Producing Hardwood Cross-Laminated Timber (HCLT) Mats from Low-Grade Red Oak Lumber

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Abstract

The use of cross-laminated timber (CLT) has significantly grown in North America, but hardwood species have not yet been deemed a viable raw material for manufacturing CLT panels. Therefore, softwood species continue to serve as the only approved material for CLT in structural applications according to ANSI/APA PRG-320. Nonstructural CLT products that utilize low-grade lumber from hardwood species, are a good option for introducing hardwoods into the CLT market.

Of the hardwood species located within Appalachia, northern red oak (*Quercus rubra*) is readily available. The purpose of this research was to develop hardwood cross-laminated timber mats utilizing low-grade red oak lumber. In order to manufacture red oak CLT mats, the best adhesive and bonding parameters had to be identified. Overall, sample CLT panels were made using three adhesives with nine different setups for each adhesive. The sample panels were processed into smaller blocks and separated for cyclic delamination and shear-block tests following the ANSI/APA PRG-320 standards.

This research determined that a phenol–resorcinol formaldehyde (PRF) adhesive produced the lowest percentage of delamination, satisfying the delamination requirements. The PRF adhesive also produced the largest percentage of wood failure in shear-block testing, however, the results fell short of meeting the requirements. A Taguchi statistical analysis was used to predict the optimal bonding parameters for each adhesive. The optimized bonding parameters for the polyurethane (PUR) adhesive produced favorable results, indicating the delamination results have the potential to nearly meet the standard requirements, while the predicted shear results would exceed the requirements.

Softwood species are currently the dominant source of lumber used to manufacture cross-laminated timber (CLT) products for structural and construction applications. Conversely, hardwoods are predominantly utilized for furniture, flooring, and other traditional uses and have not been used in CLT products.

Hardwoods have not been widely used in CLT products because of a number of challenges that must be overcome before gaining acceptance in CLT manufacturing. These challenges include differences in the markets for hardwoods (appearance) and softwoods (structural), differences in lumber grading systems, available sizes of hardwood lumber, differences in drying between hardwoods and softwoods, and idiosyncrasies of gluing hardwoods (Hassler et al. 2022).

Hardwood lumber manufacturers face difficulty in finding new markets for low-grade lumber (National Hardwood Lumber Association [NHLA] Grade 2A and lower). Although lower grade red oak (*Quercus* spp.) has an existing market in flooring, timber mats offer an additional competitive market for low-grade red oak. Introducing hardwood species to CLT manufacturing has the potential to expand the market for CLT products through the development of both structural CLT products and nonstructural hardwood CLT products, like timber mats, which do not require certification under PRG-320-2019, "Standard for Performance-Rated Cross-Laminated Timber" (ANSI/APA 2020). Through the creation of nonstructural, noncertified CLT products, such as timber mats, manufacturers could bypass PRG-320, which is specific to the building industry.

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Hardwood cross-laminated timber (HCLT) mats constructed with low-grade red oak lumber could expand the market for low-grade lumber, while also introducing hardwood manufacturers to CLT manufacturing. These HCLT mats could be used in forestry, construction, energy, and transmission and distribution industries as temporary roadways for heavy equipment. This solution allows the equipment to easily navigate rough terrain, while also reducing the ground compaction and soil erosion associated with heavy equipment use.

To date, there are no published studies that evaluate red oak as a suitable species for CLT panel manufacturing. And, even more critically, there are no studies that have comprehensively identified the bonding parameters of red oak lumber specifically for use in CLT manufacturing.

This study focused on producing a proof of concept for HCLT mats constructed with red oak lumber. In order to accomplish this, several weather-resistant adhesives that effectively bond to lumber using conventional CLT panel manufacturing methods were identified. After suitable adhesives were selected for this study, only the bonding properties of each adhesive were quantified because mechanical properties are less important and unregulated for nonstructural CLT panels. The production and testing of HCLT mats can then be demonstrated to provide a full proof of concept.

The following goals, related to the development of a proof of concept for timber mats constructed from red oak using CLT manufacturing techniques, were addressed through this study:

1. Identify weather-resistant structural grade adhesives;
2. Investigate the factors of resin type, resin spread rate, lumber moisture content, surface roughness, and pressure;
3. Evaluate the performance of each adhesive setup through cyclic delamination and shear testing; and
4. Manufacture research-scale HCLT mats for field testing.

Literature Review

Cross-laminated timber (CLT)—PRG 320 certified

CLT panels are prefabricated large-scale solid engineered wood panels used for long spans in walls, floors, and roofs. These panels can range in size, with widths between 2 and 10 feet (0.61 m and 3.05 m), lengths of up to 60 feet (18.29 m), and thickness of up to 20 inches (50.8 cm; The Engineered Wood Association 2022). CLT panels are created using laminations of dimension lumber or structural composite lumber (SCL), such as laminated veneer lumber, oriented strand lumber, or laminated strand lumber, that is orthogonally bonded with a structural adhesive (Yeh et al. 2013).

According to the current standard for CLT, ANSI/APA PRG 320-2019, any lumber that is a softwood species with a minimum published specific gravity of 0.35 is permitted for use (ANSI/APA 2020). It is recommended that the lumber maintain a moisture content of 12 percent $\pm$ 3 percent to reduce the development of internal stresses due to shrinkage, and to ensure proper bond quality of the product. E-Class lumber, lumber that is graded based on the modulus of elasticity, or V-class lumber, which is visually graded, can be used in the construction of CLT panels (Yeh et al. 2013). The minimum grade of lumber in the longitudinal layers of CLT must have a visual grade of No. 2, or machine stress rating (MSR) of 1.2E (1.2×10^6 psi). The transverse layers do not require an MSR rating, and only require a visual grade of No. 3 (ANSI/APA 2020).

