Challenges Facing the Development and Market Introduction of Hardwood Cross-Laminated Timbers

Curt Hassler Joseph F. McNeel Levente Denes
Jonathan Norris Balasz Bencsik

Abstract

The interest in softwood-based cross-laminated timber (CLT) production has in turn generated a great deal of interest in producing CLT from hardwood species. This prospect of a new market for hardwood lumber is a significant driver behind efforts to gain certification of hardwoods within American Panel Association (APA) PRG 320, Standard for Performance-Rated Cross-Laminated Timber. However, a number of challenges present significant hurdles for gaining acceptance of hardwoods in CLT manufacturing. These include differences in how softwoods and hardwoods are produced and marketed (e.g., structural lumber markets [softwoods] vs. appearance-grade markets [hardwoods]), lumber grading differences, available sizes of hardwood lumber, drying differences between hardwoods and softwoods, and gluing particularities with hardwoods. This paper identifies the various issues involved with introducing hardwoods into a softwood-dominated market and what it will take to be competitive within the overall CLT market.

Interest in mass timber products for construction has swept both Europe and North America in recent years, with new manufacturing facilities cropping up across both continents. This growth has been sustained by readily available softwood species in the sizes and grades required in cross-laminated timber (CLT) manufacturing. Whether the raw material is western US softwoods, European spruce, or southern pines, these necessary raw material requirements are easily met and sustained. The only major confounding factor recently has been the significant run up in softwood lumber pricing, with the Producer Price Index for softwood lumber nearly doubling between 2019 and 2022.

As with any industry, hardwood lumber manufacturers have generally viewed Mass Timber as a significant opportunity to develop new markets for hardwood lumber. A recent survey conducted by Adhikari et al. (2021) suggests that about 10 percent of 124 mills surveyed during their study felt their mills could produce structural grade hardwood lumber without significant modification. However, 37 percent of the 124 responding mills also employed structural graders, suggesting that these mills already milled structural softwood lumber and probably considered sawing structural grade hardwood to be very similar to the approaches used with softwoods, which is not generally the case. About 90 percent of the 124 responding sawmills indicated that they are not ready to begin producing structural grade hardwood lumber and would need additional resources.

Profitability is of primary concern when entering any new market. Adhikari et al. (2021) learned from their survey of hardwood sawmills that more than 30 percent of the participating sawmills required a return of more than 10 percent over National Hardwood Lumber Association (NHLA) lumber prices to produce hardwood for CLT panels. Fifteen percent of the sawmills required 1 to 5 percent higher lumber value, and another 26 percent of the respondents required 5 to 10 percent higher value to enter the market.

Most of the comparisons made through their survey focused solely on hardwood lumber value, even though much of the low-grade hardwood would be generated by sawing up cants. Experience suggests that a better price comparison would be with pallet cants and railroad crossties. Both of these products currently have a higher value per 1,000 board feet (MBF) than sawn lumber, so the market

The authors are, Research Professor (chassler@mail.wvu.edu), Professor & Director (jmcneel@wvu.edu [corresponding author]), and Post-Doctoral Fellow (balazs.bencsik@mail.wvu.edu), Appalachian Hardwood Center, West Virginia Univ., Morgantown, West Virginia; and Associate Professor (ldenes@mail.wvu.edu), and Graduate Research Assistant (jn0041@mix.wvu.edu), Wood Sci. and Technol., West Virginia Univ., Morgantown, West Virginia.
This paper was received for publication in August 2022. Article no. 22-00048.

Forest Prod. J. 72(4):276–283.
doi:10.13073/FPJ-D-22-00048

entry point for many mills will be much higher than what was alluded to in this article.

Unfortunately, the industry's interest in producing large volumes of structural grade hardwood lumber specifically for the CLT industry has ignored certain unique aspects of hardwood raw material requirements and manufacturing differences that do not exist with softwood when supplying CLT manufacturing markets. The survey results published by Adhikari et al. (2021) also suggested that resources considered necessary for structural grade hardwood lumber by most of the responding hardwood lumber mills predominantly included added surfacing equipment, certified structural graders knowledgeable in grading hardwoods, and additional kiln capacity. This paper attempts to define and quantify in greater detail other more significant challenges and issues that must be addressed if a viable hardwood CLT industry is to be developed.

Softwood Versus Hardwood Lumber Grading

Softwoods are the primary species for satisfying dimensional, structural lumber markets. Lumber is available in standard sizes (e.g., 2 by 4 [50.8 by 101.6 mm], 2 by 6 [50.8 by 152.4 mm]) that are surfaced and dried to moisture contents compatible with CLT board requirements. Additionally, these softwood products are graded either visually or using machine stress rating (MSR) grading systems for structural purposes, in accordance with the rules set forth by the recognized grading agencies (American Lumber Standard Committee 2022), with regular inspections of the grading process at individual mills by a certified grading or inspection agency.

Structural lumber grades are based on the size and location of a variety of defects, including knots, wane, decay, splits, holes, shake, warp, crook, twist, cup, slope of grain, and skip. The visual grade designations for structural lumber are Select Structural, No. 1, No. 2, and No. 3, and all lumber considered for use in CLT panels must receive the appropriate structural grade in order to be manufactured into CLT panels. Each structural grade has its own specific limitations for the defects listed above. One example of the definitions and specifications for visually grading lumber are promulgated, maintained, and administered by the Northeastern Lumber Manufacturers Association, Inc. (NELMA). In fact, NELMA (2021) is the only organization that includes grading rules and design values for eastern hardwoods.

