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Face bonding strength of cross laminated northern hardwoods and softwoods lumber

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A R T I C L E I N F O

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A B S T R A C T

Producing cross-laminated timber (CLT) has opened a new market for the lumber industry in North America, while few hardwood species have been studied in the U.S. for CLT production. Combining hardwood species in mixed hardwood CLT or in hybrid CLT can be a solution to boost the market of the undervalued hardwoods. However, the knowledge gap on bonding hardwoods needs to be filled to provide evidence of feasibility. This study focused on the face bonding properties of the cross laminations made of seven hardwood species and two softwood species from the Great Lakes region using two commercial structural adhesives, the phenol resorcinol adhesive (the Resorcinol) and the melamine urea formaldehyde adhesive (the Melamine). A total of 45 combinations of the selected species were studied for the bonding strength (shear under compression) and the percentage of wood failure. For single species samples, the bond strength was positively related to the specific gravity of wood and the bond strength of hardwoods was 33% and 82% stronger than that of softwoods bonded with the Resorcinol and the Melamine respectively. The mixed hardwoods showed higher bonding strength (the Melamine: 5.45 MPa, the Resorcinol: 5.28 MPa) than mixed softwoods (the Melamine: 2.8 MPa and the Resorcinol: 2.7 MPa). Among the Resorcinol bonded mixed combinations, 54% had a percentage of wood failure less than 80%, while the Melamine bonded had only 4 out of 22 which had a percentage of wood failure less than 80%. The overall bonding strength of the hybrid combinations was 5% weaker than that of the mixed hardwoods. All hybrid combinations bonded with the Melamine met the 80% wood failure criterium, but some bonded with the Resorcinol had a percentage of wood failure less than 80%. Anatomical features, especially pore distribution, played a key role in the bonding performance. However, the Melamine adhesive consistently achieved over 80% wood failure across all pore distribution types.

1. Introduction

As a novel-engineered wood product, cross-laminated timber (CLT) has become a value-added option for wood structures in recent years and has gained acceptance in both residential and commercial structure applications in many parts of the world, particularly in Europe and North America [1]. Numerous low-rise, mid-rise, and tall buildings built around the world using CLT elements have demonstrated the advantages of CLT over traditional building materials (steel and concrete), including faster installation, reduced construction wastes, improved thermal performance, lower embodied energy, lower greenhouse gas emissions, and more design versatility [2–4]. CLT has been proven to be suitable in a wide range of structures [5] and structural components, such as roofs, walls, and floors [1,6]. The standard for performance-rated cross-laminated timber [7] published in 2011 and subsequent updates have stimulated the acceptance of CLT in the construction industry. In 2015, the International Code Council (ICC) adopted ANSI-approved CLT panels in the International Building Code (IBC) [8].

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CLT panels are made of orthogonal layers of sawn lumber that are face-glued together to form a massive timber composite. The laminations within each layer may be edge glued. Commercial CLT panels for building structures are exclusively made from softwoods, primarily spruce and firs. However, some inherent properties of softwoods, such as low rolling shear strength, can limit the CLT's capability to carry out-of-plane loads [9,10]. Hardwoods are generally known to have higher density and strength properties than softwood species. The incorporation of hardwood species in CLT for strength reinforcement to meet local and global needs of high performance in a structure has been considered. The increasing interest in using hardwood species for advanced structural materials in the U.S. and globally is also due to the anticipated increase in hardwood timber resources in the near future.

Several studies have illustrated the potential of using hardwood species in CLT production with pilot-scale manufacture and mechanical experiments [11–13]. Birch (*Betula pendula*) was tested for both glulam and CLT production and proven to be capable of providing sufficient mechanical properties [13]. The studies on CLT panels made of yellow poplar (*Liriodendron tulipifera*) showed that the bending stiffness and strength of the panels exceeded the required values in the ANSI/APA PRG320 standard [7] with adequate bonding properties [14,15]. However, the CLT panels made of hybrid poplar (*Populus* spp.) were found to meet the requirement only for bending strength while the stiffness needed to be improved [12].

While most previous studies on hardwood CLT directly focused on the overall mechanical properties of the CLT panels, the investigation of the face bonding properties of cross-laminated hardwood lumber is limited. Bonding hardwoods is complex due to several factors, including the complexity of hardwood anatomy structure, variant densities, and surface properties such as machining, permeability, and extractive content [16]. The common wood extracts, including starch and acidic substances, were found to negatively influence melamine urea formaldehyde and phenol resorcinol formaldehyde adhesives, depending on the contents on the surfaces rather than the origin of the wood [17].

To bridge the knowledge gap in bonding hardwoods, in this study, we investigated the bonding properties of several common hardwood and softwood species from the Great Lakes Region of U.S., which were cross-laminated using two commercially available adhesives for mass timber production, e.g., the melamine urea formaldehyde and the phenol resorcinol formaldehyde. We specifically examined the effects of wood density and anatomical features on the bonding shear strength and percentage of wood failure when cross-laminating single species, mixed species, and hybrid combinations. The related study with cyclic delamination tests on the other criteria of adhesive bonding quality can be found in the previously published paper by the team [18].

2. Materials and methods

2.1. Sample preparation

A total of seven hardwood species and two softwood species were used in this study. The investigated hardwood species included sugar maple (*Acer saccharum*), red maple (*Acer rubrum*), northern red oak (*Quercus rubra*), white ash (*Fraxinus americana*), yellow birch (*Betula alleghaniensis*), American basswood (*Tilia americana*) and quaking aspen (*Populus tremuloides*). The softwood species were red pine (*Pinus resinosa*) and eastern white pine (*Pinus strobus*). All hardwood lumber boards were purchased from Northern Hardwoods (South Range, MI) as 38 mm thick kiln-dried Select and Better grade lumber. The softwood lumber was purchased from the local 41 Lumber store (Houghton, MI) as 51 mm thick kiln-dried boards. Only defect-free boards/sections were used for laminations. The width of the boards ranged between 152 mm and 305 mm. Table 1 shows detailed information about the specific gravity (SG), pattern of change from earlywood to latewood, and species code used in this study for each wood species. Five diffuse porous (DiffP) and two ring porous (RingP) hardwood species were included in the study, along with one abrupt transition (Abr) and one gradual transition (Grd) softwood species.

Table 1
Lumber materials, SG, and major anatomical features.