Once the lumber has been graded and dried to the desired moisture content, machining and adhesive application must occur. The lumber must be planed or surfaced on all four sides to improve the effectivity of bonding and ensure dimensional uniformity (Yeh et al. 2013). After surfacing, the longitudinal and transverse pieces must be cut to fit the dimensions of the press. Adhesive application should occur shortly after planing (i.e., surfaced 4 sides) to reduce problems associated with oxidation, aging, and dimensional instability. The bonding surface should be free of any substances such as oils, greases, or release agents, which would have negative effect on bond quality. The adhesive spread rate should be applied in accordance with adhesive manufacturer's recommendations. Generally, the correct spread rate can be seen when a slight and even squeeze-out is present along the entire bond line, as illustrated in Figure 1 (Yeh et al. 2013).

After the adhesive has been spread on each board, panel layup and assembly pressing occur. Lumber defects should be carefully examined while producing the layup because the panel must have a minimum effective bonding area of 80 percent (ANSI/APA 2020). A hydraulic press is used to generate the vertical clamping force necessary to bond each layer. The amount of vertical pressure applied is dependent on the adhesive used, and the adhesive manufacturer should be consulted to determine the optimum level.

Side clamping, with a pressure between 40 and 80 psi (276 and 550 kPa), is also recommended (Yeh et al. 2013), because it ensures that edge joint gaps between laminations do not exceed 1/4 inch (6.4 mm) for face layers, or 3/8 inch (9.5 mm) for all other layers (ANSI/APA 2020). Pressing times vary by the adhesive used. In general, phenol–resorcinol formaldehyde (PRF) systems have the longest pressing times, followed by polyurethane (PUR), and emulsion polymer isocyanate (EPI; Yeh et al. 2013).

There are additional steps that must be taken in order to create a structural panel according to PRG 320. Based on the scope of this research, it is irrelevant to discuss topics such as quality control, machining, grade stamps, and packaging, for nonstructural products such as timber mats.

Timber mats—non-PRG 320 certified product

Timber mats, also known as access, crane, dragline, construction, or environmental mats, are often used in heavy industrial applications to reduce ground pressure and decreases rutting, erosion, and other soil disturbances associated with heavy equipment use. General uses for mats include temporary roadways, platforms, or bridges, and they are deployed by the mining, power

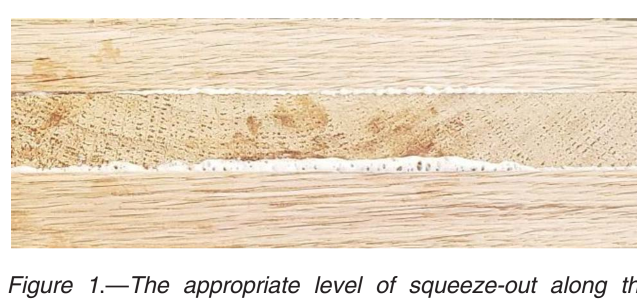

Figure 1.—The appropriate level of squeeze-out along the bond lines after pressing.

transmission, general construction, and logging industries (Shmulsky et al. 2021).

Traditional timber mats are constructed of solid wood timbers that have a thickness between 8 inches (20.3 cm) and 12 inches (30.5 cm; Spartan Mat 2020b), and are held together with steel bolts or rods (Herberg 2018). Dimensions for mats vary by manufacturer, but the most common sizes include widths of 4 feet (1.2 m) or 8 feet (2.4 m), lengths between 14 feet (4.3 m) and 20 feet (6.1 m), in 2-foot (0.61 m) increments, and a thickness of 3, 5, 7, or 9 plies. The mat market has expanded to include mats of other constructions including composite, laminated, and CLT (Spartan Mat 2020b).

Other types of mats have been researched and developed, such as the bolt-laminated hardwood mats evaluated by Owens et al. (2020); however, they are beyond the scope of this study, so this literature review will compare the features of traditional bolted mats and CLT mats. Traditional timber mats use large members of green solid mixed hardwoods, mixed oak species, or Douglas fir (*Pseudotsuga menziesii*) that are between 8 inches (20.3 cm) and 12 inches (30.5 cm) thick (Shmulsky et al. 2021). CLT timber mats, such as those manufactured by Spartan Mat and Sterling Solutions, are generally constructed with 2-inch by 8-inch (5.1 cm by 20.3 cm) southern yellow pine lumber and bonded with a structural adhesive (Mahamid et al. 2017).

Spartan Mat currently produces CLT mats from southern yellow pine, using grades of Southern Pine Inspection Bureau (SPIB) #2 and better for the parallel layers, and SPIB #3 and better for the perpendicular layers. The adhesive used to bond the panels is Loctite UR 5151, a polyurethane manufactured by Henkel AG & Co. KGaA (Düsseldorf, Germany). The mats are produced in various dimensions with lengths ranging from 14 feet (4.3 m) to 28 feet (8.5 m), widths of 4 feet (1.2 m) or 8 feet (2.4 m), and thickness of 3, 5, or 7 plies (Spartan Mat 2020a).

CLT mats may have additional upfront manufacturing costs when compared with traditional mats because of the need for adhesives, kiln drying, and specialized pressing and processing equipment, whereas traditional mats require significant amounts of manual labor combined with common hand tools. Although a higher initial investment is required to manufacture CLT mats, these mats can be made faster, with significantly reduced manual labor. These benefits allow manufacturers to reduce costs when compared with traditional mats.

