The effects of species, adhesive type, and cure temperature on the strength and durability of a structural finger-joint

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Abstract

This research project evaluated the effects of adhesive type, wood species, and cure temperature on the strength and durability properties of a finger-joint. The adhesives were a resorcinol-formaldehyde (RF), a polyurethane/aqueous emulsion polymer (PU/AEP), and a resorcinol-formaldehyde/soy-isolate (RF-Soy) honeymoon system. The species of wood were keruing (*Dipterocarpus* spp.), southern pine (*Pinus* spp.), and Douglas-fir (*Pseudotsuga menziesii*). The cure temperatures of the adhesives were ambient (26° to 35°C, 78° to 95°F) and elevated (43° to 49°C, 110° to 120°F). Joints were subjected to three test procedures: a tension test, a bending test, and a bending test following a cyclic delamination procedure. The response variables measured for each of the bending tests included modulus of rupture, modulus of elasticity, and percent wood failure. The response variables measured for the tension tests were tensile strength and percent wood failure. The end-joints bonded with RF adhesive performed the best in flexural and tensile strength of the three adhesives studied. However in most cases, the end-joints bonded with PU/AEP could be considered a comparable system. The RF-Soy honeymoon system generally had the lowest strength and wood failure across most species/adhesives variables. Given adequate adhesive performance, strength and stiffness of the joints studied were dependent on density of the wood species, with keruing having the greatest density.

A finger-joint is a multiple scarf joint, shorter in length than most scarf joints, that can be utilized to manufacture lumber in practically unlimited lengths. Finger-jointed lumber allows unwanted knots and other grain anomalies to be removed as well as the use of short pieces of wood for structural and nonstructural lumber products. In addition, finger-joints can be manufactured with strengths up to 75 percent of the strength of the clear wood in many species (USDA 1999).

Clear economic advantages exist for finger-jointed lumber. A finger-joint cuts away many times less wood than a scarf joint (Madsen and Littleford 1962). Another economic advantage for finger-joints is greater monetary return because of upgraded lumber. In addition, sales personnel have smaller quantities of lower grade lumber to contend with, and have an increased utilization of raw materials (Jokerst 1981). Finger-jointing also reduces variation in the final product, such as less tendency to warp because the grain is randomized over the length of the piece.

Jokerst (1981) elaborated on finger geometric relationships, including finger pitch (P), fingertip thickness (t), finger length (L), and the finger slope (tan q) (**Fig. 1**). The tip thickness should be as thin as possible because this design feature achieves maximum strength and reduces the abrupt stress changes caused by finger-joints. Research has shown that decreased slope of the finger results in higher tensile strength of the joint. However, slopes smaller than 1/12 have

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Forest Prod. J. 54(3):66-75.

Table 1. — Adhesive component characteristics from MSDS and technical bulletins.

Component	Nonvolatile solids	pH	Specific gravity	Viscosity	Major components
	(%)			(mPa·s, cP)	
RF resin G1181C	50 to 55	7.6 to 8.0	1.1	370 to 520	RF, ethanol
RF catalyst G1131B	Powder	3.0 to 5.0	0.45	NA[a]	Paraformaldehyde
Emulsion WD3-A322	45 to 50	6.0 to 6.5	1.15 to 1.25	5000 to 7000	Calcium carbonate synthetic rubber vinyl compound
Polyurethane UX-100	100, homogenous solution	NA	1.12 to 1.18	3000 to 6000	Polyglycol PMDI
Soy Eka 3050	~42	~10	1.13	~900	Sodium-hydroxide hydrolized soya isolate

[a]NA = not applicable.

little or no increase in joint tensile strength. In addition, when slope and tip thickness are kept constant, joint strength increases with increasing pitch. Also, a proportional relationship has been found between joint strength and gluebond area. Given that a joint has adequate slope, pitch, and gluebond area, tip thickness becomes the determinant for joint strength. A thinner tip will have more strength than a thicker one (Richards 1962). Thus, most nonstructural joints have thick fingertips, and structural joints have thin, almost pointed fingertips.

This study evaluated the effects of adhesive (glue) type, wood species, and cure temperature on strength and durability properties of a structural finger-joint. The species studied were keruing (*Dipterocarpus* spp.), southern pine (*Pinus* spp.), and Douglas-fir (*Pseudotsuga menziesii*). Keruing is a Southeast Asian hardwood and southern pine and Douglas-fir are native U.S. softwoods. The adhesives studied were resorcinol-formaldehyde (RF), a polyurethane isocyanate/aqueous emulsion polymer (PU/AEP), and a resorcinol-formaldehyde/soy-isolate (RF/Soy) honeymoon system. The concept of separate application adhesives capable of setting faster than conventional adhesives was developed in the United States (Tiedeman and Sanclemente 1973, Tiedeman et al. 1973) and in other countries (Pizzi and Roux 1978, Van der Westhuizen et al. 1978) principally to bond large components where presses were impractical. Kreibich (1974) described these honeymoon systems in more detail. Two excellent chapters that describe some work on these honeymoon adhesives for finger-jointing wood are Kreibich and Hemingway (1989) and Pizzi and Cameron (1989).