Lumber Category	Commercial name (Botanical name)	Species code	SG at 12% MC [21]	Anatomic Features (Earlywood/ latewood change patterns)
Hardwood	Sugar maple (*Acer saccharum*)	SM	0.63	Diffuse porous
	Red maple (*Acer rubrum*)	RM	0.54	Diffuse porous
	Yellow birch (*Betula alleghaniensis*)	YB	0.62	Diffuse porous
	Basswood (*Tilia americana*)	BW	0.37	Diffuse porous
	Quaking Aspen (*Populus tremuloides*)	QA	0.38	Diffuse porous
	Northern red oak (*Quercus rubra*)	RO	0.63	Ring porous
	White ash (*Fraxinus americana*)	WA	0.60	Ring porous
Softwood	Red pine (*Pinus resinosa*)	RP	0.46	Abrupt
	Eastern white pine (*Pinus strobus*)	WP	0.35	Gradual

All lumber pieces were planed to 32 mm thick and then cut to 457 mm in length. Each board were straightened using a jointer. The boards were stored in the environmental room set at 21 °C and 65% relative humidity (RH) for four weeks to reach an equilibrium moisture content (EMC) in the range of 12 ± 3%, as determined using the oven-dry method. All the hardwood boards achieved an EMC between 9% and 12% and the softwood boards achieve an EMC of approximately 12%. The wood moisture content (MC) of 12% is recommended by ASTM D905 for gluing [19] and, it is critical for the proper curing of adhesives as well [20]. The conditioned boards were then planed to 25.4 mm thick, with the thickness variations limited to ± 0.20 mm across the width and ± 0.30 mm along the length direction within 24 h of gluing.

Two commercially available adhesives provided by Hexion Inc., Columbus, OH, for mass timber production were used for face bonding. One was phenol resorcinol formaldehyde, Hexion CASCOPHEN® G-1131A and G113B (the hardener), hereafter referred as the Resorcinol; the other was melamine urea formaldehyde adhesive, Hexion Cascomel™ 4720 and Wonderbond™ 5025 A (hardener), hereafter referred as Melamine. The adhesive and hardener were mixed using a mixer set at 328 rpm for each type of adhesive system. After they were fully mixed, the adhesives were evenly applied on both bonding surfaces using a rubber roller. Both adhesives were applied at a rate of 34.2 g/m^2 and cured at 21 °C for 8 h under a clamping pressure of 0.862 MPa followed by curing at the same temperature without pressure. The pressure was consistent for all groups to eliminate the potential effects by the pressure difference. The pressure was determined as half of the upper boundary suggested by the provider. The total curing time for both adhesives was 24 h. When the boards reached the target EMC, they were edged-glued with commercial wood glue, Titebond®, and then cut into 228.6 mm × 228.6 mm laminates for cross-lamination. Edge-gluing eliminated the gaps between the laminations within each layer. All face-gluing of the samples was done within 24 h after the final planing [7].

A total of 45 combinations were investigated, as shown in Table 2, and they were grouped into three categories: (1) single species, (2) mixed hardwoods or softwoods, and (3) hybrid hardwoods and softwoods. Single species samples were made of each individual wood species, resulting in 9 types. The mixed combinations of the hardwoods included (1) the combinations of the five diffuse-porous species,

Table 2
Combination matrix of tested species for each type of adhesive.

		Diffuse porous					Ring porous		Abrupt	Gradual
		SM	RM	YB	BW	QA	RO	WA	RP	WP
Diffuse Porous	SM	SM-SM								
	RM	RM-SM	RM-RM							
	YB	YB-SM	YB-RM	YB-YB						
	BW	BW-SM	BW-RM	BW-YB	BW-BW					
	QA	QA-SM	QA-RM	QA-YB	QA-BW	QA-QA				
Ring Porous	RO	RO-SM	RO-RM	RO-YB	RO-BW	RO-QA	RO-RO			
	WA	WA-SM	WA-RM	WA-YB	WA-BW	WA-QA	WA-RO	WA-WA		
Abrupt	RP	RP-SM	RP-RM	RP-YB	RP-BW	RP-QA	RP-RO	RP-WA	RP-RP	
Gradual	WP	WP-SM	WP-RM	WP-YB	WP-BW	WP-QA	WP-RO	WP-WA	WP-RP	WP-WP

resulting in 10 combinations; (2) the combinations of the five diffuse-porous with the two ring-porous species, resulting in 10 combinations; and (3) the combination of the two ring-porous species. All these resulted in a total of 21 mixed combinations of hardwoods. The two softwood species made only one mixed combination of softwoods. The hybrid combinations were the different pairs made of one of the two softwoods and one of the seven hardwoods, resulting in 14 hybrid combinations of hardwood and softwoods.

2.2. Block shear test

The preparation and testing of adhesive-bonded shear blocks followed the American Society for Testing and Materials (ASTM) D905 standard [19]. A total of 900 shear blocks, each measuring 50 mm × 50 mm x 48 mm, as depicted in Fig. 1, were prepared, which included 450 glued with the Melamine and 450 glued with the Resorcinol. Each type of combination had ten replicates. The width and length of the bonding area for each specimen were measured to the nearest 0.25 mm to establish the shear area.

The block shear tests were conducted using the ATS Universal test machine (model 1630A) with a 30 kips (133 kN) load cell. Test

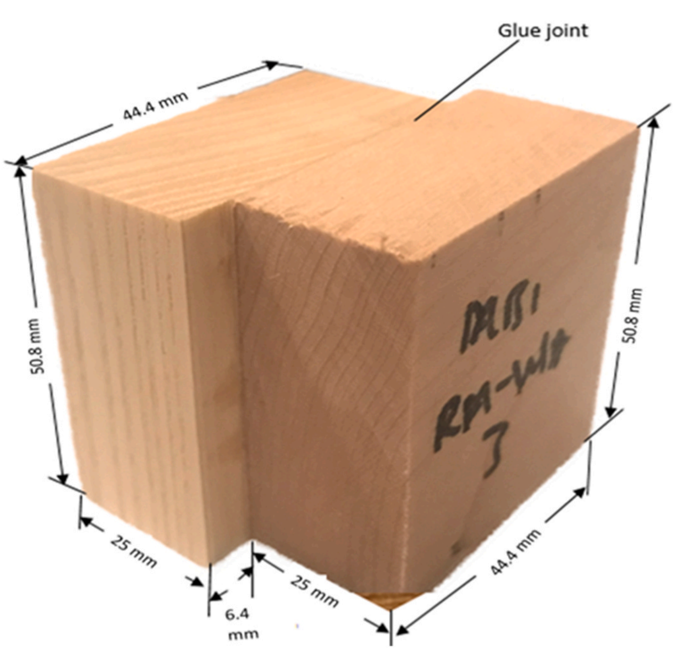


Fig. 1. A sample of the cross-lamination with a mixed combination of SM and WA.

specimens were affixed to the shear testing fixture (Tinius Olsen Model 125208). The load was applied at a rate of 5 mm/min. The maximum load for each shear block was recorded.