Red oak

Within the matting industry, mixed oak species are one of the most commonly used species groupings (Shmulsky et al. 2021). According to the 2021 edition of *Standard Grading Rules for Northeastern Lumber* (NELMA 2021a), northern red oak is included as a mixed oak species. Red oak, specifically northern red oak, serves as the primary wood species for this study because of its popularity as a matting material, availability throughout most of Appalachia, and high strength characteristics.

Northern red oak is a ring porous hardwood species that exhibits nearly white sapwood, and heartwood that is brown with a red tinge. The wood is heavy and exhibits a high volumetric shrinkage value of 13.7 percent (Glass and Zelinka, 2010). This species is commonly found in the eastern United States and Canada and serves as an important commercial species, often used to make furniture, cabinets, flooring, interior trim, and general joinery (Sander 1990).

Red oak has been used for a variety of purposes for its appearance, but the mechanical and bonding properties of this particular species are what make it versatile. Red oak is a strong species, with a modulus of rupture (MOR) of 57,000 kPa (8,300 psi) and modulus of elasticity (MOE) of 9,300 MPa (1.35×10^6 psi) when green (Senalik and Farber 2021). When dried to a moisture content of 12 percent the MOR increases to 99,000 kPa (14,300 psi), while the MOE increases to 12,500 MPa (1.82×10^6 psi; Senalik and Farber 2021).

Red oak is defined as bonding satisfactorily, which indicates it will bond well with high-quality adhesives when bonding conditions are well controlled. High density and strength of oak allows higher loads to be placed on the bondline, resulting in higher strength values for the glued product. Although the higher density of oak can increase the strength of the final glued product, it can also cause bonding difficulties because high-density woods have thicker cell walls and smaller diameter lumens, potentially resulting in poor adhesive penetration. However, this can be overcome through the use of higher pressures to bring contact between the wood surfaces and adhesive (Frihart and Hunt 2010). Care must be taken when bonding this species because overpenetration of adhesives can occur as a result of the large number of radially oriented rays as well as easy flow within the vessels (Frihart and Hunt 2021). Additionally, red oak can be difficult to bond with some phenol–formaldehyde adhesives (Frihart and Hunt 2010).

Overall, red oak has high strength characteristics, high density, an ability to bond well, high levels of durability, and a history of being used in mats, making it an ideal species for use in CLT mats if the bonding issues can be resolved.

Adhesives

Adhesives used for commercial CLT panels that meet the criteria set by ANSI APA/PRG 320 include polyurethanes, emulsion polymer isocyanates, melamine, and phenolic-based adhesives (Yeh et al. 2013). Structural adhesives that are capable of withstanding long-term cycles of soaking and drying include phenol–formaldehyde, resorcinol–formaldehyde, phenol–resorcinol–formaldehyde, emulsion polymer isocyanate, melamine formaldehyde, and isocyanate type adhesives. Additional adhesives that are capable of withstanding short periods of soaking water include melamine–urea formaldehyde, epoxy, and polyurethane (Frihart and Hunt 2010).

Based on their structural use, ability to withstand long periods of soaking and drying, and availability within the United States, three adhesive options—emulsion polymer isocyanate (EPI), phenol–resorcinol–formaldehyde (PRF), and polyurethane (PUR)—were the focus of this study.

EPI adhesives are generally used for laminated beams, lamination of plywood to steel, metals, and plastics, as well as doors and other architectural materials (Frihart and Hunt 2010). EPI adhesives are two-part systems that contain a liquid emulsion and separate isocyanate hardener. The hardener reacts with emulsion and is capable of curing at room or elevated temperatures (Sellers et al. 1988). High pressure is required when using EPI adhesives. This adhesive type displays high wet and dry strength while also being very resistant to water and damp atmospheric conditions. Additionally, EPI adhesives show high resistance to prolonged and repeated wetting and drying cycles (Frihart and Hunt 2010).

PRF adhesives are primarily used for laminated timbers and assembly joints that must endure severe service conditions (Sellers et al. 1988). PRF systems are two-part systems that contain a liquid resin and powder hardener. The hardener reacts with the liquid resin and cures between 70° and 150°F (21°C and 66°C; Frihart and Hunt 2010). This system is characterized as having high wet and dry strength, while also being unaffected by water, molds, grease, oil, and most solvents (Ebnesajjad 2011).

Polyurethane adhesive is typically used for general home and shop purposes, as well as panelized walls and floors, specialty laminates, and the installation of gypsum board. This adhesive is supplied as a one- or two-component system. The adhesive is directly applied to one surface that has been treated with water or a primer. The contact with water activates the adhesive and allows it to cure at room temperature (Ebnesajjad 2011). PUR type adhesives have high wet and dry strength and are resistant to water and damp atmospheres, but have limited resistance to prolonged and repeated wetting and drying cycles (Frihart and Hunt 2010).

Bonding studies

Few studies have evaluated the bond performance of hardwoods in CLT applications, however, Michigan Technological University in collaboration with the USDA Forest Service, and the New Zealand Forest Research Institute examined the durability of adhesive bonds in cross-laminated northern hardwoods and softwoods (Musah et al. 2021). The study involved creating single-species cross-laminations, hardwood cross-laminations, softwood cross-laminations, and hybrid cross-laminations that combined hardwood and softwood species. Two adhesives were used to bond each setup, a melamine formaldehyde and a phenol–resorcinol formaldehyde. Both adhesives were applied using each manufacturer's parameters, respectively.