Materials and methods

Lumber

Approximately 3.54 m^3 (1,500 BF) each of keruing (*Dipterocarpus* spp.), southern pine (*Pinus* spp.), and Douglas-fir (*Pseudotsuga menziesii*) in nominal dimensions 51 mm by 152 mm by 2.44 m (2 in. by 6 in. by 8 ft.) were tested. After end-jointing, the lumber was machined to a cross section of 32 mm by 121 mm (1.25 in. by 4.75 in.). The Malaysian-source keruing was obtained from Overseas Hardwoods Company, Mobile, Alabama, and was the highest grade available as rated by the *Malaysian Grading Rules* (clear, without knots). The kiln-dried southern pine was purchased from Shuqualak Lumber Company, Shuqualak, Mississippi, and was a special structural clear grade. The U.S. Northwest-source Douglas-fir was purchased in part from McEwen Lumber Company, Mobile, Alabama, with the balance being purchased from Klumb Forest Products, Loxley, Alabama, and was kiln-dried Grade C and Better. Regardless of grade, the lumber for end-jointing was screened for straightness of grain and the absence of deleterious growth characteristics. Also, lumber moisture content (MC) was measured and found to be within the range of 11 to 13 percent, ovendry basis. The measured density of the three species was 780 kg/m^3 for keruing, 580 kg/m^3 for Douglas-fir, and 550 kg/m^3 for southern pine at the reported MCs.

Adhesives

The RF resin for this study was Cascophen G1181C resin in combination with Cascoset G1131B hardener catalyst (**Table 1**) (Borden Chemical 2001a, 2001b). Both the resin and the hardener are manufactured by Borden Chemical, Springfield, Oregon, and are typically mixed in a 5:1 ratio, respectively (**Table 2**). The hardener is a mixture of filler and paraformaldehyde (Borden Chemical 2001a, 2001b). The RF resin adhesives have been utilized for structural wood bonding for about 60 years in the United States (Perry 1944, Moult 1977) and are still relied on for special application to this date (Dressler 1994).

No reported application of an RF resin with a soy hydrolyzate to bond finger-joints was found in the literature. To date in commercial applications, the soy component has been utilized in the honeymoon system with a phenol-resorcinol-formaldehyde (PRF) resin rather than an RF resin (Kreibich 1997). However, interest existed in comparing the performance of the RF resin/catalyst formulation in a combined RF/Soy honeymoon system for determining the influence of the soy component on dry-wood bonding strength. The soy-based component in the RF/Soy honeymoon system was Eka 3050 manufactured by Eka Chemical Company, Albany, Oregon, (formerly HTI 3050, manufactured by Hopton Technologies, Inc. 1999) (Akzo Nobel 2001). The instructions for application of the PRF/Soy honeymoon system published by OmniTech (2001) were followed with the exception that RF resin was substituted for PRF resin. In addition, a hardener recommended for RF resin (Borden Chemical 2001a, 2001b) was substituted for that recommended for PRF resin. The soy component, EKA 3050, was applied to one side of the joint, and the RF adhesive was applied to the other side of the joint, for a honeymoon system. Initial pilot test observations revealed that when the joint was closed, the two adhesive components, for all practical purposes, immediately gel, similar to previously reported experiments with PRF/Soy systems (OmniTech 2001).

Table 2. — Cost analyses assuming equal weight application for three adhesive systems.

Adhesive mix ingredient	Ratio	Ingredient cost f.o.b.	Mix ratio cost	Applied wet mix cost	Applied mix solids
	(parts)	($/kg [$/lb.])	($ for kg [$ for lb.])	($/kg [$/lb.])	(%)
RF resin G1181C	5	5.79 [2.63]	28.95 [13.15]		
RF catalyst G1131B	1	3.17 [1.44]	3.17 [1.44]		
Total	6		32.12 [14.59]	5.35 [2.43]	~60
Polyurethane UX-100	4	5.50 [2.50]	22.00 [10.00]		
Emulsion WD3-A322	1	2.51[1.14]	2.51 [1.14]		
Total	5		24.51 [11.14]	4.91 [2.23]	~90
RF G1181C & G1131B mix	1	5.35 [2.43]	5.35 [2.43]		
Soy Eka 3050	1	2.42 [1.10]	2.42 [1.10]		
Total	2		7.77 [3.53]	3.89 [1.77]	~51