The bonding strength was expressed as the shear strength determined using Eq. (1) according to ASTM D905:

$$f_v = \frac{p_{\max}}{A_v} \tag{1}$$

where the shear strength f_v is calculated as the ratio of the maximum load P_{max} over the shear area A_v. The wood failure percentage was estimated immediately after the bonding strength test following the procedures described in ASTM D 5266 [21]. The wood failure was calculated using Eq. (2):

$$P_{wf} = \frac{R_{wf}}{R_g} \times 100 \tag{2}$$

where P_{wf} is the percentage of wood failure, R_{wf} is the measured area of wood failure, and R_g is the area of the bonding interface. The three types of wood failures observed in the study are shown in Fig. 2 [21]. Per requirement of PRG 320 [7], the average wood failure rate shall be equal to or greater than 80%, which will be a reference value for the following discussion.

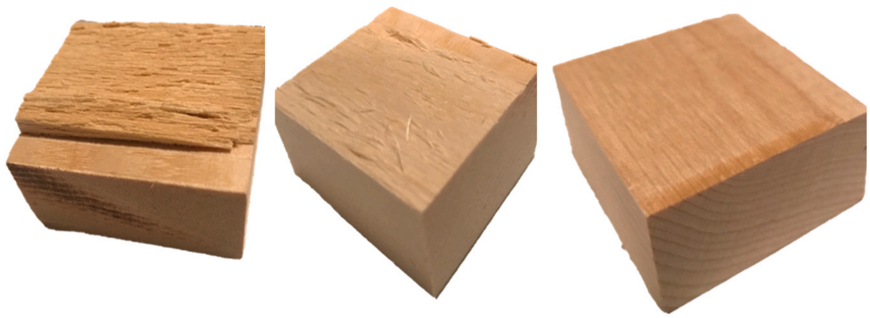
T-tests were conducted to analyze if the difference in between groups of results is significant to examine the significance of the controlled variables. The difference among multiple groups of results were analyzed using Tukey multiple comparison.

3. Result and discussion

3.1. Bonding properties of single species samples

The average and standard deviation (STDEV) of the bonding strength of the samples with each species and the adhesives are summarized in Table 3 and shown in Fig. 3. The reference SG of each examined species from the wood handbook [21] are also listed. Overall, the average bonding strength of the cross-lamination of the individual hardwoods combinations was separately 33% and 82% stronger than that of softwoods for Resorcinol ($p = 6.58 \times 10^{-4}$) and Melamine ($p = 4.74 \times 10^{-10}$). The two lowest bonding strengths were observed in white pine, bonded with the Melamine (2.43 MPa), and basswood, bonded with Resorcinol (2.96 MPa). Ring porous hardwoods tend to have lower bonding strength than diffuse porous hardwoods with similar SG, as seen in red oak and white ash. With the t-test analysis, no substantial difference was observed in the bonding strength between the adhesives with the same single species cross-laminated sample types.

Fig. 4 indicates that all softwood samples demonstrated an over 80% wood failure rate. The Melamine resulted in the highest wood failure



(a) Deep wood failure (b) Shallow wood failure (c) Glue failure

Fig. 2. Wood failure types observed in the study.

Table 3
bonding strength results for single species samples.

Species	SG at (12% MC [21]	Resorcinol				Melamine			
		Bonding Strength (MPa)		P_{wf} (%)		Bonding Strength (MPa)		P_{wf} (%)	
		Average	STDEV	Average	STDEV	Average	STDEV	Average	STDEV
SM	0.63	9.38	1.14	45.8	25.29	7.5	1.57	52.5	33.93
RM	0.54	6.03	1.62	80	7.45	7.08	2.4	54.5	28.72
YB	0.62	4.44	1.55	18.8	20.26	8.49	1.19	56	35.02
BW	0.37	2.96	0.39	85	11.06	3	0.63	91.8	17.1
QA	0.38	3.97	0.93	56.5	23.69	4.12	0.63	88.6	12.29
RO	0.63	6.31	1.09	81.4	18.76	5.93	1.38	74	21.06
WA	0.6	5.78	1.89	84	16.63	4.35	1.87	95	10.8
RP	0.46	4.92	1.34	84.5	14.23	3.6	1.27	88.5	13.95
WP	0.35	3.15	0.77	87.5	10.87	2.43	0.58	96.3	9.38

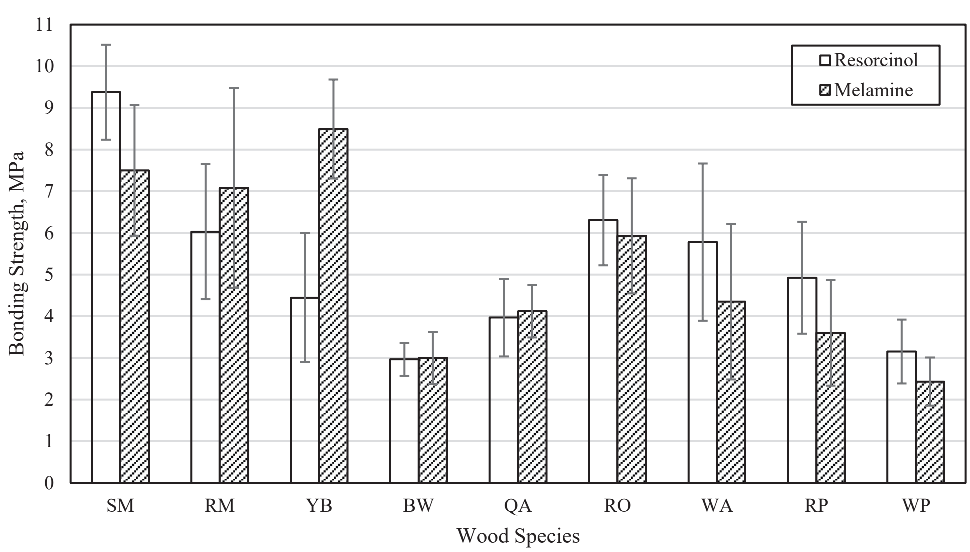


Fig. 3. The bonding strength of the single species samples with Resorcinol and Melamine.

percentage at 92%. Hardwood cross laminations bonded with Resorcinol adhesive averaged a 65% wood failure. The highest bonding strength was observed in sugar maple bonded with Resorcinol (9.4 MPa) and yellow birch bonded with the Melamine (8.5 MPa). However, these species also exhibited low wood failure percentages for both adhesives, with the lowest rates associated with yellow birch bonded with Resorcinol.