All panels were subjected to cyclic delamination testing according to AITC Test T110-2007 (American Institute of Timber Construction 2007), and the results of using both adhesives were compared. The results for single-species red oak laminations showed that no delamination was found when using the melamine adhesive system, but the delamination failure rate was 37.5 percent when using the phenol–resorcinol formaldehyde (Musah et al. 2021). Although this study provides results for numerous CLT setups, it provides limited results because it evaluates the two adhesives, but no other application variables. Evaluating additional variables such as moisture content, spread rate, pressure, press time, as well as additional adhesives would aid in providing CLT manufacturers crucial information when attempting to determine optimal setups. Adjusting any of these variables has the potential to change performance with any adhesive.

Materials and Methods

Lumber

In order to evaluate the bonding performance of HCLT constructed with northern red oak (*Quercus rubra*), lumber was obtained from a large sawmill in northern West Virginia. The acquired lumber was initially unsurfaced (rough), kiln-dried, and consisted of a mixture of flooring and pallet grade material; and all boards had dimensions of 4/4 (1 in.; 2.5 cm) thick, 10 feet in length (3.1 m), and width of approximately 7.25 inches (18.42 cm). These board dimensions are a result of the mill's standard procedure for sawing a combination of grade lumber and pallet boards; process logs to a 7.25-inch flitch and then process the flitch through a gangsaw. The boards were effectively mill-run, with no visual override applied for structural grading purposes.

The boards were first surfaced on the two wide faces by the cooperating mill and shipped to the West Virginia University Appalachian Hardwood Center (AHC) labs where the lumber was ripped to reduce the width of each board to 6.25 inches (15.9 cm) using a straight line rip saw. After ripping, the lumber was graded in accordance with the National Hardwood Lumber Association (NHLA 2019) and Northeastern Lumber Manufacturers Association (NELMA 2021b) standards to determine the appearance and structural grades of each board, respectively.

Prior to manufacturing the 1-foot by 1-foot sample panels the boards were conditioned to a moisture content of 8, 12, or 16 percent depending on the requirements of the setup. Directly before panel manufacturing started, each board was planed to a width of 6 inches (15.2 cm) and thickness of 0.75 inch (19.1 mm). After planing, the boards were cut into 1-foot (30.5 cm) lengths using a miter saw. If sanding was required for the setup based on the experimental design, a belt sander was used directly after cutting to length.

Adhesives

Three adhesive systems were studied to determine how effectively they bond red oak CLT. Each adhesive system represents an EPI, PRF, or PUR type adhesive. The EPI used for this study is a two-component system (Anonymous 2023). An additional two-component system serves as the PRF (Anonymous 2004). The PUR selected for this study is a one-component PUR (Anonymous 2015). For specifics regarding each adhesive, refer to Table 1. All adhesives were applied and pressed under ambient temperature conditions.

Table 1.—Specifications for the emulsion polymer isocyanate (EPI), phenol–resorcinol formaldehyde (PRF), and polyurethane (PUR) adhesives following the recommendations of each manufacturer.

	Adhesives		
Factors	PRF	EPI	PUR
Hardener	HRP 155	Hardener 200	N/A
Pot life (hours)	59°F - 5 68°F - 3 77°F - 2 86°F - 1	77°F - 1	N/A
Resin-hardener mix ratio (pbw)	100:20	100:15	N/A
Wood moisture content	6–25%	6–10%	N/A
Spread rate (g/m^2)	150–250	200	129–215
Open assembly time (minutes)	5–10	10	20
Closed assembly time (minutes)	59°F - 90 68°F - 60 77°F - 30 86°F - 15	10	N/A
Pressure (psi)	116–174	175–250	N/A
Press time (hours)	59°F - 6 68°F - 4 77°F - 2.25 86°F - 1	>0.5	68°F - 2 130°F - 0.33

Experimental design

An L9 Taguchi design was implemented to determine the factors of each adhesive type that influence the results of cyclic delamination and shear testing. This method, developed by Genichi Taguchi, is used to design experiments to produce high-quality products at a low cost for the manufacturer by evaluating how different parameters affect the mean and variance of process performance characteristics. The goal of this experimental design is to build quality into a product by minimizing the deviation from a target and making it immune to uncontrollable environmental factors (Fraley et al. 2023). The L9 Taguchi Method was selected for use in this study to reduce the time and large number of combinations that result from a full factorial model. The Taguchi method optimizes the performance characteristics of a process by identifying the signal to noise (S/N) ratio of a factor at a certain level. The S/N ratio is a ratio of the determinate, or fixed contribution (signal) to an indeterminate, or random contribution (noise) of the analyzed substance (Harvey 2023). Within this study the S/N ratio for each analysis is maximized, but the equation for the S/N ratio changes based on the desired response. When the goal is to **minimize** the response (Eq. 1), the S/N ratio is calculated as

$$\frac{S}{N}ratio = -10log_{10}\frac{1}{n}\sum_{i=1}^{n} y_i^2 \qquad (1)$$

Equation 1: The equation to calculate S/N ratio when the goal is to minimize the response (Sabarish et al. 2019).

When the goal is to **maximize** the response y_i^2 in Equation 1, it is replaced with $\frac{1}{y_i^2}$,

where,

S = Signal

N = Noise

n = Number of repetitions for the experimental combinations

y = Measured value of a characteristic

i = Trial number

The objective of the Taguchi analysis is to determine the optimal setup to minimize the response of delamination in cyclic delamination testing, or to maximize the response of wood failure in shear block testing. The equations will ultimately determine the optimal settings for resin spread, moisture content, pressure, and surface roughness to achieve lower levels of delamination or higher levels of wood failure based on the results obtained from the setups of the L9 Taguchi design.