The PU/AEP adhesive was UX-100/WD3-A322 adhesive manufactured by Ashland Chemical Company (**Table 1**). This particular adhesive is a two-part system recommended by the manufacturer to be mixed in a 4:1 ratio, respectively (**Table 2**). The UX-100 component is polyurethane prepolymer with excess polymeric isocyanate (PMDI) (Ashland 1999, 2000). The WD3-A322 component is an aqueous emulsion polymer composed of synthetic rubber, vinyl compounds, and calcium carbonate filler. When mixed, the excess isocyanate in the UX-100 reacts with the water in the WD3-A322 component, initiating the curing process (Ashland 1999, 2001). Ashland has manufactured emulsion polymer isocyanates for more than 20 years (Pagel and Luckman 1981, Troughton 1986).

Each adhesive raw material was tested for viscosity, and each adhesive mix was tested for viscosity and pot life (**Table 3**). Properties of each material were found to conform to the manufacturers specifications (Spec) (**Table 3**). Major adhesive component characteristics were extracted from the product technical data sheets and material safety data sheets (**Table 1**). The actual adhesive mix ratios and an approximation of mix costs were calculated (**Table 2**).

Finger-joint manufacturing

More than 500 vertical finger-joints were glued for a 2 by 3 by 3 factorial arrangement study of treatments in split plot design. The finger-joint profile (**Fig. 1**) had a pitch (P) of 3.2 mm (0.126 in.) and a finger length of (L) 15 mm (0.591 in.). The finger tip (t) was approximately 1.2 mm thick. A process allowing five seconds of open assembly time and three seconds of closed assembly time was selected after making the test finger-joints. Joints were glued over three days in accordance with the statistical design at Overseas Hardwoods' manufacturing facility in Stockton, Alabama.

Adhesives were mixed as needed, with care taken to keep a fresh mix on hand for the finger-jointer operator. Glue was applied to both faces for the joints with stiff-bristled brushes, however, separate brushes were required for each adhesive component of the honeymoon system. All joints for heat-accelerated curing were made first on each day. These boards were stacked with stickers to allow for airflow and covered by vinyl tarpaulins with a commercial heater blowing into one side. A portable temperature recorder tracked the temperature during the curing process. In addition, an infrared thermometer periodically checked the temperature in the stack. The temperature recorder had a maximum reading of 43°C (110°F), consequently the recorder eventually read off the scale. However, the infrared temperature readings showed a range of 43° to 49°C (110° to 120°F). Joints were cured with heat for 8 hours, after which the heater was turned off. Normally, a higher temperature will insure more fully cured adhesives, leading to better bond quality. At the same time, higher temperatures can also lead to migration of wood extractives (as in keruing) interfering with bond formation. The balance of the finger-joints were cured at ambient mill temperatures, which ranged from 26° to 35°C (78° to 95°F), typical for the month of July in southern Alabama. After the finger-joint manufacturing was completed, the joints were machined to a cross-sectional size of 32 mm by 121 mm (1.25 in. by 4.75 in.).

Table 3. — Viscosity and pot life for the adhesive systems.

Adhesive ingredient or mix type	Viscosity @ 25°C		Pot life			
	Spec	Measured	Spec	Temp.	Measured	Temp.
	----------- (cP) -----------		(min.)	(°C)	(min.)	(°C)
ISOSET UX-100 polyurethane	3000 to 6000	3050	NA[a]	--	NA	--
ISOSET A322 emulsion	5000 to 7000	6125	NA	--	NA	--
ISOSET Mix	7000 to 8000	7875	15:00	21	10:00	37
Borden G1181C RF	370 to 520	425	NA	--	NA	--
G1181C & G1131B Mix	NA	1250	NA	NA	35:00	37
Eka 3050 soy	<1200	675	NA	--	NA	--
(G1181C & G1131B) & Eka 3050 mix	NA	NA	NA	NA	00:08	37

[a]NA = not applicable.

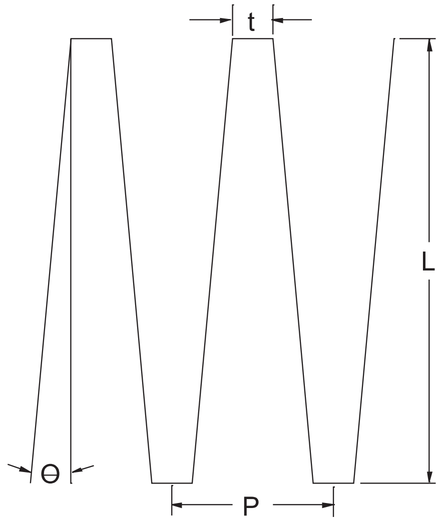

Figure 1. — Finger-joint geometry.