Additionally, the NELMA grading rules provide for nondestructive testing via MSR with an accompanying visual override for certain board characteristics that cannot be evaluated by machine. The operable measure for MSR-based grading is the modulus of elasticity (MOE).

For the purposes of CLT production, the boards within each panel must meet certain structural lumber grade requirements, according to PRG 320, Standard for Performance-Rated Cross-Laminated Timber (American Panel Association [APA] 2019). For layups based on visual grading of boards, the minimum grade for the longitudinal layers, or laminates, must be visual structural grade No. 2, whereas the minimum grade for the inner, transverse laminates must be visual structural grade No. 3. Additionally, CLT layups using MSR lumber must have a minimum MOE of 1.2 by 10^6 psi for longitudinal laminates, with visually graded structural grade 3 lumber in the transverse laminate (the minimum MOE in this case applies to layup E3 for eastern softwoods, northern species, or western woods; APA 2019).

Most important, softwood lumber with the specific dimensions and grades needed for CLT manufacturing are readily available in the marketplace. A CLT manufacturer can simply place an order with a producer or broker for the desired dimensions and grade of lumber for their manufacturing activities. The only issues may be price and timing of the shipment.

Hardwoods represent an entirely different market situation. Hardwood markets are generally focused on appearance, with the amount of clear wood in a board being the key to establishing a grade. Hardwood markets include furniture, cabinets, architectural millwork, and other products that require clear wood to be manufactured. The greater the proportion of clear wood in a board, the higher the grade and the more expensive the board. This hardwood grading protocol is promulgated and administered by the NHLA (2019). For instance, the highest grade a hardwood board can achieve is Firsts and Seconds (FAS). In general, an FAS board must contain a minimum of 83-1/3 percent clear wood based on the number of clear-face cuttings allowed for boards of specific sizes (see NHLA 2019 for detailed descriptions of each grade). The mix of hardwood lumber grades include FAS, FAS 1-Face (F1F), Selects, No. 1 Common, No. 2A Common, No. 2B Common, No. 3A Common, and No. 3B Common, from highest to lowest grade, respectively.

Additionally, these appearance-graded boards are, for the most part, not used in their graded form. They are surfaced, ripped, and crosscut into clear wood pieces of various dimensions by the consumers of these boards and then joined (e.g., glued, finger-jointed) for the manufacture of furniture, cabinets, millwork, and so forth.

Specifically, hardwood products are not typically manufactured and graded for structural applications. Part of the reason for this is that appearance-graded lumber generally has a higher market value than structural lumber, which is a low-margin, commodity product. As a result, hardwoods are rarely considered an alternative to graded structural softwood dimension lumber.

However, some industrial products sawn from hardwoods may be graded, such as railroad ties and bridge timbers. For instance, The Railway Tie Association (2003) publishes Specification for Timber Crossties and Switch Ties, which details defect limitations such as knots, decay, holes, shake, split, checks, slope of grain, bark seams, and manufacturing defects. Yet, these types of graded hardwood products do not lend themselves to effective and efficient CLT production in their marketed form.

From a lumber grading perspective then, structural grading and appearance grading are incompatible for the purposes of manufacturing hardwood CLT panels. Currently, there is no market where a CLT manufacturer can order structurally graded hardwood lumber. What is the alternative? One option is to investigate how NHLA grades of hardwood lumber might yield structural grades of hardwood lumber.

This approach was taken by West Virginia University's Appalachian Hardwood Center (WVU-AHC) for their investigation of hardwoods for CLT manufacturing. Specifically, WVU-AHC has procured packs of hardwood lumber graded as NHLA No. 2A and below to determine what these boards might yield in terms of structural lumber. These

Table 1.—Yield of NELMA structural grade lumber from yellow-poplar lumber processed (surfaced 4 sides from 4/4, rough, kiln-dried boards) by NHLA lumber grade.[a–c]

NHLA grade	NELMA grade, no. boards (%)					Total freq. (% of total per grade)
	Select Structural	No. 1	No. 2	No. 3	Below Grade	
2A	75 (17.0)	31 (7.0)	88 (20.0)	90 (20.4)	157 (35.6)	441 (100)
2B	15 (8.9)	18 (10.7)	44 (26.0)	35 (20.7)	57 (33.7)	169 (100)
3A	41 (11.6)	24 (6.8)	62 (17.5)	58 (16.4)	169 (47.7)	354 (100)
3B	7 (3.1)	7 (3.1)	28 (12.3)	28 (12.3)	158 (69.2)	228 (100)
Total	138 (11.6)	80 (6.7)	222 (18.6)	211 (17.7)	541 (45.4)	1,192 (100)

[a] NHLA = National Hardwood Lumber Association; NELMA = Northeastern Lumber Manufacturers Association, Inc.

[b] From Azambuja et al. (2021).

[c] No visual override was applied to the boards; they were analyzed as mill-run lumber.

lower grades were selected because they are significantly less expensive to procure than the higher value NHLA lumber grades (No. 1 Common and better).