The resulting S/N ratios and Desirability value provide the necessary evaluation of each adhesive. An S/N ratio of zero is desirable when the goal is to minimize the response because any other result would be negative and indicate levels of variability within the results. When maximizing the response, the highest positive S/N ratio is desirable because it also indicates low levels of variability. Desirability values are shown on the chart for each factor and indicate the individual desirability of that particular setting. The numerical value listed for desirability is the composite desirability, which indicates how favorable the results are for all responses as a whole. The highest achievable value for desirability is one.

For each tested resin, four factors were considered; resin spread, moisture content, pressure, and surface roughness. Each factor was divided into three levels, allowing a low, medium, and high level for evaluation. An example of these values using moisture content would be 8, 12, and 16 percent for the low, medium, and high values, respectively, for each factor. The levels for resin spread and pressure were determined based on the parameters recommended by the adhesive manufacturer (Table 1). All factors, except pressure, remained the same for each adhesive and its respective setup because each individual adhesive has different pressing requirements. In summary, nine setups were created for each adhesive (Table 2) to determine which factors influence the bonding quality for HCLT mats made with red oak lumber. The setups can be illustrated using PUR setup 1, where A1 is 150 g/m^2, B1 is 8 percent moisture content (MC), C1 is 70 psi, and D1 is a planed surface (Table 2).

Manufacturing and testing sample panels

Small three-layer sample panels were manufactured based on the setups generated through the Taguchi design. The panels had a length and width of 1 foot (30.5 cm) and overall thickness of approximately 2.25 inches (5.72 cm). The steps involved in constructing each sample panel included conditioning for MC, planing, cutting, gluing, layup and pressing.

Adhesive was applied according to the individual manufacturer's recommendations. With the adhesive applied, the panel was inserted into a Carver Bench Top Auto Press and programmed to the force required by the experimental design and the press time recommended by the adhesive manufacturer.

All samples in this study were subjected to the same testing procedures. Each sample was evaluated using cyclic delamination and shear block (see Fig. 2) tests according to the methods described in sections 8.2.6 and 8.2.4 of PRG 320 (ANSI/APA 2020), respectively. Upon completion of the cyclic delamination process, the percentage of delamination was visually estimated on each bond line using a 0.003-inch (0.076-mm) feeler gauge to identify areas of delamination, and a digital caliper to measure the length of delamination. Once the shear block tests were complete, the wood failure percentage was visually estimated.

It is necessary to note that the sample size for both the shear and delamination specimens is unequal. In setups that exhibited poor initial results for delamination, only one panel was used to obtain the results, while setups that performed well used three panels.

Results

Cyclic delamination

Cyclic delamination testing in accordance with PRG 320 standards yielded various results across each adhesive and associated setup. Based on PRG 320 criteria, the average delamination of all bond lines within a specimen cannot exceed 5 percent. This value was used as a guide to evaluate the potential of a tested adhesive in bonding red oak (ANSI/APA 2020).

Best delamination setups for each adhesive

The results revealed that none of the setups utilizing the EPI and PUR adhesives met APA standards. It is important to note that the standards set by PRG 320 do not have to be met because of this product is an uncertified product. However, the references to PRG 320 serve to guide our understanding of how a CLT mat might perform in the field.

The PRF adhesive exhibited the lowest average delamination percentages and met the requirements of the standard in seven out of the nine setups. PRF adhesive setup #9 displayed

Table 2.—Summary of delamination testing by adhesive type and Taguchi setup.

Red oak cyclic delamination testing summary									
Adhesive type[a]	Taguchi #	Spread rate (g/m^2)	Pressure (psi)	Moisture content (%)	Surface roughness	No. of panels	Total no. of samples	Avg. delamination	Std. dev. of delamination
EPI	1	150	150	8	Planed	1	5	61.02%	22.88%
	2		200	12	60 Grit	1	5	74.87%	19.81%
	3		250	16	150 Grit	1	3	100.00%	0.00%
	4	200	200	8	150 Grit	1	5	93.88%	5.81%
	5		250	12	Planed	1	5	86.20%	11.57%
	6		150	16	60 Grit	1	4	16.28%	4.00%
	7	250	250	8	60 Grit	1	5	71.14%	23.67%
	8		150	12	150 Grit	1	5	91.58%	10.11%
	9		200	16	Planed	1	5	70.38%	27.04%
PUR	1	150	70	8	Planed	1	5	36.25%	10.35%
	2		120	12	60 Grit	3	15	27.42%	22.13%
	3		170	16	150 Grit	1	5	46.57%	15.59%
	4	200	120	8	150 Grit	3	15	41.24%	26.14%
	5		170	12	Planed	1	5	72.53%	14.31%
	6		70	16	60 Grit	1	5	13.50%	8.90%
	7	250	170	8	60 Grit	1	5	32.40%	14.72%
	8		70	12	150 Grit	1	5	54.05%	39.29%
	9		120	16	Planed	1	5	58.04%	7.59%
PRF	1	150	100	8	Planed	3	15	31.15%	26.47%
	2		150	12	60 Grit	3	15	2.49%	5.77%
	3		200	16	150 Grit	3	14	10.27%	11.56%
	4	200	150	8	150 Grit	3	15	2.48%	4.80%
	5		200	12	Planed	3	15	3.22%	4.54%
	6		100	16	60 Grit	3	14	2.28%	6.34%
	7	250	200	8	60 Grit	3	15	4.81%	15.27%
	8		100	12	150 Grit	3	15	1.76%	3.39%
	9		150	16	Planed	4	20	1.26%	3.20%

[a] EPI is emulsion polymer isocyanate; PUR is polyurethane; PRF is phenol–resorcinol formaldehyde.

an average delamination of 1.26 percent with a standard deviation of 3.20 percent and proved to exhibit the least amount of delamination and variability. PRF setup #8 performed in a similar manner with an average delamination of 1.76 percent and standard deviation of 3.39 percent. A summary of the delamination results for each adhesive and their associated setups is provided in Table 2.