Test procedures

Three test procedures evaluated the finger-joints. These tests included a bending test, a bending test after one cycle of a cyclic delamination test, and a tension test. The bending and cyclic delamination tests were conducted at the Mississippi Forest Products Laboratory (MFPL), Starkville, Mississippi, while the tension tests (parallel to the grain) were conducted at Mississippi Laminators in Shubuta, Mississippi.

Bending test. — The bending test defined flexural properties with two-point loading (ASTM 2000a). This test is suitable for wood members of all types, including finger-jointed lumber. Some two-point loading of solid lumber was performed in this study for information. The bending apparatus was a two-point loading set-up (two load supports and two loading points) with a half-shear span of 203 mm (8 in.) and a load span of 152 mm (6 in.). The supports for the test apparatus were fixed knife-edge reaction with rollers. Each sample was tested flatwise on the apparatus with the finger-joint centered. The ASTM test standard indicates that the span length of the wood member intended for flexural properties evaluation should have a half shear span-to-board depth ratio in the range of 5:1 to 12:1. The ratio for the set-up in this study was 6.4:1. All of the bending tests were conducted on a Satec Universal Testing Machine, Model Number TL55-8800, equipped with Instron digital electronic controls. The deflection load rate was 4.6 mm (0.18 in.) per minute. Response variables measured and calculated for each sample were modulus of rupture (MOR), modulus of elasticity (MOE), and percent wood failure (WF).

Cyclic delamination and bending test. — The second test procedure was a cyclic delamination procedure (AITC 1992) followed by the bending test detailed previously. The cyclic delamination procedure calls for the samples to be weighed and then submersed in cold (25° ± 2°C, 77° ± 4°F) water in a pressure vessel under a vacuum of 635 mm (25 in.) of mercury for 30 minutes. After the vacuum is released, a pressure of 517 kPa (75 psi) is applied for 2 hours. After the 2 hours, the pressure is released and the water is drained. The specimens are then dried to within 12 to 15 percent of their original weight. The test procedure states that the drying portion takes approximately 10 hours at 71°C (160°F); however, the actual drying time is dependent on the samples reaching the proper weight. Rapid drying is critical for this test procedure in order to stress the glueline to a maximum. The study samples were dried for a period of approximately 24 hours at 60 to 71°C (140 to 160°F). One sample of each species was checked periodically to determine its weight. When all three samples reached the prescribed range of 12 to 15 percent of their original weight, the dry kiln was turned off. Prior to the bending test, each cyclic delamination sample was observed for any signs of bondline delamination and weighed in order to determine the overall average percent weight change of the samples.

Tension test. — The final test was a joint tension test (AITC 1992). The testing apparatus was a custom-built hydraulic machine with an approximate load capacity of 400 kN (90,000 lb.), at a mill site, which had been calibrated by the AITC to ensure accurate load readings for routine testing of end-jointed lumber. Samples were loaded into the testing machine with the joint centered between the tension grips. The tension grips were equipped with hydraulic clamps to secure each specimen end during the test. Each sample was loaded in tension (parallel to the grain) via two hydraulic cylinders until failure was achieved. Upon failure of the joint, its ultimate tensile load was recorded. Response variables measured and calculated for this procedure included tensile strength and WF.

Wood failure grading procedures

After reviewing ASTM D 5299 (ASTM 2000b), WF (0% to 100%) was graded for all three test regimens. Each joint contained approximately 32 fingers on each side for a total of 64 fingers. Each side of a broken joint was examined under excellent lighting conditions. The WF was not normalized. The American National Standard for Wood Products–Structural Glued Laminated Timber requires a minimum average WF of 80 percent for wet and dry use adhesives when bonding end-joints with softwoods (ANSI/AITC 1992). The standard calls for 60 percent or greater WF for wet use adhesives and 40 percent or greater for dry use adhesives when bonding end-joints with dense hardwoods (ANSI/AITC 1992). The definition of dense hardwoods was not found in the standard, but low-density hardwoods was defined as 0.42 or less specific gravity. The United States and British standards for decorative plywood and hardwood allow less WF to be present when ultimate shear loads are higher (typically with denser woods) (British Standards Institution 1985, ANSI/HPVA 2000).