Hardwood Lumber Sizes for CLT Production

From a CLT manufacturing perspective in North America, the typical dimensions of softwood boards that are used in CLT panels include a consistent finished thickness of 1 3/8 inches (34.925 mm), with a width ranging from 2.4 inches (60.96 mm) to 5 1/2 inches (139.7 mm) to 7 1/2 inches (190.5 mm) and even wider (APA 2019). Hardwood board thickness is not even specified in the same manner; rather, thickness is expressed in quarter-inch classes. For instance, 4/4 indicates a 1-inch (25.4-mm) board. Other typical thicknesses produced include 5/4 (31.75 mm), 6/4 (38.1 mm), and 8/4 (50.8 mm), with thicker pieces ranging up to 16/4 (101.6 mm). Further, these boards in a green condition generally have an additional 1/8 inch (3.175 mm) of thickness to account for shrinkage during drying. In a rough kiln-dried condition, these boards require surfacing to achieve a consistent thickness, given that the kiln-drying process may result in different shrinkage of boards and result in inconsistent thickness.

Additionally, hardwood boards are commonly produced at the sawmill in random length and random width pieces. The only standard-size materials produced at a hardwood sawmill are from the log hearts where the production of higher grades of lumber is minimal. These heart-centered products include railroad ties (e.g., 7.5 in [190.5 mm] by 9 in [228.6 mm] by 8.5 ft [2,590.8 mm]) and pallet cants (e.g., 3.5 in [88.9 mm] by 6 in in various lengths).

The most commonly sawn hardwood board thickness is 4/4 (1 in; 25.4 mm). In considering how to best approach raw material procurement for hardwood CLT, the logical choice would be to investigate the feasibility of purchasing the most commonly available raw material. This approach was taken by researchers with WVU-AHC as part of a study investigating the feasibility of using yellow-poplar (*Liriodendron tulipifera*) for CLT manufacturing, with the objective of gaining certification under the PRG 320 (APA 2019).

A sample population of 4/4 (25.4-mm) boards was obtained from a cooperating West Virginia sawmill and sawn from 7.25-inch (184.15-mm)-thick flitches. This is the mill's standard process for sawing log hearts into pallet boards: saw logs to a 7.25-inch (184.15-mm) flitch and then process the flitch through a gangsaw. The higher grade boards (NHLA grades 1 Common & Better) are sorted for appearance markets, whereas the remaining lower grade boards (2A, 2B, 3A, and 3B) are ordinarily sorted out for pallet boards. Further, the mill sorted out the 10-foot (3,048-mm) boards that were requested by WVU-AHC for the CLT research. Specifically, additional effort was required by the cooperating mill to supply boards with a standard dimension similar to that provided by the softwood structural market. Projecting this situation into a marketing effort, this additional work ultimately adds more cost to the production of hardwood lumber earmarked for CLT manufacturing.

This effort can be burdensome for a hardwood sawmill that does not have a gang saw capable of producing fixed width boards from a flitch. For example, a hardwood mill without a resaw or gang saw will have to rely on the edger operator to identify boards of a certain grade to saw to CLT required widths, which may be tenuous at best. A similar situation would be operative in a mill with a resaw producing a single board at a time, where the production of boards of a set width may be more difficult to achieve.

Structural Lumber Yields from Hardwoods

The evaluation of structural lumber yields from NHLA low-grade yellow-poplar boards was conducted by WVU-AHC. Results of this investigation for yellow-poplar are detailed in Azambuja et al. (2021). Boards provided by the cooperating West Virginia hardwood sawmill included lumber in four NHLA grade categories: No. 2A, No. 2B, No. 3A, and No. 3B. The boards were provided as 4/4 (25.4 mm), rough, and kiln dried. They were then surfaced and ripped to a fixed width of 6.25 inches (158.75 mm). The final dimension for CLT manufacture was 6 inches (152.4 mm) by 0.75 inches (19.05 mm) by 10 feet (3,048 mm). Visual structural grading results, based on the original NHLA grade (before processing), are in Table 1.

In general, the yield of structurally acceptable boards for longitudinal laminates (No. 2 and Better) from NHLA graded boards was very poor, ranging from 45.6 percent (No. 2B) down to 18.5 percent (No. 3B). In total, only 36.9 percent of the hardwood boards visually graded for structural characteristics (No. 2 and better) was found acceptable for longitudinal laminates.

From a CLT procurement perspective, the basic approach is to determine how many 4/4 (25.4 mm), rough, kiln-dried boards are required to yield 1,000 feet (surface measure) of CLT-ready boards. Taking the No. 2A NHLA graded boards, for instance, 441 boards yielded 194 boards of No. 2 and Better boards, or 970 feet (295.656 m) of surface measure (each finished board has 5 ft [1,524 mm] of surface measure @ 6 in [152.4 mm] wide by 10 ft [3,048 mm] length). Solving for 1,000 feet of surface measure for CLT-

Table 2.—The volume of 4/4, rough, kiln-dried yellow-poplar lumber required to yield 1,000 square feet per surface measure of cross-laminated timber (CLT)-ready boards, by National Hardwood Lumber Association (NHLA) grade.[a]

NHLA grade	Board feet required to yield 1 MBF of CLT-ready boards
2A	2,730
2B	2,634
3A	3,342
3B	6,516

[a] Based on data from Azambuja et al. (2021).

ready boards requires 455, 4/4, rough, kiln-dried boards. A 4/4, rough, kiln-dried board contains 6 BF, so it would require 2.73 MBF of 4/4, rough, kiln-dried boards to yield 1,000 feet (304.8 m) of surface measure of finished boards. Table 2 summarizes the volume of 4/4 (25.4-mm), rough, kiln-dried yellow-poplar footage required to yield 1,000 feet (304.8 m) of surface measure in CLT-ready boards.

It is apparent that procuring 1,000 feet (304.8 m) of surface measure of CLT-ready boards from 4/4 (25.4-mm), rough, kiln-dried boards will incur a substantial cost, from 2.634 to 6.516 times the cost per MBF of the rough, kiln-dried lumber.