Optimized settings to reduce delamination

Analysis of the PRF test results (see Fig. 3) suggest that optimal settings include a resin spread rate of 250 g/m^2, 12 percent lumber MC, pressure of 150 psi (1.03 Mpa), and a pre-layup surface roughness of 150 grit. These settings resulted in a predicted mean value of −8.00 percent delamination and an S/N ratio of −0.69

Optimal settings for the PUR setups include a resin spread rate of 200 g/m^2, MC of 8 percent, pressure of 70 psi (0.48 Mpa), and surface roughness of 60 grit. These settings resulted in a predicted mean value of 5.93 percent delamination and an S/N ratio −23.69.

The optimal settings of the EPI adhesive, include 200 g/m^2 for resin spread rate, 16 percent MC, pressure of 150 psi (1.03 Mpa), and surface roughness of 60 grit. These settings resulted

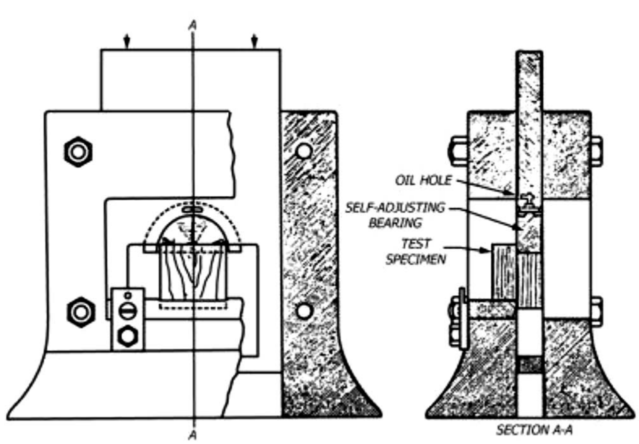

Figure 2.—The shearing tool used for shear block testing (D14 Committee 2021).

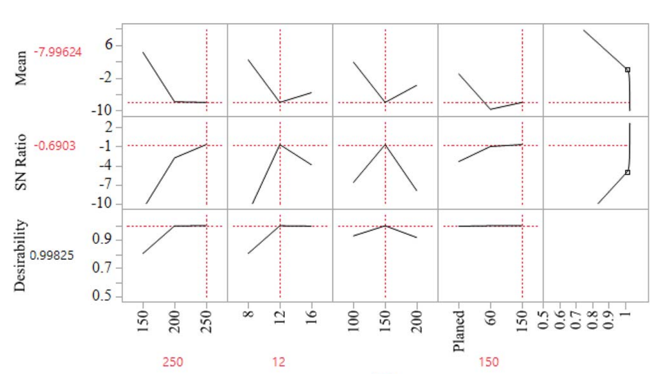

Figure 3.—Optimal settings for reducing delamination using the phenol–resorcinol formaldehyde (PRF) adhesive.

Table 3.—Summary of the optimal settings to improve delamination performance.

Delamination summary of optimized settings and predicted performance						
Adhesive type[a]	Resin spread (g/m^2)	Moisture content (%)	Surface roughness	Mean delamination (%)	S/N ratio	Desirability
EPI	200	16	150	16.28	−24.42	0.90
PUR	200	8	70	5.93	−23.69	0.94
PRF	250	12	150	−8.00	−0.69	1.00

[a] EPI is emulsion polymer isocyanate; PUR is polyurethane; PRF is phenol–resorcinol formaldehyde.

in a predicted mean value of 16.28 percent delamination and an S/N ratio of −24.42.

A summary of the optimal settings to reduce delamination for each adhesive can be found in Table 3.

Shear block tests

The shear block testing followed procedures outlined in PRG 320 and produced diverse results among each adhesive and associated setup. Section 6.3.3 of PRG 320 requires the average wood failure of tested specimens to be greater than or equal to 80 percent (ANSI/APA 2020). A summary of the results detailing the shear stress and percentage of wood failure is available in Table 4.

Best performing shear block setups for each adhesive

The results of shear block testing produced a broad range of results. None of the setups were able to meet the 80 percent threshold for wood failure. The best performing adhesive was the PRF using setup #7, which produced an average of 76.35 percent wood failure with a standard deviation of 18.81 percent. PUR setup #7 also performed well, with an average of 75.42 percent and standard deviation of 23.69 percent.

Optimized settings to increase wood failure

Optimal settings for the EPI setup were defined by the Taguchi analysis to be 200 g/m^2 for resin spread rate, 8 percent MC, pressure of 150 psi (1.03 Mpa), and surface roughness set at 'planed.' These settings resulted in a predicted mean value of 70.67 percent wood failure and an S/N ratio of 46.41.

For PUR, the optimal settings predicted by the Taguchi analysis include a resin spread rate of 200 g/m^2, MC of 8 percent, pressure of 70 psi (0.48 Mpa), and surface roughness of '60 grit.' These settings resulted in a predicted mean value of 84.39 percent wood failure and an S/N ratio 43.44 (Fig. 4).

Table 4.—Summary of shear testing by adhesive type and Taguchi setup.