The results showed that the species with SG > 0.5 have good bond strength, but the percentage of wood failure is below 80%. Less dense woods such as white pine, basswood, white ash, and red pine had wood failure rates exceeding 80% with both commercial adhesives. For denser woods, red maple and red oak bonded with Resorcinol and aspen bonded with Melamine also recorded wood failure over 80%. Red oak, red maple, and aspen for both adhesives showed a good bond strength and fair wood failure percentage, which may illustrate the potential to be used in hardwood CLT (Cross Laminated Timber). The lowest wood failure rates were observed in yellow birch and sugar maple, with the minimum average failure percentage observed in yellow birch samples bonded with Resorcinol. The two softwoods (red pine and white pine) with SG < 0.5 recorded a very high wood failure percentage, while red pine outperformed white pine in bonding strength.

Fig. 5 shows the relationship between average bonding strength and

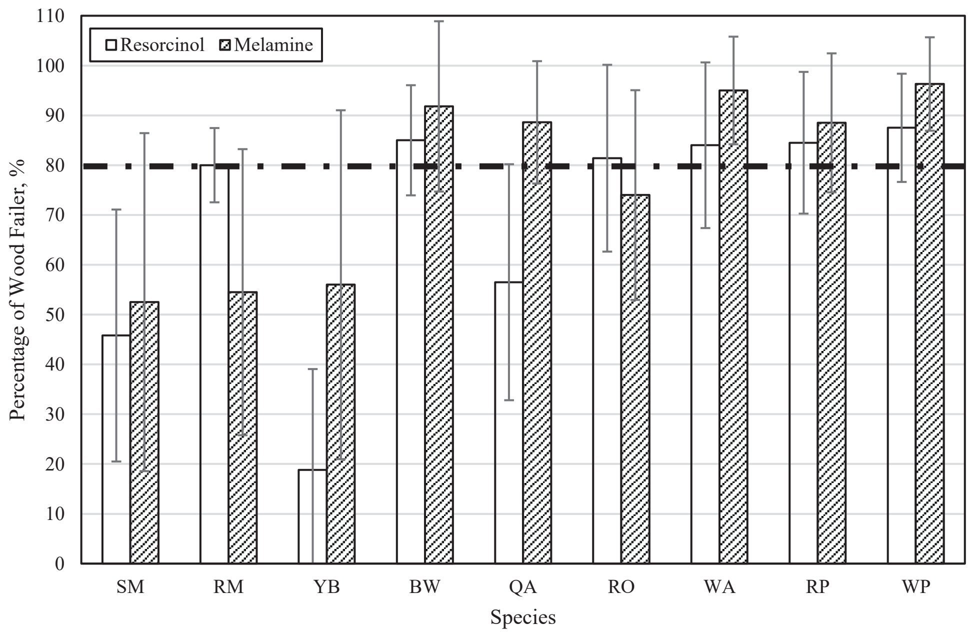


Fig. 4. The percentage of wood failure percentage of the single species samples.

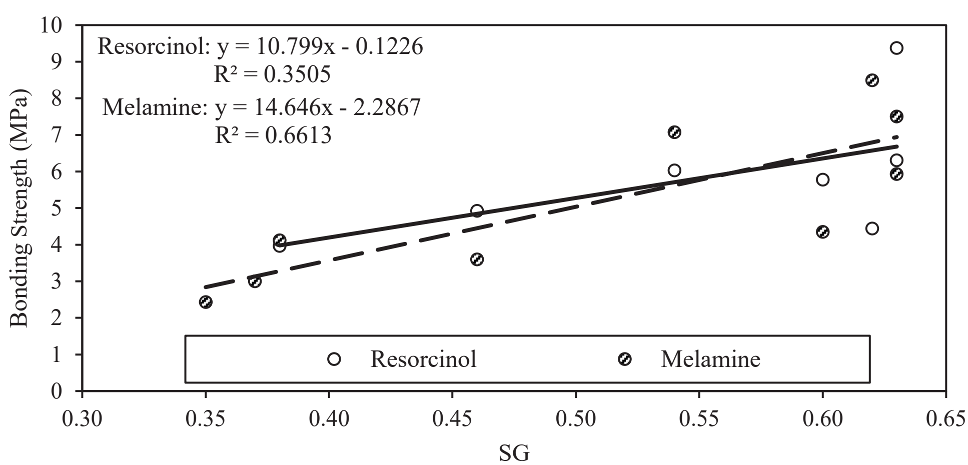


Fig. 5. The single species samples bonding strength vs. the SG of each species, for both adhesives.

species reference SG. An increasing trend can be observed for both the Melamine and the Resorcinol samples. Though the R^2 for the trendline of Resorcinol-bonded samples is 0.35, which indicates the fitting is not robust, the equations of the fitted lines show the increase for Melamine-bonded samples is more than that of Resorcinol-bonded samples. However, red maple with an SG of 0.53 recorded a higher bonding strength than white ash with an SG of 0.6 ($P = 0.006$ for Melamine, $P = 0.377$ for Resorcinol). In addition, yellow birch with an SG of 0.62 recorded higher bonding strength than red oak with an SG of 0.63 ($P = 1.5 \times 10^{-4}$ for Melamine, $P = 0.003$ for Resorcinol). Though red oak and sugar maple have the same SG of 0.63, the bonding strength performance of the sugar maple (8.4 MPa) was 16% higher than the bonding strength of the red oak (6.1 MPa) ($P = 0.014$ for Melamine, $P = 3.98 \times 10^{-6}$ for Resorcinol). These differences with varying strength could be attributed to the pore distribution patterns of the species. Also, using measured results of the samples instead of reference SG values may provide a better demonstration of the trend, which will be conducted in future studies.

A high wood failure percentage is accepted in the industry as evidence of wood bonding durability. The single species sample types that meet the 80% wood failure rate requirement per the Wood Handbook [21] and PRG 320 [7] for blocks tested at 12% MC for qualification and adhesive lot testing for Melamine include white ash, aspen, basswood, red pine, and white pine, and for Resorcinol, red maple, red oak, basswood, white ash, red pine and white pine.