These boards were essentially mill run, so the obvious option is to incorporate a visual override protocol at the mill to eliminate boards that would obviously not make at least a No. 2 structural grade (and perhaps a No. 3 structural grade). This would help reduce the footage necessary to achieve the desired outcome in CLT-ready boards. This option was not studied as part of the WVU-AHC research.

The other potential avenue for additional research is to evaluate No. 1 Common boards for CLT production. Lower grade lumber (No. 2A and No. 2B) will require about 2.6 times the cost to achieve a desired volume of CLT-ready lumber; therefore, the difference in cost between one MBF of No. 1 Common and one MBF of No. 2A or 2B Common will be significantly exacerbated.

However, could the yield of higher grade structural boards be more economically efficient using No. 1 Common lumber, rather than these lower grades? This option was not explored by WVU-AHC but does offer sufficient merit for study.

WVU-AHC has also assessed the yields of structural boards from both soft maple (*Acer rubrum*) and red oak (*Quercus rubra*), using 4/4, rough, kiln-dried boards. Preliminary results for these species indicate similar yield patterns as those noted for yellow-poplar.

Earlier research at WVU-AHC evaluated the yield of structural lumber of six hardwood species (Pahl et al. 1992, McDonald et al. 1996) processed from graded railroad switch ties and ungraded mill-run pallet cants. The difference between this study and the study by Azambuja et al. (2021) was that the boards produced in the latter were sorted from the processing of flitches through a gangsaw.

In the study by Pahl et al. (1992), 2 by 7-inch (50.4 by 177.8-mm) boards were sawn from the graded switch ties and 2 by 6 inches (50.4 by 152.4 mm) from ungraded pallet cants. All resulting boards were visually graded for structural application. Table 3 shows the results of that research.

Table 3.—Structural lumber yields of yellow-poplar lumber sawn from graded switch ties and ungraded, mill-run pallet cants.

	Structural grade (%)				
Type	Select Structural	No. 1	No. 2	No. 3	Below Grade
Mill-run cant	10	5	32	26	27
Graded switch tie	42	22	25	9	2

Fifty-three percent of the visually graded boards were No. 3 and Below Grade for the mill-run pallet cants, a result similar to the structural grade results from Azambuja et al. (2021) for NHLA grades No. 2A and No. 2B (56 and 55%, respectively). However, the processing of *graded* railroad switch ties into 2 by 7 (50.4 by 177.8-mm) boards raised the yield of No. 2 and better structurally graded boards to 89 percent, a dramatically different result, generally attributed to using graded switch ties in the study.

These results infer that the production of structural lumber from graded, heart-centered cants may be a better option for securing structural hardwood lumber. This allows the hardwood sawmill to continue manufacturing higher grade, more valuable lumber, from the outer portions of logs. The trade-off then becomes an economic decision between simply producing cants for existing markets or processing them into nominal 2-inch (50.4-mm)-thick boards. Of course, the latter decision must account for the additional processing and grading needed to meet structural lumber specifications for No. 2 and Better structural, as required by PRG 320 in the parallel laminates.

Structural Grading Options

The foregoing discussion has been in the context of visual grading of structural lumber. In the case of mill-run lumber from flitches (Azambuja et al. 2021) and from mill-run pallet cants (Pahl et al. 1992, McDonald et al. 1996), the resulting board grades were heavily skewed to No. 3 and Below Grade boards.

Previous research has indicated that machine stress rating of hardwoods can yield better results than visual grading. Green et al. (1994) performed both MSR and visual grading of 803 pieces of 2 by 8 mixed-oak boards. Results showed that while

> . . .only 1% of the lumber qualified as Select Structural by visual grading, 36% of it could be assigned an MSR grade with properties equal to or greater than those of Select Structural. (Senalik and Green 2020:34)

Another study, unpublished by Green, Wolcott and Hassler (Senalik and Green 2020), compared visual grading and MSR grading of 2 by 6 (50.4 by 152.4-mm) lumber sawn from log heart cants for several hardwood species. These were the same boards produced in the Pahl et al. (1992) study. Results showed that MSRs of these boards were 10 to 20 percent higher than visually graded properties.

> Thus, research to date indicates the possibility of achieving higher yields for a specified set of allowable properties using the MSR process. (Senalik and Green 2020:36)

Table 4.—Bending modulus of elasticity (MOE_b) analysis of yellow-poplar boards grouped by visual structural grades.[a]

	Visual grade				
	Select Structural	No. 1	No. 2	No. 3	Below Grade
No. of boards	137	80	221	207	490
No. of boards $<1.20 \times 10^6$ psi[b]	1	1	4	4	29

[a] Based on data from Azambuja et al. (2021).
[b] The minimum MOE required for boards used in the production of cross-laminated timber panels is 1.20×10^6 psi (11,4445 MPa), based on data published in PRG 320 (APA 2019).

More recent research conducted at WVU-AHC with yellow-poplar for production of CLT showed similar results to these earlier studies. Azambuja et al. (2021) subjected 1,135 yellow-poplar visually graded boards to nondestructive proof-loading to determine their MOE. The minimum MOE required for boards used to produce CLT panels is 1.20 by 10^6 psi (11,4445 MPa), so that figure was chosen to determine what proportion of the boards could meet the minimum MOE specifications required for boards used in CLT panels (APA 2019). Table 4 summarizes those results.

