiln to achieve 6–8 percent MC. The board MC in the current research was between 6 and 8 percent to match industry standards from the lumber provider. Differences in the drying methods could potentially affect defect development between all these studies; however, these grade differences could also result from sourcing and processing of the raw material.

Pahl et al. (1992) evaluated lumber from graded switch ties, which was procured and processed into 2-inch-thick by 7-inch-wide boards. In contrast, the current research used boards taken from the mill production line, with a target thickness of 1 inch (2.54 cm) commonly manufactured by the industry, a target length of 120 inches (305 cm), and a range of widths (averaging around 7.25 in [18.42 cm]). These dimensions were common to the mill manufacturing process at the mill that donated this lumber for the research.

Table 4.—Final Northeastern Lumber Manufacturers Association (NELMA) grade distribution based on preprocessing (rough lumber) National Hardwood Lumber Association (NHLA) grade.

	NELMA Grade					Total freq.[a]
NHLA Grade	SS	No. 1	No. 2	No. 3	BG	(% of total)[b]
2A						
Freq.[a]	75	31	88	90	157	441
% of total[b]	6	3	7	8	13	(37)
% of NELMA[c]	54	39	40	43	29	
% of NHLA[d]	17	7	20	20	36	
2B						
Freq.[a]	15	18	44	35	57	169
% of total[b]	1	2	4	3	5	(14)
% of NELMA[c]	11	23	20	17	11	
% of NHLA[d]	9	11	26	21	34	
3A						
Freq.[a]	41	24	62	58	169	354
% of total[b]	3	2	5	5	14	(30)
% of NELMA[c]	30	30	28	27	31	
% of NHLA[d]	12	7	18	16	48	
3B						
Freq.[a]	7	7	28	28	158	228
% of total[b]	1	1	2	2	13	(19)
% of NELMA[c]	5	9	13	13	29	
% of NHLA[d]	3	3	12	12	69	
Total						
Freq.[a]	138	80	222	211	541	1,192
(% of total)[b]	(12)	(7)	(19)	(18)	(45)	(100)

[a] Frequency is the number of boards present in each row and column combination.

[b] The total percentage was calculated by dividing the row and column combination by the total number of boards (1,192).

[c] The percentage of NELMA grades was calculated by dividing the row and column combination frequency by the total number of boards in the respective NELMA grade.

[d] The percentage of NHLA grades was calculated by dividing the row and column combination frequency by the total number of boards in the respective NHLA grade.

Elasticity distribution of low-grade yellow-poplar

Although NELMA visual grading indicated that a large proportion of NHLA low-grade lumber met structural grades requirement, a large percentage of the lumber graded visually was Below Grade (45.4%). To verify whether Below Grade lumber was truly unsuited for CLT manufacturing, nondestructive proof loading was used in the study as an alternative grading approach. Figure 3 shows the distribution in modulus of elasticity (MOE_b) found for the NHLA low-grade lumber as determined by nondestructive evaluation.

Figure 3 shows the normal distribution of the population of low-grade yellow-poplar lumber tested using nondestructive proof loading. Normality was confirmed by the Skewness and Kurtosis results. The MOE_b design values of a population are usually calculated from their mean, which, for this distribution, was 1.66×10^6 psi (11,445 MPa). The minimal MOE_b value was 0.77×10^6 psi (5,308 MPa) and the fifth percentile was 1.25×10^6 psi (8,618 MPa) showing that a majority of boards (96.6%) presented an acceptable MOE_b relative to the minimal requirement for CLT panels as outlined in ANSI/APA PRG 320-2019 (2020) of 1.20×10^6 psi (8,273 MPa). Only 39 boards (3.4 percent) did not meet the minimum MOE_b requirement specified in ANSI/APA PRG 320-2019 (2020).