3.2. Bonding properties of mixed combinations

As mentioned in Section 2.2, there were a total of 45 combinations investigated in this study. Except for the nine single species sample types, there are 21 hardwood mixed combinations, 1 softwood mixed combination, and 14 hardwood-softwood hybrid combinations. Table 4 presents the average bonding strength and percentage of wood failure of the mixed combinations. The bonding strength and percentage of wood failure of hardwood mixed combinations are shown in Figs. 6 and 7 as well. Red maple-sugar maple, red maple-yellow birch, and sugar maple-white ash cross lamination recorded the highest average bonding strength (>7.0 MPa) in Melamine, as in Resorcinol yellow birch-sugar maple, red oak-sugar maple, red maple-red oak and basswood-white ash recorded the highest bonding strength (>7.0 MPa). The hardwood

Table 4
Bonding strength and percentage of wood failure of the cross-laminated mixed combinations.

Combinations	Melamine				Resorcinol			
	Bonding Strength (MPa)		Percentage of wood failure		Bonding Strength (MPa)		Percentage of wood failure	
	Average	STDEV	Average	STDEV	Average	STDEV	Average	STDEV
Hardwood	5.45	2.65	85	25	5.28	2.35	75	26
RM-SM	8.70	2.30	59	40	6.20	1.50	30	20
YB-SM	5.70	3.30	33	36	7.70	2.10	59	23
YB-RM	7.70	2.40	81	18	4.80	2.20	66	31
BW-SM	6.10	4.50	98	5	5.00	1.70	87	13
BW-RM	3.50	1.70	94	14	4.00	1.10	85	27
BW-YB	3.80	1.50	91	15	2.70	1.10	96	8
QA-SM	5.00	2.30	95	10	3.80	2.80	62	30
QA-RM	5.80	3.10	97	7	4.30	2.00	77	27
QA-YB	3.70	1.60	66	33	4.20	1.70	65	37
QA-BW	3.70	0.30	85	25	4.20	0.90	67	21
RO-SM	5.20	3.10	83	18	7.70	1.50	65	31
RO-RM	6.80	1.70	82	16	7.60	0.70	74	22
RO-YB	6.80	1.60	76	24	5.90	1.20	71	24
RO-BW	4.60	3.80	89	22	3.30	1.20	94	14
RO-QA	3.70	1.30	97	5	4.20	1.30	89	12
WA-SM	7.40	2.00	98	6	5.30	2.80	90	17
WA-RM	6.90	1.80	88	29	6.00	1.90	71	21
WA-YB	6.70	1.30	99	3	5.30	2.00	80	23
WA-BW	3.50	1.40	97	7	7.20	4.10	94	12
WA-QA	4.10	0.80	89	26	5.60	2.20	90	10
WA-RO	5.10	1.10	99	2	5.80	2.00	72	23
Softwood	2.80	0.70	91	13	2.70	0.70	77	22
WP-RP	2.80	0.70	91	13	2.70	0.70	77	22

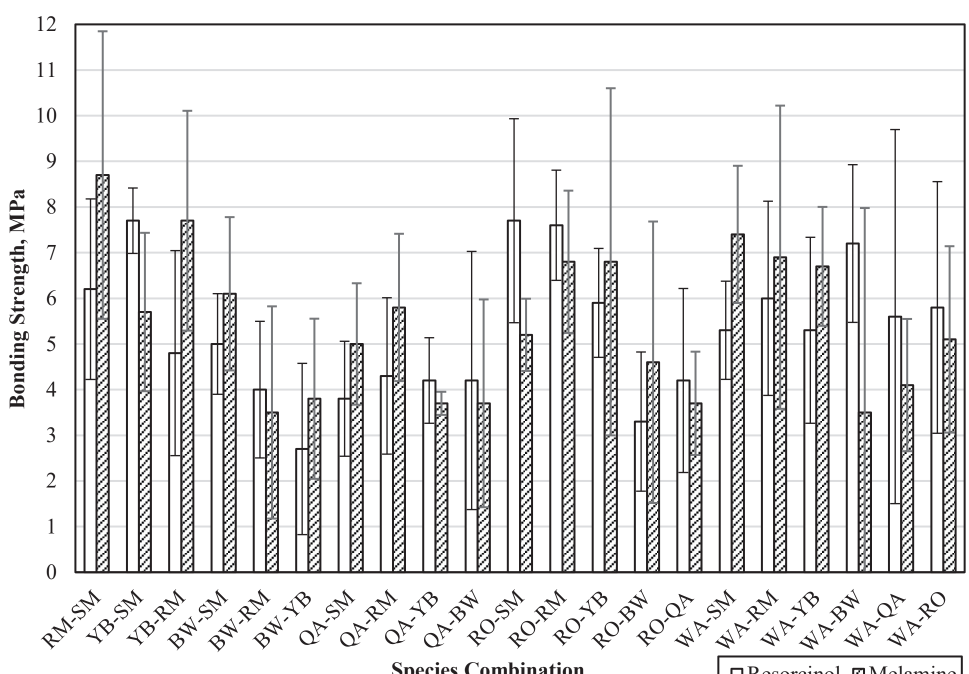


Fig. 6. Bonding strength of the hardwood mixed combination samples (the error bars are standard deviations).

mixed combinations exhibited an average bonding strength of 5.45 MPa (standard deviation of 2.65 MPa) for Melamine and a bonding strength of 5.28 MPa (standard deviation of 2.35 MPa) for Resorcinol. In contrast, the mixed softwoods samples had the lowest bonding strength of 2.8 MPa for Melamine and 2.7 MPa for Resorcinol. The multiple comparison analysis using Tukey HSD indicates that the differences between hardwood cross-lamination compared to softwood cross-lamination were significant ($p = 0.002$). Out of the 22 mixed combinations of hardwoods and softwoods, 12 combinations, representing 54% of the mixed combinations bonded with Resorcinol, was below 80% of the average wood failure. Whereas with Melamine, all the mixed combinations had a wood failure percentage above 80% except for red oak - yellow birch (76%), aspen - yellow birch (66%), red maple – sugar maple (59%) combinations and the worst being yellow birch - sugar maple (33%) combinations.