Statistical design

Three species, three adhesives, and two cure temperatures were studied (18 treatments). Each treatment combination was replicated nine times. Consequently, 162 samples were finger-jointed for each of the 3 test procedures (486 total finger-joints). The statistical model was a three-by-three-by-two factorial arrangement of treatments in a

Table 4. — LSMean separation two-point dry bending test MOR, species by adhesive interaction.

Treatment combination	Mean	t-group[a]				COV[b]
	(MPa [psi])					
Keruing-RF	88.77 [12,875]	A				17
Keruing-PU/AEP	81.47 [11,816]	A	B			14
Douglas-fir-RF	74.56 [10,814]		B			12
Southern pine-PU/AEP	74.09 [10,745]		B			15
Southern pine-RF	72.85 [10,566]		B			18
Douglas-fir-PU/AEP	68.42 [9,923]		B	C		18
Douglas-fir-RF/Soy	61.98 [8,989]			C	D	20
Southern pine-RF/Soy	60.10 [8,717]				D	19
Keruing-RF/Soy	56.56 [8,203]				D	22

[a]Treatment combinations having the same capital letter are not significantly different following a t-test having a 0.05 level of significance.
[b]COV = coefficient of variation, which equals sample standard deviation expressed as a percentage of the sample mean.

Table 5. — LSMean separation two-point dry bending test MOR, cure by adhesive interaction.

Treatment combination	Mean	t-group[a]			COV[b]
	(MPa [psi])				
Heat cure-RF	81.18 [11,774]	A			17
Cold cure-PU/AEP	79.64 [11,551]	A			13
Cold cure-RF	76.27 [11,062]	A			19
Heat cure-PU/AEP	69.68 [10,106]		B		19
Cold cure-RF/Soy	61.50 [8,920]			C	19
Heat cure-RF/Soy	57.59 [8,352]			C	21

[a]Treatment combinations having the same capital letter are not significantly different following a t-test having a 0.05 level of significance.
[b]COV = coefficient of variation, which equals sample standard deviation expressed as a percentage of the sample mean.

split-plot design. For this design, the effects due to the day (1, 2, or 3) of manufacture and the cure temperature (ambient and elevated) made up the main-plot unit. The effects due to the species type, and adhesives made up the sub-plot unit. An analysis of variance (ANOVA) was applied to analyze the response variables measured in this study. All statistical analyses were performed with a 0.05 level of significance. The least squared means (LSMeans) procedure performed mean separations by utilizing a t-test on significant interactions resulting from the ANOVA analysis. The LSMeans procedure accounted for different error terms when an interaction occurred between a main-plot factor and a sub-plot factor.

Results and discussion

Finger-joint dry bending tests

The analysis of variance (ANOVA) for the dry MOR showed no significant three-way interaction (species, adhesive, and cure temperature). However, significant interactions between species and adhesive type as well as cure and adhesive type were indicated. Although not included, mean response plots for significant interactions can be graphed to aid in visualization of treatment trends.

Dry MOR–species by adhesive interaction. — The species by adhesive interaction showed no significant difference between keruing-RF and keruing-PU/AEP in dry bending, both being in the highest bending strength combination grouping (**Table 4**). However, the keruing-PU/AEP combination was not significantly different from many other combinations. In summary, these end-joint test results show keruing as having the highest dry bending strength of the species when bonded with RF and PU/AEP adhesives. When soy was added to the bondline with RF, a significant reduction existed in dry bending strength for all three species.

Dry MOR–cure by adhesive interaction. — The LSMeans analysis for the dry MOR cure by adhesive interaction showed more clear-cut results than did the analysis of the species by adhesive interaction, in that no treatment combination groups for this interaction overlapped (**Table 5**). No significant differences among heat cure-RF, cold cure-PU/AEP, and cold cure-RF in dry bending strength existed, each being in the highest grouping. Next, the heat cure-PU/AEP combination was significantly different than all other combinations. The lowest dry bending strength and significantly different group included the cold cure-RF/Soy and heat cure-RF/Soy. Again, these results show the detractive effect of the soy on the RF honeymoon assembly. The PU/AEP adhesive was the only one found to have a significant difference between heat cure and cold cure. This difference is probably only coincidental because of the curing nature of the PU/AEP adhesive. Preliminary tests on the PU/AEP adhesive pot life showed that the exothermic reaction produced an adhesive temperature of 60°C (140°F). The heat curing temperature applied was well below the temperature achieved by the curing adhesive alone.

The ANSI/AITC (1992) standard for structural glued laminated timber has no specific value for minimum strength requirements of end-joints. Rather, end-joints must only meet the minimum strength requirements of the qualification stress level or QSL, which is determined by the end use of the product. When RF adhesive finger-jointed versus solid lumber (from this study) were compared for dry MOR by two-point loading, the finger-jointed dry MOR was 69 percent of the solid lumber across the three-species. In this study the two-point loading MOR test results of solid lumber were about 10 percent higher than the published values for single (center)-point testing MOR results for solid lumber (USDA 1999). This higher number was attributed to the higher density (580 kg/m^3) of the "related" Douglas-fir lumber utilized in this study versus the published density (450 kg/m^3) in the literature for the same species.