In the literature, modulus of elasticity in bending for yellow-poplar has been reported above 1.20×10^6 psi (8,273 MPa) by several studies (Green and Evans 1987, Faust et al. 1990, Lim et al. 2010, Ross 2010, American Wood Council 2018). These results were calculated by performing the test edgewise, but flatwise results were chosen in the present research to simulate board stresses in a CLT panel. Attempts to produce complementary edgewise data were impractical

Table 5.—Postprocessing Northeastern Lumber Manufacturers Association (NELMA) grade distribution based on the before processing National Hardwood Lumber Association (NHLA) grades of 2A and below.

Study	Sample source	Moisture content	NHLA grade	SS	No.1	No.2	No.3	B.G.
Pahl et al. (1992)	Switch ties	Green	2A & below	42.1	22.1	25.4	8.8	1.7
		Dry		33.6	18.1	25.6	18.9	3.8
Faust (1990)	Random logs	Green	Not reported	Not reported	45.2	36.4	17.7	0.7
		Dry (6%)	Not reported	Not reported	54.6	15.5	6.1	23.8
Current	Random logs	Dry (6–8%)	2A & below	11.6	6.7	18.6	17.7	45.4

because of board widths of ¾ inch (1.9 cm), which caused warp instead of a linear deformation.

To compare MOE_b results within the visual grading system, boards were grouped by their NELMA grade in Table 6. NELMA grading uses a structurally focused visual set of rules to quantify the mechanical resistance of lumber according to defect presence and position. Therefore, it is expected that higher NELMA grades present greater strength. MOE_b can be obtained by nondestructive evaluation, but the value is an indicator of material stiffness and not directly a measure of actual board strength, because defects that do not influence MOE can greatly affect strength. The results of the study showed a positive correlation to the NELMA grades because higher grades presented higher average MOE_b. However, results of the Tukey analysis (95% confidence) indicate that not every group had a statistically significant difference in average MOE_b between NELMA grades. Specifically, there was a statistically significant difference in average MOE_b between Select Structural and No. 3 and Below Grade, No. 1 and Below Grade, and No. 2 and Below Grade. Also, from the coefficient of variation results, Below Grades boards had a greater variation that was likely due to the large number of defects in this grade. Considering the average of MOE_b, lumber within any NELMA grade evaluated would meet the requirements of 1.20×10^6 psi (8,274 MPa) minimum for MOE_b defined in ANSI/APA PRG 320-2019 (2020).

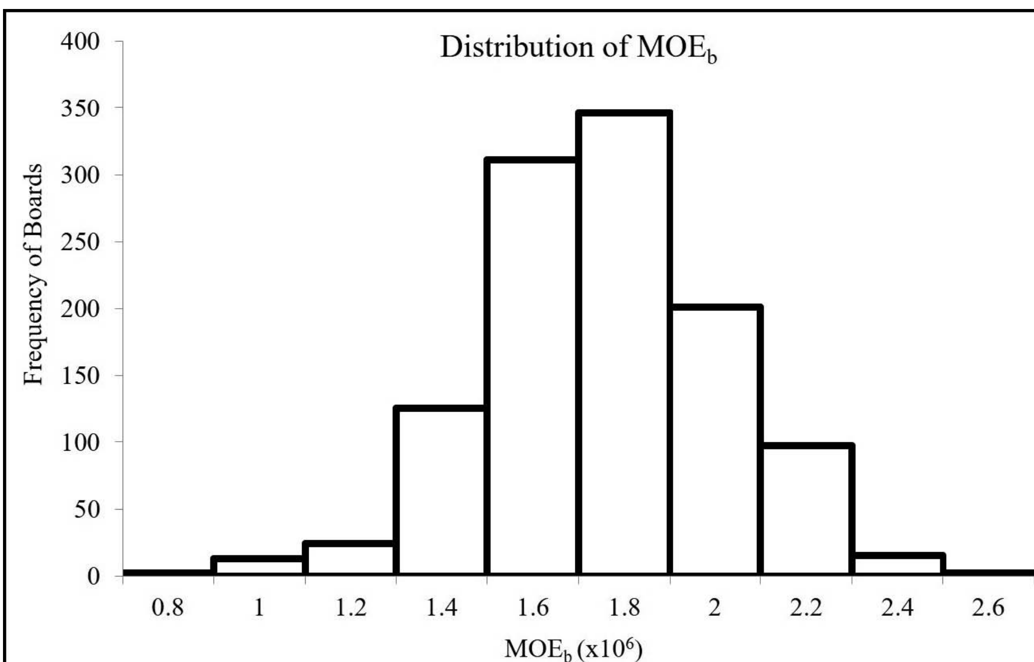
Relative worth of structural low-grade yellow-poplar