3.3. Bonding properties of hybrid combinations

Fig. 8a-d and Table 5 show the bonding properties of the hybrid combination samples. Particularly, Fig. 8(a) and (b) are for the

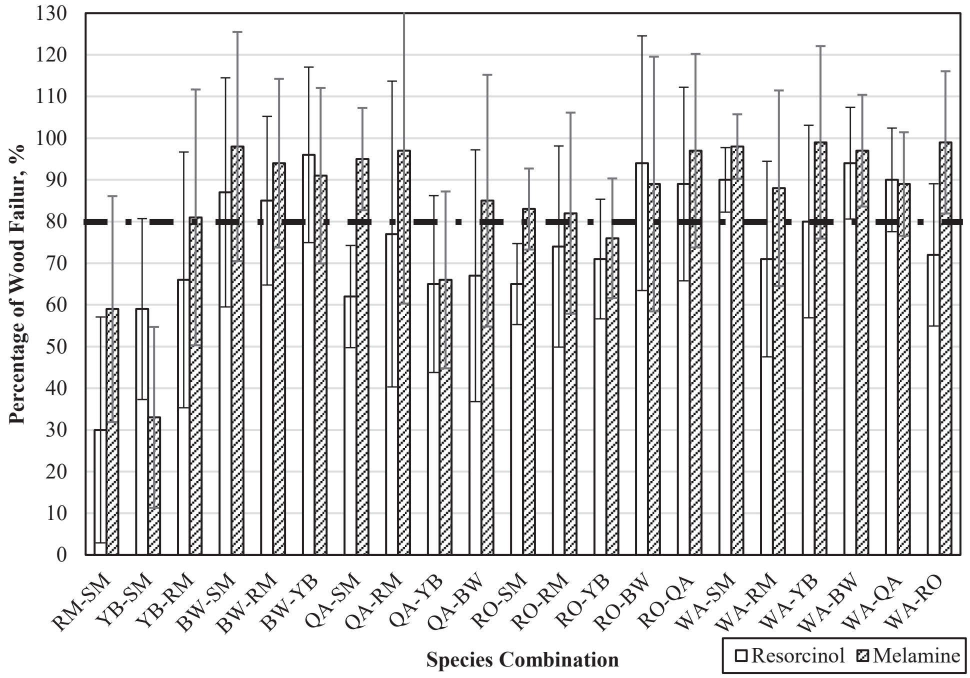


Fig. 7. Wood failure percentages of the hardwood mixed combination samples (the error bars are standard deviations).

Table 5
Bonding strength and percentages of wood failure of the cross-laminated hybrid combinations.

Mix species combination	Melamine				Resorcinol			
	Bonding Strength (MPa)		Percentage of wood failure		Bonding Strength (MPa)		Percentage of wood failure	
	Average	STDEV	Average	STDEV	Average	STDEV	Average	STDEV
Hybrid	4.02	2.03	93	14	3.85	2.13	88	19
RP-SM	5.60	3.70	86	23	5.90	3.30	89	12
RP-RM	5.30	2.20	99	3	5.00	2.40	70	26
RP-YB	3.90	1.90	98	6	4.40	2.40	89	13
RP-BW	3.40	0.70	99	3	3.30	0.50	99	3
RP-QA	4.20	1.20	94	10	4.00	1.30	92	8
RP-RO	3.80	1.90	98	6	5.50	3.60	96	10
RP-WA	3.50	1.30	87	15	3.80	1.60	96	10
WP-SM	5.70	3.40	90	19	3.00	2.40	72	31
WP-RM	3.60	1.80	90	16	3.60	1.90	83	13
WP-YB	4.50	1.90	94	9	3.60	1.50	84	17
WP-BW	2.70	1.10	93	12	2.20	0.90	75	29
WP-QA	2.70	0.80	87	14	3.30	1.10	90	14
WP-RO	3.50	1.30	93	22	3.60	1.90	94	11
WP-WA	3.90	1.40	96	13	2.70	0.70	99	3

Resorcinol bonded sample, and (c) and (d) are the Melamine bonded samples. Overall, the hybrid combinations demonstrated a high bonding strength of 4.02 MPa (standard deviation of 2.03 MPa) for Melamine and 3.85 MPa (standard deviation of 2.13 MPa) for Resorcinol. White pine - sugar maple, red pine - sugar maple, and red pine-red maple cross lamination recorded the bonding strength greater than 5.0 MPa, and with Resorcinol red pine - sugar maple (5.9 MPa), red pine - red oak (5.5 MPa) and red pine - red maple (5.0 MPa) recorded higher bonding strengths. White pine-aspen (2.7 MPa) and white pine–basswood (2.2 MPa) had the lowest bonding strength of 2.7 MPa when bonded with Melamine and 2.2 MPa when bonded with Resorcinol respectively.

As shown in Fig. 8(a), when bonded with Resorcinol, the average bonding strengths of Red Pine (RP) and the hardwoods hybrid combinations are higher than that of White Pine (WP) and the hardwoods hybrid combinations. At the same time, as shown in Table 6, the difference is significant for Basswood ($p = 0.002$), Sugar Maple ($p = 0.045$), and White Ash ($p = 0.026$) and not significant for Red Maple ($p = 0.078$), Quaking Aspen ($p = 0.101$), Red Oak ($p = 0.078$) and Yellow Birch ($p = 0.201$). For Melamine, the differences for Red Oak ($p = 0.314$), Yellow Birch ($p = 0.269$), Basswood ($p = 0.069$), and White Ash ($p = 0.271$) are insignificant, while for Red Maple ($p = 0.038$), Aspen ($p = 0.002$), and Sugar Maple ($p = 0.024$), the bonding strength with Red Pine is significantly higher than that with White Pine. For both Resorcinol and Melamine samples, the differences between the percentage of wood failure of Red Pine hybrid bonding and White Pine hybrid bonding were statistically insignificant, except for Basswood with Melamine ($p = 0.009$). The results illustrated that for both Melamine and Resorcinol, the hybrid bonding with Red Pine provided higher strength and comparable wood failure percentage compared with hybrid combination bonding with White Pine.