Dry MOE–species by adhesive interaction. — The ANOVA for the dry bending test MOE showed no significant three-way interaction but did show a species by adhesive interaction to be significant. The LSMeans analysis for the species-adhesive interaction was also very clear-cut with no treatment

Table 6. — LSMean separation two-point dry bending test MOE, species by adhesive interaction.

Treatment combination	Mean	t-group[a]	COV[b]
	(GPa [psi])		
Keruing-RF/Soy	25.10 [3,640,025]	A	15
Keruing-PU/AEP	21.83 [3,165,601]	B	10
Keruing-RF	21.80 [3,161,012]	B	20
Douglas-fir-RF	15.75 [2,284,720]	C	16
Southern pine-RF/Soy	15.74 [2,283,555]	C	17
Douglas-fir-PU/AEP	15.63 [2,266,923]	C	22
Southern pine-PU/AEP	15.61 [2,263,392]	C	16
Southern pine-RF	15.28 [2,215,779]	C	19
Douglas-fir-RF/Soy	15.17 [2,200,306]	C	19

[a]Treatment combinations having the same capital letter are not significantly different following a t-test having a 0.05 level of significance.
[b]COV = coefficient of variation, which equals sample standard deviation expressed as a percentage of the sample mean.

Table 7. — LSMean separation two-point dry bending test WF, species by adhesive interaction.

Treatment combination	Mean	t-group[a]	COV[b]
	(%)		
Douglas-fir-PU/AEP	89	A	8
Douglas-fir-RF	84	A B	8
Southern pine-RF	84	A B	11
Douglas-fir-RF/Soy	84	A B C	12
Southern pine-PU/AEP	84	A B C	10
Keruing-RF	81	B C	9
Keruing-PU/AEP	77	C	14
Southern pine-RF/Soy	67	D	19
Keruing-RF/Soy	46	E	29

[a]Treatment combinations having the same capital letter are not significantly different following a t-test having a 0.05 level of significance.

combination groups overlapping. By LSMean, the keruing-RF/Soy yielded the highest and significantly different dry bending MOE combination (**Table 6**). However, this result should not be evaluated by itself because this treatment combination was listed in the lowest grouping for dry MOR. Such conflicting results could be caused by the samples failing with a low load and very minimal deflection. The next group showing no significant dry bending MOE difference occurred between the keruing-PU/AEP and keruing-RF combinations. The lowest grouping included Douglas-fir-RF, southern pine-RF/Soy, Douglas-fir-PU/AEP, southern pine-PU/AEP, southern pine-RF, and Douglas-fir-RF/Soy. When RF finger-jointed lumber versus solid lumber (from this study) were compared by two-pointed loading, the finger-jointed dry MOE was 77 percent of the solid wood across the three species.

Dry bending WF–species by adhesive interaction. — The ANOVA for WF showed no significant three-way interaction but a significant species by adhesive interaction. The LSMeans results for the dry bending WF interaction were complex, with the three highest groupings overlapping and the two lowest groups significantly different from the rest (**Table 7**). The highest treatment group for dry bending WF included Douglas-fir-PU/AEP, Douglas-fir-RF, southern pine-RF, Douglas-fir-RF/Soy, and southern pine-PU/AEP. Southern pine-RF/Soy and keruing-RF/Soy were the lowest two significantly different dry-bending WF groups. In general, soy added to RF in bondlines did not enhance WF for any of the three species. More research is needed to explain this performance. PU/AEP yielded the highest WF with Douglas-fir but in general was comparable to RF among the three species.

In dry bending tests, all species/adhesive combinations met the ANSI/AITC (1992) WF requirements for wet use structural applications except for southern pine-RF/Soy (80% WF for softwoods) and keruing-RF/Soy (60% WF for dense hardwoods). All combinations, however, met the ANSI/AITC (1992) WF standard for dry use structural applications except southern pine-RF/Soy (80% for softwoods and 40% for dense hardwoods).

Finger-joint cyclic delamination/bending test

Three response variables (MOR, MOE, and WF) were measured for each sample in the cyclic delamination/bending test. All samples were observed for end-joint delamination after the cyclic delamination procedure, and no delamination was observed on any of the samples for each end-joint combination. The ANOVA for the MOR after cyclic delamination testing showed no significant three-way interaction. However, the ANOVA for this test showed a species by adhesive and a species by cure interaction. The results of both LSMeans procedures showed many treatment combination groups to be overlapped for the MOR after cyclic delamination testing (**Tables 8** and **9**, respectively).