To evaluate potential economic value as structural lumber when purchasing NHLA Grade 2 and 3, the relative worth

Table 6.—Bending modulus of elasticity (MOE_b) analysis of the boards grouped by Northeastern Lumber Manufacturers Association (NELMA) grades.

	NELMA Grade				
Statistic	SS	No.1	No.2	No.3	BG
Number of boards	137	80	221	207	490
Mean (10^6 psi)	1.74	1.70	1.68	1.66	1.61
Min. (10^6 psi)	1.19	1.10	0.89	0.86	0.77
Max. (10^6 psi)	2.35	2.37	2.43	2.34	2.47
Number of boards ($<1.20 \times 10^6$ psi)	1	1	4	4	29
Skewness	0.25	0.26	0.09	0.11	−0.21
Kurtosis	−0.32	0.85	0.27	0.25	0.36
Coefficient of Variation (%)	13.5	13.2	14.6	15.9	17.0
Tukey HSD[a]	a	ab	ab	bc	c

[a] Columns with the same letter did not present a statistically significant difference in average MOE_b as determined using a Tukey honestly significant difference test with $\alpha = 0.05$.



MOE population analyzes	
# Boards	1137
Mean (10^6 psi)	1.66
Minimum (10^6 psi)	0.77
Maximum (10^6 psi)	2.47
5th percentile (10^6 psi)	1.25
# Boards <1.2 x10^6 psi	39
Skewness	-0.09
Kurtosis	0.42
Coefficient of Variance (%)	0.16

Figure 3. —Distribution of modulus of elasticity in flatwise bending (MOE_b) values for low-grade yellow-poplar and relevant statistics.

using current market prices was analyzed. The relative worth of each grade based on their NELMA visual grade is presented in Table 7, and the relative worth based on the developed MOE_b categories is presented in Table 8.

In relation to relative worth, this value would fluctuate over time and according to the current price of each of the NHLA grades. Using the data from March 2021, based on both resulting NELMA grades and MOE_b categories, the NHLA grade that presented the higher total relative worth was grade 2B, while the least feasible grade was 3B. However, the current prices for dry lumber in grades 2B, 3A, and 3B are not available from market reports and a prediction of the value was made by adding a drying cost to the green 2B values for these grades. In the analysis, 2B, 3A, and 3B were treated as being in the same price category, because these grades were material sold combined together as pallet stock. Under the situations evaluated in March 2021, the result of the relative worth analysis suggests that purchasing NHLA 2B has the best potential if the intention of using the lumber is in a structural application considering both NELMA and MOE categories. The relative worth calculation is also useful when purchased lumber must meet a certain NELMA grade or MOE_b classification. For example, if the structural lumber must meet No. 1 and higher grades, then the SRs values of one (1) would be used for No. 1 and SS grades, and a value of zero (0) would be assigned for SRs of other grades. Under this scenario, NHLA 2A lumber becomes more attractive.

Conclusions

This research focused on an evaluation of the structural characteristics of a large sample of low-grade yellow-poplar lumber for use in CLT panel production. The boards were evaluated before and after processing and the parameters used for evaluation were NELMA visual structural grade and nondestructive testing.