The percentage of wood failure of hybrid combinations was higher than those of mixed hardwoods and mixed softwoods for both types of adhesives. All hybrid combinations exceeded the required 80% average percentage of wood failure when bonded with Melamine, while for Resorcinol bonded samples, red pine – sugar maple (70%), white pine – basswood (75%) and white pine – sugar maple (72%) combinations

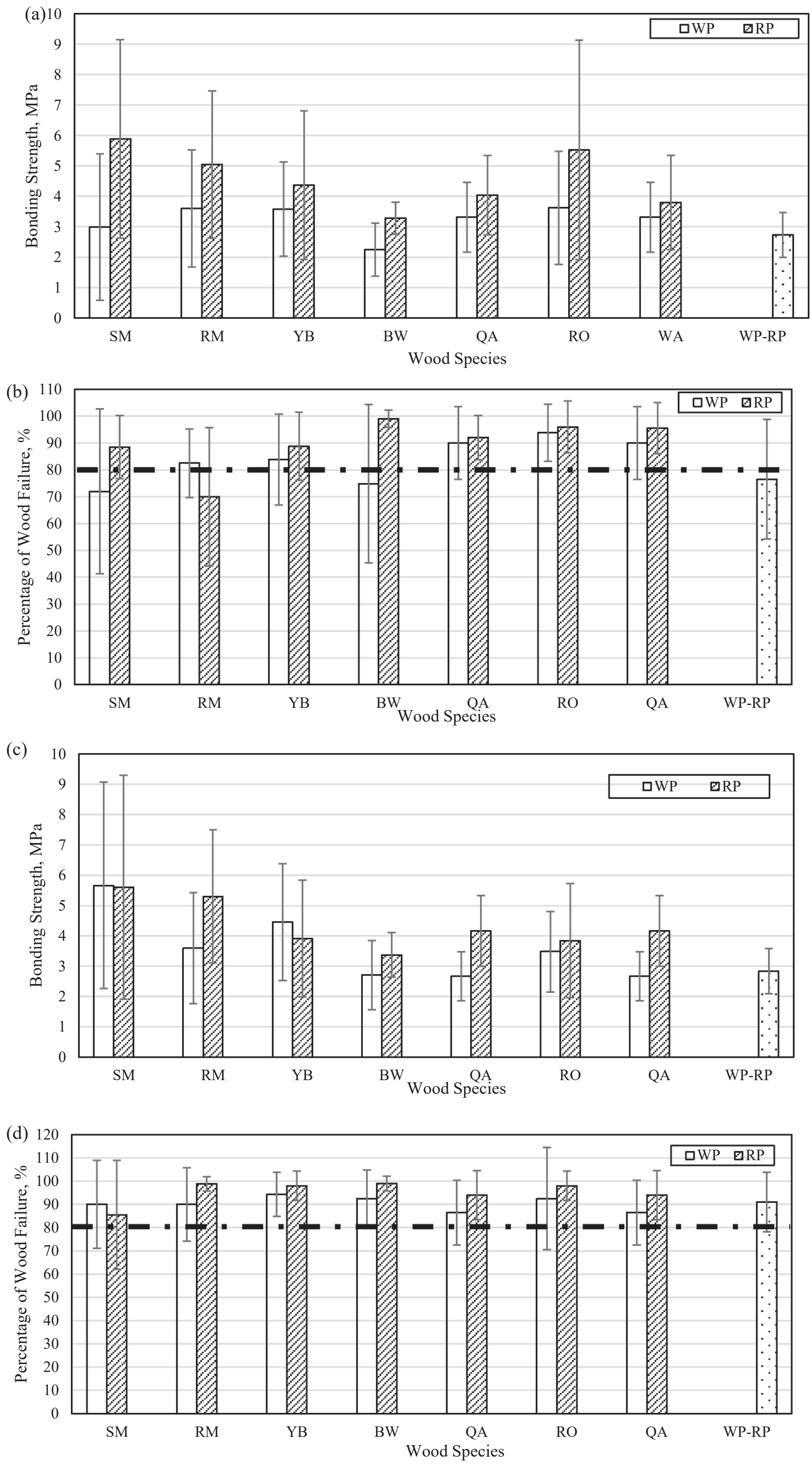


Fig. 8. Bonding properties of the hybrid combination samples with error bars. Fig. 8a: Bonding strength of Resorcinol bonded hybrid samples. Fig. 8b: Percentage of wood failure of Resorcinol bonded hybrid samples. Fig. 8c: Bonding strength of Melamine bonded hybrid samples. Fig. 8d: Percentage of wood failure of Resorcinol bonded hybrid samples.

Table 6
P-values for hybrid combination samples bonding properties between white pine and red pine combinations.

—	Bonding strength		Percentage of wood failure	
	Resorcinol	Melamine	Resorcinol	Melamine
SM	0.045	0.024	0.111	0.406
RM	0.078	0.038	0.051	0.093
YB	0.201	0.269	0.159	0.232
BW	0.002	0.069	0.062	0.009
QA	0.101	0.002	0.096	0.347
RO	0.078	0.314	0.229	0.317
WA	0.026	0.271	0.082	0.171

failed the requirement.

3.4. *Discussion of effects of wood anatomic structures on the bonding properties*

Following the anatomical features of the wood concerning the earlywood/latewood transition patterns, as shown in Fig. 9, the average bonding strength of each adhesive type among the combinations was significantly different ($p < 0.003$), while the difference between the two adhesive types was not significant ($p = 0.995$). Using Bonferroni's correction to compare the wood anatomical features of the two commercial adhesives indicated that the DiffP-DiffP (Diffusive Porous-Diffusive Porous) cross lamination is significantly higher in bonding strength when compared with Grd-DiffP(Gradual Transition-Diffusive Prorous) ($p = 0.00$), Grd-RingP (Gradual Transition-Ring Porous) ($p = 0.02$) and Abr-Grd (Abrupt Transition-Gradual Transition) cross lamination ($p = 0.01$) whiles the rest was not significant (Supplementary Sheet 1). Fig. 9 showed that for the Melamine, DiffP-RingP cross lamination has the highest average bonding strength (5.6 MPa) followed by DiffP-DiffP (5.4 MPa) and RingP-RingP cross lamination (5.1 MPa). The lowest was Abr-Grd (2.8 MPa) cross lamination. Meanwhile, in the Resorcinol RingP-RingP and DiffP-RingP cross lamination recorded the highest bonding strength of 5.80 MPa followed by DiffP-DiffP cross lamination (4.71 MPa) where Abr-Grd cross lamination recorded the lowest (2.73 MPa).

The results of percentage of wood failure in Fig. 9 showed that all Melamine bonded samples had their percentage of wood failure greater than 80%, while for Resorcinol bonded samples, the Abr-Grd, RingP-RingP, and DiffP-RingP recorded lower percentage of wood failure of 77%, 69%, and 69% respectively. Although there was no specific trend in adhesive performance with mean bonding strength, DiffP-RingP, DiffP-DiffP, and RingP-RingP combinations tends to have higher bonding strength in both adhesives and exceeding 80% in all of the samples with Melamine.