Thirty-nine boards (3.4%) out of the 1,135 boards tested did not meet the MOE threshold specifications, which implies that machine stress rating may ultimately be the better alternative for evaluating hardwood boards for CLT production. WVU-AHC is currently evaluating and comparing visual grading and machine stress rating for soft maple and red oak, again in the context of CLT production. Preliminary results indicate similar outcomes for both species to those noted for yellow-poplar relative to grade yield.

CLT Panel Options

The selection of 4/4 boards to conduct CLT research at WVU-AHC necessarily translates to the production of five-layer CLT boards (three parallel layer and two perpendicular layers). With the final thickness of boards being 0.75 inches (19.05 mm), the panel thickness would be 3.75 inches (95.25 mm). This is very similar to European CLT layups with boards 20, 30, and 40 mm thick (roughly , 19/16, and 1.5 in, respectively).

A CLT panel manufactured of 2 by 4 (50.4 by 101.6 mm), 2 by 6 (50.4 by 152.4 mm), or 2 by 8 (50.4 by 203.2 mm) softwood boards would contain at least three layers (two parallel layers and one perpendicular layer). Given the thickness of the softwood boards at 1.5 inches (38.1 mm), the softwood CLT panel would be approximately 4.5 inches (1,14.3 mm; approximately—a small amount of wood must be removed prior to CLT panel layup because a fresh surface is required for gluing).

Producing an equivalent three-layer hardwood CLT panel at 4.5 inches (114.3 mm) thick, would obviously require 7/4 (44.45-mm) boards (finished thickness would be 1.5 in [38.1 mm]). Unfortunately, 7/4 (44.45-mm) lumber is not a typical thickness sawn by hardwood sawmills and would require another significant change in the conventional lumber manufacturing process used currently and would not be well-accepted by an industry faced with an uncertain CLT market. This is further evidenced by the fact that the third-party pricing publications do not provide pricing for 7/4 (44.45-mm) lumber (HMR 2022; Hardwood Publishing 2022).

Drying Hardwood Lumber for CLT Production

According to APA PRG 320, CLT boards must have a moisture content (MC) of 12 ± 3 percent. For softwood CLT manufacturers this is not an issue because softwood lumber can be easily purchased in the marketplace with an MC of 15 percent or less and marked ''MC-15'' or ''KD-15.''

By comparison, hardwood lumber is generally dried to between 6 and 8 percent MC for the furniture, cabinet, and millwork markets (Simpson 1999). Thus, hardwood mills and kiln operations would have to adjust their drying schedules to achieve a higher MC. This may not be an issue because it would presumably reduce the cost of kiln-drying, assuming that enough demand was available to achieve full kiln charges with CLT-destined lumber.

Depending on the hardwood species being considered for CLT manufacturing, the length of time to dry could be an issue. Senalik and Green (2020) state that a typical drying schedule for southern yellow pine (*Pinus echinata*) structural lumber is 1 to 2 days. By comparison, Wang and Simpson (2020) discuss drying of red maple (*Acer rubrum*) for structural purposes and found that a kiln schedule that is more severe than that allowed for appearance-grade processing, could be accomplished in 5 days, without any additional structural degrade compared with the milder schedule. Presumably, similar results could be obtained when drying 4/4 (25.4-mm) yellow-poplar lumber.

Economic considerations, as outlined above, dictate that the approach to incorporating hardwoods into CLT manufacturing is to use No. 2A and below lumber. However, No. 2A and lower grade lumber is not typically kiln-dried by the producing sawmill but sold green to pallet and flooring manufacturers. The question is whether hardwood mills would be willing to consume kiln space with low-grade lumber for CLT manufacturers at the expense of drying their higher grade, high-value lumber. The situation could be further exacerbated if a CLT manufacturer was able to procure 6/4 (38.1-mm), 7/4 (44.45-mm), or 8/4 (50.8-mm) boards of NHLA No. 2A Common and lower and the accompanying increased kiln residence time to reach the desired moisture content.

Gluing Hardwoods for Structural Purposes

Gluing hardwood lumber for structural purposes is another significant issue for prospective CLT manufacturing. Although hardwoods have been glued for furniture, cabinet, and millwork purposes, where the products are primarily in service in indoor settings, the use of glued hardwoods in exterior settings has not been researched to any significant degree.

Manufacturing hardwood CLT panels requires an effective adhesive to securely bond the laminates. This bonding is more complicated than for softwoods because of the complex nature of hardwoods. Bonding difficulties arise from the anatomical, structural, and chemical differences between hardwoods and softwoods and even between different hardwood species. The higher shrinking and swelling coefficients of hardwoods, exacerbated by their higher density and more pronounced orthotropy, produce significant stresses between the adhesive and the wood substrate. If these stresses cannot be absorbed by the bond line, a bond failure will occur that generally results in delamination, where the bond between wood and adhesive fails.

Most engineered wood products are used in construction and are consequently exposed to more severe exterior conditions. When exposed to water, high humidity, or extreme temperatures, bonded structures lose their strength, but can fully or partially recover after the severe conditions end. Bonding strength and durability depend on environmental conditions, material properties, adhesive characteristics, technological parameters, and the internal stresses combined with the applied loads.

Delamination testing is perhaps the most severe test that APA-certified CLT panels must undergo. The testing treats samples from a panel to cyclic wetting and drying through a vacuum process and is specifically structured to test bond line durability (APA 2019). Bond line durability has not been evaluated for adhesives in hardwood-based mass timber product applications and the limited research currently in the literature does not identify those adhesive systems most effective in producing hardwood-based CLT panels.