Cyclic delamination/MOR–species by adhesive interaction. — For the MOR species by adhesive interaction after cyclic testing, keruing-RF and southern pine-RF were not significantly different from each other and were in the highest significance grouping (**Table 8**). The lowest grouping for MOR after cyclic delamination testing included southern pine-RF/Soy and keruing-RF/Soy. Comparison of dry MOR strength to MOR strength after the cyclic delamination procedure shows the severity of the vacuum-pressure-water soak-dry cycle test when used to evaluate adhesive bonds. As an average across the variables for dry MOR, strength was about 71 MPa, and MOR strength after the delamination cycle was about 48 MPa, approximately a 32 percent reduction. The species-adhesive MOR order remained similar for both test procedures.

Cycle delamination/MOR–species by cure interaction. — The highest MOR cyclic delamination treatment grouping in the LSMeans output for the species by

Table 8. — LSMean separation post delamination two-point bending MOR, species by adhesive interaction.

Treatment combination	Mean	t-group[a]	COV[b]
	(MPa [psi])		
Keruing-RF	60.78 [8,815]	A	19
Southern pine-RF	55.03 [7,981]	A B	19
Keruing-PU/AEP	51.42 [7,458]	B C	22
Douglas-fir-RF	49.39 [7,163]	B C	23
Southern pine-PU/AEP	47.13 [6,835]	C	16
Douglas-fir-PU/AEP	45.54 [6,605]	C D	21
Douglas-fir-RF/Soy	43.96 [6,376]	C D	22
Southern pine-RF/Soy	40.10 [5,816]	D E	16
Keruing-RF/Soy	35.32 [5,123]	E	23

[a]Treatment combinations having the same capital letter are not significantly different following a t-test having a 0.05 level of significance.
[b]COV = coefficient of variation, which equals sample standard deviation expressed as a percentage of the sample mean.

Table 9. — LSMean separation post delamination two-point bending MOR, species by cure interaction.

Treatment combination	Mean	t-group[a]	COV[b]
	(MPa [psi])		
Southern pine-Heat cure	50.61 [7,340]	A	20
Keruing-Cold cure	49.75 [7,216]	A B	23
Keruing-Heat cure	48.60 [7,048]	A B C	39
Douglas-fir-Cold cure	47.87 [6,942]	A B C	27
Douglas-fir-Heat cure	44.72 [6,486]	B C	15
Southern pine-Cold cure	44.22 [6,414]	C	22

[a]Treatment combinations having the same capital letter are not significantly different following a t-test having a 0.05 level of significance.
[b]COV = coefficient of variation, which equals sample standard deviation expressed as a percentage of the sample mean.

cure interaction included southern pine-heat cure, keruing-cold cure, keruing-heat cure, and Douglas-fir-cold cure (**Table 9**), with southern pine-heat cure having the highest MOR average. The occurrence of this species by cure interaction has many possible explanations. Many variations exist among the species in this experiment, including penetrability of the species, density, and extractive content. Adding heat to keruing for example will cause the natural wood resins (extractives) to flow to the surface, which in turn can affect how the adhesive performs.

Cyclic delamination/MOE. — The ANOVA for the MOE after the cyclic delamination showed no three-way interaction, no two-way interaction, and only one main effect. The main effect found to be significant was species. The LSMeans showed that keruing was significantly the highest species for MOE after water treatment (**Table 10**). Douglas-fir and southern pine were not significantly different from one another for MOE after water treatment.

Cyclic delamination/WF. — The ANOVA procedure for the third variable measured, WF, showed no three-way interaction, no two-way interaction, and two main effects after the cyclic delamination test. The main effects found to be significant were species and adhesive. Each species was found to be significantly different from the others after the LSMeans analysis in the following order: Douglas-fir, southern pine, and keruing (**Table 11**). The WF results after the cyclic water treatment were 6.7 percent higher than for the dry WF results, with most of this variation occurring with keruing (68% WF dry versus 75% WF after accelerated aging). This difference in WF may have been due to the MOR strength being less after the accelerated-aging treatment, thus not stressing the adhesive bondline to the same degree, or the effect of redrying the water-soaked lumber. One important feature was that no joint delamination occurred for any of the cyclic delamination samples.