4. Conclusion

In this study, the face bonding strength of cross laminated 7 hardwoods and 2 softwoods from the Great Lakes region were studied. Two adhesive systems, the Melamine and the Resorcinol, were used in cross-laminating 45 combinations of the 9 wood species in a two-layer configuration. The combinations included 9 single species sample types of each species, 21 mixed hardwoods combinations of the seven hardwoods, 1 mixed softwoods combination of the two softwoods, and 14 hybrid combinations of the hardwoods and the softwoods. A total of 900 shear blocks were prepared from the laminated panels and tested according to ASTM D905 for bonding strength and percentage of wood failure. The test results and the analyses led to the following conclusions:

1. For single species sample types, white ash, aspen, basswood, red pine, and white pine bonded with the Melamine, and red maple, red oak, basswood, white ash and white pine bonded with the Resorcinol met the 80% wood failure criteria specified in ANSI/AITC A190.1. Moreover, the hardwood individual combinations outperformed the softwoods by 33% ($p = 6.58 \times 10^{-4}$) and 82% ($p = 4.74 \times 10^{-10}$) with the Resorcinol and the Melamine, respectively.
2. Mixed combinations of the hardwoods exhibited higher average bonding strengths of 5.45 MPa for the Melamine and 5.28 MPa for the Resorcinol, compared to the mixed combination of the softwoods, which have an average bonding strength of 2.8 MPa for the Melamine and 2.7 MPa for the Resorcinol. Among the 22 mixed

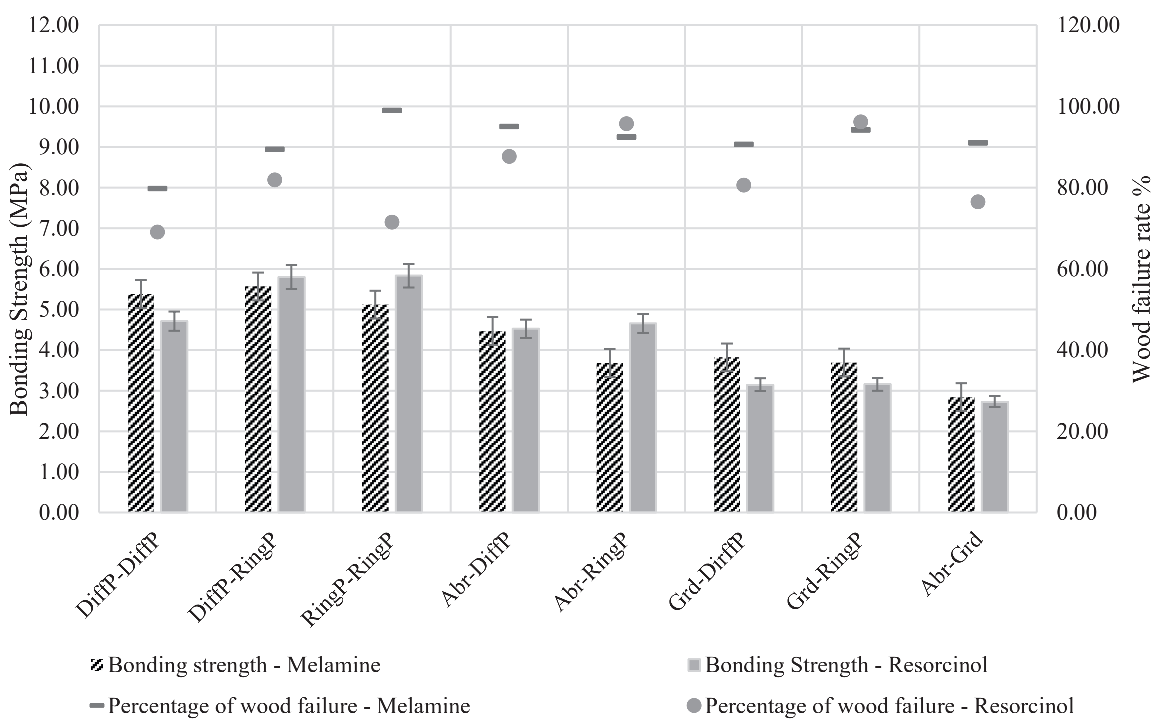


Fig. 9. Comparisons of bonding strength and percentage of wood failure among combinations of wood anatomic structures. (the error bars are standard deviations).

combinations, 54% of the Resorcinol bonded combinations had their percentage of wood failure below 80%, while for the Melamine bonded combinations those had low percentage of wood failure included red oak – yellow birch (76%), aspen – yellow birch (66%), red maple – sugar maple (59%), and yellow birch – sugar maple (33%).

3. Hybrid combinations showed an overall bonding strength 5% lower than the mixed combinations of the hardwoods. Despite this, all the Melamine bonded hybrid combinations met the necessary 80% average percentage of wood failure threshold. However, some of the Resorcinol bonded hybrid combinations fell short of the requirement for wood failure, including red pine - sugar maple (70%), white pine - basswood (75%), and white pine - sugar maple (72%).
4. Anatomical features, particularly pore distribution, played a role in wood failure percentage and bonding strength. While no consistent trend emerged in adhesive performance based on mean bonding strength, diffuse porous–ring porous and ring porous–ring porous combinations consistently showed high bonding strength. The Melamine adhesive consistently achieved over 80% wood failure rates across all pore distribution types, emphasizing its reliability in various wood combinations.

This study attempts to fill the knowledge gap of using mixed and hybrid species in cross laminated timber products, which is allowed by the PRG320 standard yet lack of design reference. It is critical for enhancing hardwoods utilization in mass timber manufacturing due to the smaller volumes of each individual species of a very diverse species of hardwood lumber. The results showed that certain selection of adhesives and species to mix or to hybrid for cross lamination can provide satisfactory bonding strength and quality. Gluing parameters, such as adhesive application rate, pressure, and time of curing under pressure, were not investigated in this study, while changing those parameters may improve the bonding strength of some less satisfactory combinations. Future studies in face gluing difference species in cross laminations also need to focus on large or full-size panels to take consideration of the effects of other factors in the manufacturing process.

CRediT authorship contribution statement

Reza Hosseinpourpia: Writing – review & editing. **Robert Ross:** Writing – review & editing, Supervision. **Xinfeng Xie:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization. **Xiaolei Jiang:** Writing – review & editing. **Munkaila Musah:** Writing – original draft, Methodology, Investigation, Conceptualization. **Xiping Wang:** Writing – review & editing, Resources, Funding acquisition, Conceptualization. **Yunxiang Ma:** Writing – review & editing, Writing – original draft, Visualization, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.conbuildmat.2024.135405.

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