Several structural adhesive systems already used with softwoods reliably meet the prescribed strength and durability requirements, but these systems need further research to confirm satisfactory performance with hardwoods. Four commonly used structural adhesives that may be suitable for use with hardwoods include phenol resorcinol formaldehyde (PRF), melamine formaldehyde, emulsion polymer isocyanate, and one-component (1C) or two-component (2C), polyurethanes (PURs).

The first two adhesive types are considered in situ polymerized resins because they infiltrate into cells walls prior to curing and form relatively rigid cross-links. The emulsion polymer isocyanate and the 1C polyurethane resins comprise preformed polymers with higher molecular weights and produce a more flexible glue-line with different strain and creep distributions (Frihart 2009). This could be one of the possible explanations as to why PRF resins perform so well in wet conditions and durability tests. Assessing the bonding quality of hardwoods in wet conditions and cyclic delamination revealed that extrapolation of the test results achieved with softwoods to hardwoods is not always possible.

When a PUR primer with a very short activation time was used with a PUR adhesive system, the delamination performance of ash, beech, and oak glulam specimens significantly improved. In the case of face-milled oak samples, the primer was not effective, and delamination remained well above the 5 percent acceptance level (Luedtke et al. 2015).

In another study (Bockel et al. 2020), a 2C PUR adhesive was used to determine the tensile strength of lap joints made of European beech (*Fagus sylvatica*). Calcium carbonate as filler was added to the adhesive in an effort to increase the modulus of elasticity. Tensile strength results for modified 2C PUR polymer fillers were comparable to industrial 1C PUR values, but the addition of filler did not result in an improvement in wet conditions.

The strength and durability of the bond line is also influenced by surface preparation. An article written by Knorz et al. (2014) demonstrated that shear strength of bonded ash in dry conditions was the same regardless of adhesive type; however, in the case of polyurethane adhesive, the wood failure was below 80 percent for the planed and sanded specimens.

The extractives from hardwoods can affect glue line properties through surface wettability, polarity, and permeability. Bockel et al. (2019) found that polyurethane adhesives are negatively affected by acid extractives (common in many hardwoods), whereas melamine urea-formaldehyde degrades in contact with starch and gallic acid.

A study that examined the effect of wood characteristics on the adhesive bond quality of yellow-poplar lumber identified which characteristics of yellow-poplar influenced adhesive bond quality (Hovanec 2015). The study analyzed the effects of adherend thickness, lamination orientation, and orthotropic orientation in relation to bonding yellow-poplar. The strength and durability of the bond lines were quantified through cyclic delamination and shear block tests.

The two most significant factors affecting bond strength were found to be laminate orientation and adherend thickness. Parallel laminated samples tended to have higher average shear strength and wood failure than did perpendicular laminated samples. Samples with thinner adherends had significantly higher levels of wood failure than did samples with thicker adherends. Overall, none of the tested effects had clear impacts on bond durability, and yellow-poplar was found to host adhesive bonds with the strength and durability necessary for use in CLT.

An additional study focusing on the performance of yellow-poplar CLT panels examined the stiffness and strength in four- and five-point bending, as well as the shear by compression loading, and resistance to delamination (Mohamadzadeh and Hindman 2015). The values recorded for bending stiffness, bending strength, and resistance to delamination met the requirements of APA PRG-320, whereas the wood failure in shear by compression loading did not meet the required value. The shear strength of yellow-poplar CLT was also found to exceed that of CLT produced from softwood species. The mechanical performance of yellow-poplar CLT was acceptable, and the authors concluded that hardwood species have the potential to be used in CLT for structural applications.

Researchers affiliated with Michigan Technological University evaluated the durability of adhesive bonds in cross-laminated northern hardwoods and softwoods (Musah et al. 2021). The overall goal of the study was to assess the feasibility of using hardwoods, mixed hardwoods, as well as combining hardwoods and softwoods for developing structural grade CLT panels. The seven hardwoods used in the study consisted of sugar maple (*Acer saccharum*), red maple, northern red oak, white ash (*Fraxinus americana*), yellow birch (*Betula alleghaniensis*), basswood (*Tilia americana*), and quaking aspen (*Populus tremuloides*). The two softwood species included in the study were red pine (*Pinus resinosa*) and eastern white pine (*Pinus strobus*).

Two commercially available adhesive systems were used to bond the panels. The phenol resorcinol system included CASCOPHEN G-112A resin and G113B hardener. The melamine adhesive system used Cascomel 4720 resin and Wonderbond 5025A hardener. Four types of two-layer cross-laminated billets were created for delamination testing. The four types included single species, mixed hardwoods, hybrids of hardwoods and softwoods, and mixed softwoods, resulting in 45 different combinations.

Mixed hardwood cross-laminations and hybrid cross-laminations met the requirements of the American Institute of Timber Construction (2005) 110 cyclic delamination testing and both adhesive systems performed adequately; however, the phenol resorcinol adhesive was more effective in bonding mixed hardwood laminations. The mixed hardwood samples demonstrated better performance in the delamination test than single species samples, and the results show the feasibility of using mixed hardwood species in cross-laminations.

The best combinations for cross-lamination were found to be the hardwood–softwood hybrid. The results of this study display significant opportunities for hardwoods in CLT because the hardwoods could be used as a value-added product to enhance the visual aesthetics of current softwood CLT panels while also contributing to the overall strength of the structure.