The sampled population of NHLA grades 2A and below yellow-poplar lumber produced 651 boards out of a sample population of 1,192 boards, or 54.6 percent of the tested boards, that met visual NELMA structural grades. Results from nondestructive proof-loading tests indicated that 96.6 percent of the boards met the minimum MOE_b specified CLT panel production under ANSI/APA PRG 320-2019

Table 7.—Relative worth of dry yellow-poplar per National Hardwood Lumber Association (NHLA) grade based on Northeastern Lumber Manufacturers Association (NELMA) results.[a]

	SS	No.1	No.2	No.3	BG	Total
Relative Strength to Ratio (SR)	0.66	0.60	0.49	0.30	0	
NHLA Grade (Price)						
Frequency						
2A (690)	75	31	88	90	157	441
2B (600)	15	18	44	35	57	169
3A (600)	41	24	62	58	169	354
3B (600)	7	7	28	28	158	228
Total	138	80	222	211	541	1,192
Relative worth						
2A (690)	0.163	0.061	0.142	0.089	0	0.454
2B (600)	0.098	0.107	0.213	0.104	0	0.520
3A (600)	0.127	0.068	0.143	0.082	0	0.420
3B (600)	0.034	0.031	0.100	0.061	0	0.226
Total	0.421	0.266	0.598	0.336	0	1.621

[a] Relative worth was determined using lumber price data for March 2021 from the Hardwood Market Report.

Table 8.—Relative worth of dry yellow-poplar per National Hardwood Lumber Association (NHLA) grade based on bending modulus of elasticity (MOE_b) results.[a]

	MOE_b distribution ($\times 10^6$ psi)					
	>2	1.8–2	1.5–1.8	1.2–1.5	<1.2	Total
Relative Strength to Ratio	1	0.90	0.75	0.60	0	
NHLA Grade (price)						
Frequency (number of boards)						
2A (690)	67	86	198	62	11	424
2B (600)	22	34	74	30	1	161
3A (600)	19	66	152	94	12	343
3B (600)	6	15	104	67	15	209
Total	114	201	528	253	39	1,135
Relative worth						
2A (690)	0.229	0.265	0.508	0.127	0.000	1.128
2B (600)	0.228	0.317	0.575	0.186	0.000	1.305
3A (600)	0.092	0.289	0.554	0.274	0.000	1.209
3B (600)	0.048	0.108	0.622	0.321	0.000	1.098
Total	0.597	0.978	2.258	0.908	0.000	4.741

[a] Relative worth was determined using lumber price data for March 2021 from the Hardwood Market Report.

(2020). These findings provide evidence that a significant proportion of NHLA classified low-grade yellow-poplar lumber has the potential for being reclassified and used for structural purposes, particularly as a raw material for manufacturing CLT panels. Additionally, the specific gravity of yellow-poplar is listed as 0.43 in the National Design Specification for Wood Construction, which is above the minimum required value of 0.35 stated in ANSI/APA PRG 320-2019 (2020). Finally, in terms of grading, the nondestructive test results showed a higher yield than visual grading and should be further evaluated as a more efficient and economical means for structurally grading low-grade hardwood lumber for CLT applications. Proof-loading lumber in the final processed form may be a more useful grading approach in composite applications, rather than stand-alone single-use structural member applications. However, more research is needed to correlate NHLA low-grade lumber MOE_b to MOR before such a system could be fully implemented for CLT manufacturing purposes.

From the relative worth calculated for each of the four lower grades of the NHLA rules, the grade that presented more feasible potential to be used in the production of CLT panels is the grade 2B Common. Although this result is dependent upon the current relative price, and the results may vary according to the current price of each of the NHLA grades at a certain time.

Any large-scale change in grading methods by hardwood lumber manufacturers will depend on investment and a market able to justify the investment. Although, based on these results, regrading low-grade hardwood lumber, primarily used in pallet manufacturing, would add considerable value to this lumber and potentially provide usable feedstock for producing CLT panels. However, more research in using both NELMA graded and non-destructively evaluated yellow-poplar in CLT panels is needed to verify the structural capacities as described in ANSI/APA PRG 320-2019 (2020).

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