Red oak shear testing summary							
Adhesive type[a]	Taguchi #	Avg. shear stress (kPa)	Std. dev. of avg. shear stress (kPa)	Avg. shear stress (PSI)	Std. dev. of avg. shear stress (PSI)	Avg. wood failure	Std. dev. of avg. wood failure
EPI	1	5,531.88	1,429.47	802.30	207.32	39.69%	32.22%
	2	3,429.22	1,836.91	497.35	266.41	9.69%	6.94%
	3	2,211.08	1,221.60	320.68	177.17	3.64%	5.95%
	4	6,836.66	785.79	991.54	113.97	41.33%	25.18%
	5	5,582.97	596.84	809.71	86.56	50.63%	24.35%
	6	5,356.03	894.76	776.80	129.77	52.50%	26.96%
	7	6,357.50	1,038.12	922.04	150.56	45.63%	24.42%
	8	6,460.11	1,521.07	936.93	220.60	48.67%	31.19%
	9	7,180.93	1,478.36	1,041.47	214.41	44.67%	16.63%
PUR	1	6,406.07	1,268.39	929.09	183.96	41.33%	30.09%
	2	4,247.10	1,289.50	615.97	187.02	51.49%	31.19%
	3	6,435.74	1,138.92	933.39	135.37	12.81%	9.30%
	4	5,834.72	1,383.84	846.22	200.70	71.77%	25.90%
	5	6,468.47	1,444.29	938.14	209.47	33.75%	28.79%
	6	4,479.29	1,442.17	649.64	209.16	52.92%	21.26%
	7	7,271.32	923.92	1,054.58	134.00	57.50%	26.27%
	8	6,346.26	1,363.52	920.41	197.76	75.42%	23.69%
	9	5,147.47	925.30	746.55	134.20	9.00%	13.63%
PRF	1	5,824.27	1,468.92	844.71	213.04	23.65%	22.83%
	2	6,171.36	759.01	895.05	110.08	32.50%	25.74%
	3	4,737.80	1,173.59	687.14	170.21	26.25%	19.77%
	4	6,617.52	1,231.07	959.76	178.55	60.10%	27.06%
	5	5,814.25	991.75	843.26	143.84	57.87%	26.76%
	6	5,577.58	946.15	808.93	137.22	50.38%	24.33%
	7	5,380.46	939.21	780.34	136.22	76.35%	18.81%
	8	5,100.35	949.28	739.72	137.68	49.47%	23.11%
	9	6,046.40	1,229.65	876.93	178.34	69.32%	28.04%

[a] EPI is emulsion polymer isocyanate; PUR is polyurethane; PRF is phenol–resorcinol formaldehyde.

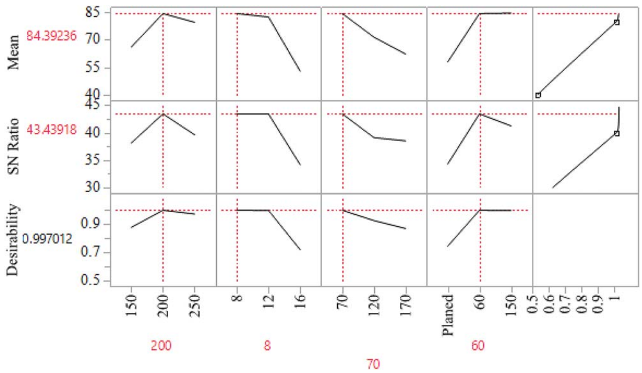

Figure 4.—Optimal Settings for increasing wood failure using the polyurethane (PUR) adhesive.

For PRF, a resin spread rate of 250 g/m^2, 8 percent MC, pressure of 150 psi (1.03 Mpa), and surface roughness of '60 grit' were considered optimal through Taguchi analysis. These settings resulted in a predicted mean value of 76.96 percent wood failure and an S/N ratio of 37.69.

A summary of the optimal settings to improve shear performance for each adhesive can be found in Table 5.

Discussion

Delamination

Of the 27 total setups tested, 7 setups using the PRF adhesive met the delamination requirements of PRG 320. None of the setups using the two other adhesive types were able to reach the requirements of the standard. Fortunately, the Taguchi analysis shows that significant reductions in delamination can be achieved using the predicted optimal settings, especially for the PUR.

The delamination results when using the EPI adhesive with setup #6 matches the optimized results of the Taguchi analysis. This indicates that 16.28 percent approximates the lowest amount of delamination that can be achieved with this adhesive, and that, for the variables being considered, it cannot be further optimized. Currently, there are no studies that evaluate the use of EPI to bond red oak, and the reason for its performance cannot be explained. As a result of the results obtained using this adhesive, it cannot be recommended to bond red oak lumber to manufacture HCLT mats.

The predicted optimal settings for the PUR found that 5.93 percent delamination could be achieved, indicating a significant reduction in delamination when using this adhesive. Although the PUR did not achieve the 5 percent delamination threshold, its use in HCLT mats constructed with red oak should be investigated further. Even though this does not satisfy PRG 320, the amount of delamination is low, and the standard does not have to be fulfilled because of the nonstructural nature of this product. Additionally, using the PUR allows for a 2-hour press time, which is half the time required for the PRF. The reduced press time would allow manufacturers to create more mats per day, without a significant compromise in quality when compared with using the PRF. There may also be some environmental benefits of using PUR instead of PRF, although these issues were not addressed by our study.

The lowest average delamination of the PRF setups was 1.26 percent. The Taguchi analysis predicted the optimal settings for the PRF to produce −8.00 percent delamination, indicating that no delamination should occur with the optimized settings.

The study conducted by Musah et al. (2021) utilized Cascophen G-1131A, a phenol–resorcinol-based adhesive, achieving a delamination rate of 37.5 percent (Musah et al. 2021). The difference in the results obtained from this study, compared with theirs, could be associated with the different formulas used to manufacture the respective adhesives. Additionally, Musah et al. did not evaluate the performance of each factor at different levels, only using a MC of 12 percent, planed surface, pressure of 125 psi, and spread rate of 50 pounds per thousand square feet (Musah et al. 2021).