According to the Wood Handbook,

> Although adhesives for hardwoods and softwoods generally differ by chemical type according to product markets, adhesives must be specifically formulated for hardwoods and softwoods, including specific species within the groups, or have adjustable working properties for specific manufacturing situations. (USDA Forest Products Laboratory 1999:7)

Tests of commonly available adhesives suitable for CLT panels have been initiated at WVU-AHC to determine the efficacy of these adhesives for hardwoods being used in CLT applications. Testing is being conducted on three hardwood species; yellow-poplar, soft maple, and red oak, using three different adhesives at three different moisture contents (8, 12, and 16%), with gluing parameters at levels specified by the manufacturer (spread rate, pressure, clamping time, and surface preparation).

Current Availability of Hardwoods for CLT Manufacturing

For hardwoods to be competitive with softwoods for CLT manufacturing, there must be an equivalent level of available raw material (i.e., boards). As stated earlier, softwood lumber is readily available in the marketplace, in commonly required sizes, surfaced (i.e., S4S, or surfaced-4-sides), and at the suggested moisture condition, in grades required by the softwood CLT manufacturers.

What is the current state of hardwood lumber for CLT manufacturing? The most commonly available hardwood lumber, in quantities that can be ordered and delivered in a similar timeframe to softwood lumber, is 4/4 (25.4-mm), unsurfaced, kiln-dried, with an assumption that it can be procured in specific lengths without paying a premium and that mills will be amenable to drying the lower grades of hardwood lumber. Setting aside the less likely possibility of procuring thicker material, what characteristics are required to make them suitable for CLT manufacturing?

- Boards must be conditioned to approximately 12 percent MC to meet PRG 320 requirements and to achieve adhesive efficacy.
- They must be surfaced on four sides.
- They must be structurally graded to yield No. 2 and No. 3 structural grade boards.

The most efficient first step in the preparation process is to grade the boards in the rough condition using structural grading standards. Research at WVU-AHC has shown that procuring NHLA No. 2A and lower grade boards resulted in 55 to 81 percent of the boards grading out as either No. 3 or Below Grade (see Table 1).

Purchasing hardwood lumber at 6 to 8 percent MC, reconditioning that lumber to a moisture content of approximately 12 percent, and surfacing boards prior to grading means additional costs incurred for boards that will not meet grade specifications. Unfortunately, following moisture conditioning and surfacing, boards must be regraded to ensure that no below-grade boards remain. Additionally, if the perpendicular layer boards are targeted as No. 3 structural grade, it would be very difficult to achieve the proper proportion of structural grade No. 2s and No. 3s for manufacturing purposes.

The other option is to apply MSR testing to the boards rather than visually grade them. Applying a visual override of the boards in the rough, kiln-dried form and then using MSR testing on the boards could be an economically viable alternative to simply using a visual grading process. As illustrated by Azambuja et al. (2021), only 3.4 percent of the boards failed to meet the minimum MOE for CLT manufacturing (without the benefit of a visual override, which could have further reduced the number of failures).

Obviously, each of these steps will add costs to the lumber. Can the various steps needed to procure acceptable hardwood CLT lumber result in a competitive price when compared with more readily available softwood CLT lumber? This question MUST be answered if hardwoods can successfully penetrate the softwood dimension market.

Conclusions

CLT represents a new, value-added opportunity for hardwoods, so there has been a rush to explore the viability of hardwood CLT manufacturing. Though commendable, there are at least two critical issues that need to be addressed:

- Gaining certification approval of hardwoods (yellow-poplar initially) by the American Panel Association under PRG-320 standards.
- Incorporating some level of production focused on producing structurally graded boards using the conventional lumber manufacturing approaches common to the hardwood industry.

Realistically, the first issue is perhaps easier to address. A great deal of panel testing and documentation goes into certification, but that effort is more narrowly focused than the latter issue. Convincing the hardwood industry to produce structural lumber, in a way that is competitive with the softwood industry, is a more monumental task. Without a well-defined market for structural hardwoods, the hardwood industry will necessarily be reluctant to move forward under such uncertainty. It will ultimately take one or two champions within the industry to recognize the potential for hardwood-based CLT panels and move forward to produce structural grade hardwoods for the CLT marketplace.

Acknowledgments

This research was supported through a US Department of Agriculture Forest Service Wood Innovations Project (Project 17-DG-14200004-290, Producing CLT Panels from Low Value Appalachian Hardwoods).

Literature Cited

Adhikari, S., H. Quesada, B. Bond, and T. Hammett. 2021. Current status of hardwood sawmills to produce structural grade hardwood lumber. *Mass Timber Construct. J.* (4):1.

American Institute of Timber Construction (AITC). 2005. Standard for structural composite lumber (SCL) for use in structural glued laminate timber. 402-2005. AITC, Portland, Oregon.

American Lumber Standard Committee, Inc. 2022. Grade rules writing organizations. American Lumber Standard Committee, Frederick, Maryland. www.alsc.org/untreated_graderuleorg_mod.htm. Accessed August 1, 2022.

American Panel Association (APA). 2019. Standard for Performance-Rated Cross-Laminated Timber, ANSI/APA PRG 320-2019. American Panel Association, Tacoma, Washington. 40 pp.

Azambuja, R., D. B. DeVallance, and J. McNeel. 2021. Evaluation of low-grade yellow-poplar (*Liriodendron tulipifera*) as raw material for cross-laminated timber panel production. *Forest Prod. Soc., Forest Prod. J*. 72(1):1–10.