Shear

None of the adhesives or test setups were able to reach the 80 percent threshold for wood failure while subjected to shear block testing. However, the Taguchi analysis was capable of finding setups for each adhesive that would significantly improve the predicted amount of wood failure.

The EPI setup with the highest average wood failure produced 52.50 percent. The analysis produced an optimized setting that predicts a mean wood failure of 70.67 percent, an increase of 18.17 percent over the initial setup with the best performance.

The PUR with the largest percentage of wood failure yielded an average of 75.42 percent. The optimal settings suggest that a wood failure of 84.39 percent can be reached, making it the only setup with the potential to exceed the requirements of PRG 320. The optimal settings with the PUR insinuate that it can compete with the PRF adhesive, as seen previously in the results for delamination testing.

The Taguchi analysis was able to slightly optimize the settings for the PRF, going from a peak average of 76.35 percent to a predicted average of 76.96 percent. This indicates that the best performing setup was close to its maximum potential and there was little room for optimization.

Conclusions

This research suggests that red oak is a good candidate for HCLT mats based on the results obtained through cyclic delamination and shear block testing, but only when the appropriate adhesive and manufacture settings are used. While this is an optimistic statement, the results from the Taguchi analysis

Table 5.—Summary of optimal settings to improve shear performance.

Shear summary of optimized settings and predicted performance							
Adhesive type[a]	Resin spread (g/m^2)	Moisture content (%)	Pressure (psi)	Surface roughness	Predicted mean wood failure (%)	S/N ratio	Desirability
EPI	200	8	150	Planed	70.67	46.4	1.00
PUR	200	8	70	60	84.39	43.4	1.00
PRF	250	8	150	60	76.96	37.7	0.95

[a] EPI is emulsion polymer isocyanate; PUR is polyurethane; PRF is phenol–resorcinol formaldehyde.

predict what the optimal results could be. However, it is important to note that these predicted results have not been validated through testing, which is beyond the scope of this article. The information obtained from this study can also be used to further advance red oak HCLT into structural applications, while also furthering the future development and use of hardwoods in CLT.

Cyclic delamination testing is the most important test for determining what adhesive is suitable for bonding HCLT mats because of the extended periods of exposure to exterior conditions. The setups utilizing PRF had the best performance of the tested adhesives, with seven of the nine PRF setups producing less than 5 percent delamination. The majority of the setups with this adhesive met the requirements of PRG 320 and were far lower than those produced using the other tested adhesives, so PRF seems to be the most resistant to delamination of the tested adhesives for red oak mats.

Future research

Many opportunities exist to research the use of hardwoods in mass timber applications because hardwood utilization in mass timber products, particularly using red oak, is virtually nonexistent. Many of the adhesives developed for CLT products were specifically made for species such as spruce (*Picea* spp.), pine (*Pinus* spp.), and fir (*Abies* spp.). They may work for these species, but additional research must include the development of adhesives specific to hardwoods. One such method for red oak could include increasing the molecular weight of the resin to reduce the absorption of resin due to the large vessels. This would greatly increase the bonding properties of hardwoods and could potentially create new markets for HCLT products. Additional adhesive types that could be tested for exterior structural applications would include melamine–formaldehyde and isocyanate adhesives because they are rated for these uses (Frihart and Hunt 2010).

Although the PRF produced the best results, the PUR should still be considered for use once the optimized results have been verified. The optimized results suggest that an average delamination of below 6 percent can be achieved, indicating that it could be used in place of the PRF. Additionally, using the PUR would allow manufacturers to produce more mats per day as a result of the lower cure time of this adhesive.

At this time, the optimal settings generated through the Taguchi analysis have not been specifically verified. Future research requires using the optimized settings to create test specimens that can verify the predicted results, especially for the PRF and PUR adhesives.

Additionally, the red oak HCLT mats must undergo field testing to evaluate the performance of the mats to understand how they perform in real-world applications. At this time, red oak HCLT mats with a length of 9 feet (2.74 m) and width of 3 feet (0.91 m) have been produced using the optimized settings for the PRF and await field testing through the AHC.

Outside of noncertified products, red oak shows potential as a raw material for CLT in structural applications where certification is required. The predicted delamination results from the L9 Taguchi analysis fulfill the 5 percent requirement set by PRG 320 when using the PRF and are within 1 percent of satisfying the requirements when using the PUR. The shear testing results are also favorable for certification because the predicted wood failure using the PUR exceeds the 80 percent threshold set by PRG 320, while the PRF comes within 3 percent of meeting that requirement. Both delamination and shear properties have proven that red oak serves as a viable species for structural CLT applications but would require additional research into properties such as bending, thermodynamics, fire resistance, and earthquake resistance before red oak could enter the structural market.

Finally, red oak could serve to increase the aesthetic value of CLT panels. This could be achieved through three different approaches. One approach would be to use red oak as the sole species for the panel. Another would be to create a mixed-species panel that uses traditional spruce, pine, and fir lumber for the interior layers, with higher grade red oak used for the face layers. The problem with a single-species red oak panel would be the weight, because red oak is significantly denser than softwood species. The mixed-species panels, using red oak lumber or veneer, would greatly reduce the weight when compared with single-species panels, but would also require additional research to determine how to bond the different species together. Mixed-species CLT, specifically combinations of red pine (*Pinus resinosa*) and red oak, as well as eastern white pine (*P. strobus*) and red oak have been studied by Musah et al. (2021), but the study only evaluated two adhesives, and did not use methods conducive to commercial manufacturing.

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