Bockel, S., S. Harling, J. Konnerth, P. Niemz, G. Weiland, E. Hogger, and F. Pichelin. 2020. Modifying elastic modulus of two-component polyurethane adhesive for structural hardwood bonding. *J. Wood Sci.* 66:69 (2020). https://doi.org/10.1186/s10086-020-01917-9

Bockel, S., I. Mayera, J. Konnerth, S. Harling, P. Niemz, C. Swaboda, M. Beyer, N. Bieri, G. Weiland, and F. Pichelin. 2019. The role of wood extractives in structural hardwood bonding and their influence on different adhesive systems. *Int. J. Adhes. Adhes.* 91(June 2019):43–53. https://doi.org/10.1016/j.ijadhadh.2019.03.001

Frihart, R. C. 2009. Adhesive groups and how they relate to the durability of bonded wood. *J. Adhes. Sci. Technol*. 23(4):601–617. https://doi.org/10.1163/156856108X379137

Green, D. W., R. J Ross, and K. A. McDonald. 1994. Production of hardwood machine stress rated lumber. *In:* Proceedings of the 9th International Symposium on Nondestructive Testing of Wood. Forest Products Society, Madison, Wisconsin. pp. 141–150. https://intrans.iastate.edu/app/uploads/2018/08/green94a.pdf. Accessed November 4, 2022.

Hardwood Publishing. 2022. Weekly Hardwood Review. Hardwood Publishing, Charlotte, North Carolina.

HMR. 2022. Hardwood Market Report. HMR, Memphis, Tennessee.

Hovanec, D. 2015. Effect of wood characteristics on adhesive bond quality of yellow-poplar for use in cross-laminated timbers. Master's thesis. Davis College of Agriculture, Natural Resources and Design, West Virginia University, Morgantown. 99 pp. https://doi.org/10.33915/etd.5826

Knorz, M., M. Schmidt, S. Torno, and J-W. van de Kuilen. 2014. Structural bonding of ash (Fraxinus excelsior L.): Resistance to delamination and performance in shearing tests. *Eur. J. Wood Prods*. 72:297–309. https://doi.org/10.1007/s00107-014-0778-8

Luedtke, J., C. Amen, A. van Ofen, and C. Lehringer. 2015. 1C-PUR-bonded hardwoods for engineered wood products: Influence of selected processing parameters. *Eur. J. Wood Prod*. 73(2):167–178. https://doi.org/10.1007/s00107-014-0875-8

McDonald, K. A., C. C. Hassler, J. E. Hawkins, and T. L. Pahl. 1996. Hardwood structural lumber from log heart cants. *Forest Prod. J*. 46(6):55–62.

Mohamadzadeh, M. and D. Hindman. 2015. (rep.). Mechanical performance of yellow-poplar cross laminated timber. Report No. CE/VPI-ST-15-13. Virginia Polytechnic Institute and State University, The Charles E. Via, Jr. Department of Civil and Environmental Engineering, Blacksburg, Virginia. 20 pp.

Musah, M., X. Wang, Y. Dickinson, R. J. Ross, M. Rudnicki, and X. Xie. 2021. Durability of the adhesive bond in cross-laminated northern hardwoods and softwoods. *Construct. Build. Mater.* 307. https://doi.org/10.1016/j.conbuildmat.2021.124267

National Hardwood Lumber Association (NHLA). 2019. Rules for the measurement and inspection of hardwood and cypress. National Hardwood Lumber Association, Memphis, Tennessee.

Northeastern Lumber Manufacturers Association, Inc. (NELMA). 2021. Standard grading rules for Northeastern lumber. Northeastern Lumber Manufacturers Association, Inc., Cumberland Center, Maine.

Pahl, T. L., J. E. Hawkins, C. C. Hassler, and J. Slahor. 1992. Efficient utilization of hardwoods for timber bridges. Final Project Report, submitted to USDA Forest Products Laboratory, Madison, Wisconsin. 78 pp.

Senalik, C. A. and D. W. Green. 2020. Chapter 4: Grading and properties of hardwood structural lumber. *In:* Undervalued Hardwoods for Engineered Materials and Components, Second ed. R. J. Ross and J. R. Erickson (Eds.). General Technical Report FPL-GTR-276. US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, Wisconsin. pp. 27–38. https://www.fpl.fs.usda.gov/documnts/fplgtr/fpl_gtr276.pdf. Accessed November 4, 2022.

Simpson, W. T. 1999. Chapter 12: Drying and control of moisture content and dimensional changes. *In:* Wood Handbook—Wood as an Engineering Material. General Technical Report FPL–GTR–113. US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, Wisconsin. pp. 21-1–12-21. https://www.fpl.fs.usda.gov/documnts/fplgtr/fplgtr113/ch12.pdf. Accessed November 4, 2022.

The Railway Tie Association. 2003. Specifications for Timber Crossties and Switch Ties. The Railway Tie Association, Fayetteville, Georgia. 9 pp.

US Department of Agriculture (USDA) Forest Products Laboratory. 1999. Wood handbook: Wood as an engineering material. General Technical Report FPL-GTR-113. Reprinted by the US Department of Agriculture, Forest Service, Forest Products Society, Madison, Wisconsin.

Wang, X. and W. T. Simpson. 2020. Chapter 5: Drying and heat sterilization of hardwood lumber for structural uses. *In:* Undervalued Hardwoods for Engineered Materials and Components. Second edition. R. J. Ross and J. R. Erickson (Eds.). General Technical Report FPL-GTR-276. US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, Wisconsin. pp. 39–48.