For the WF adhesive main effect, the LSMeans showed that the RF and PU/AEP adhesives were in the highest significance group after the cyclic delamination test (**Table 12**). The RF/Soy adhesive yielded significantly lower WF than the other two adhesives. One explanation for the RF/Soy adhesive lower performance is that the delamination procedure, while not showing any bondline delamination, may have weakened the bond. Also, the RF/Soy adhesive ranked near the bottom in the dry WF test results (65% across the three species, **Table 7**). This overall low WF performance of the RF/Soy adhesive with dry wood could be due to soy isolates typically being recommended for high-MC (>30%) wood gluing applications. Because the finger-joints in this study bonded dry wood, the lower MC of the wood could have impeded the adherence (or wetting) of the soy component to the wood. In fact, a substantial portion of the cured adhesive remained on one side of the joint while bare wood showed on the other. This separation may be caused by inadequate adhesive penetration into the wood due to the soy component gelling so quickly with the RF component, or due to the very viscose, high molecular weight of the soy component as well as the wood cell lumen size.

Finger-joint tension test

The response variables collected from the tension test (parallel to the grain) were tensile strength and WF. The ANOVA analysis showed that no significant three-way interaction existed, and that a significant two-way species by adhesive interaction was present.

Tensile strength–species by adhesive interaction. — The LSMeans comparison for the species by adhesive interaction had many overlapping groups; however, it did show a single treatment combination (keruing-RF) to be significantly higher in tensile strength (**Table 13**). Because keruing has the highest density of the three species in this study, it would be expected to have high strength characteristics. The lowest tension strengths were Douglas-fir-RF/Soy, southern pine-RF/Soy, and keruing-RF/Soy, with keruing-RF/Soy significantly lower than all other groups. Tension tests in this study for parallel-to-grain RF-bonded finger-joints of Douglas-fir

Table 10. — LSMean separation post delamination two-point bending MOE, species main effect.

Treatment combination	Mean	t-group[a]	COV[b]
	(GPa [psi])		
Keruing	15.61 [2,263,685]	A	18
Douglas-fir	11.39 [1,652,271]	B	21
Southern pine	10.49 [1,521,052]	B	22

[a]Treatment combinations having the same capital letter are not significantly different following a t-test having a 0.05 level of significance.

[b]COV = coefficient of variation, which equals sample standard deviation expressed as a percentage of the sample mean.

Table 11. — LSMean separation post delamination two-point bending WF, species main effect.

Treatment combination	Mean	t-group[a]	COV[b]
	(%)		
Douglas-fir	84	A	12
Southern pine	79	B	12
Keruing	75	C	14

[a]Treatment combinations having the same capital letter are not significantly different following a t-test having a 0.05 level of significance.

[b]COV = coefficient of variation, which equals sample standard deviation expressed as a percentage of the sample mean

Table 12. — LSMean separation post delamination two-point bending WF, adhesive main effect.

Treatment combination	Mean	t-group[a]	COV[b]
	(%)		
RF	83	A	10
PU/AEP	81	A	12
Soy/RF	74	B	15

[a]Treatment combinations having the same capital letter are not significantly different following a t-test having a 0.05 level of significance.

and southern pine yielded about 57 percent of the strength of the published results of solid wood of the same species at 12 percent MC.

Tension WF–species by adhesive interaction. —The second variable measured for the tension test (parallel to the grain) was WF. The ANOVA for this variable again showed no three-way interaction and a species by adhesive two-way interaction. The LSMeans output showed that Douglas-fir-PU/AEP, southern pine-PU/AEP, Douglas-fir-RF, Douglas-fir-RF/Soy, and southern pine-RF were all members of the highest significant treatment combination for tension WF (**Table 14**). The lowest WF LSMeans grouping consisted of keruing-RF/Soy and keruing-PU/AEP. The overall average WF for the dry MOR (77%) was generally consistent with the overall average WF for tensile strength (82%).

Adhesive costs

While adhesive costs were not a consideration in setting up this study, economics is important for any technical issue. On a mix basis, the cost of the RF and PU/AEP adhesives was competitive, with the RF/Soy system being much cheaper than both (**Table 2**). When comparing applied glueline costs of the delivered adhesive solids content (service performance excluded), the PU/AEP system is the most economical delivered glueline followed by the RF/Soy and RF adhesives, respectively (**Table 2**). However, it took about 90 percent delivered solids content of the PU/AEP adhesive to reach a comparable performance to the RF system, which had a delivered

Table 13. — LSMean separation tension test tensile strength, species by adhesive interaction.

Treatment combination	Mean	t-group[a]	COV[b]
	(MPa [psi])		
Keruing-RF	71.20 [10,326]	A	17
Keruing-PU/AEP	63.76 [9,247]	A B	27
Southern pine-RF	61.08 [8,858]	B C	20
Southern pine-PU/AEP	56.63 [8,213]	B C D	15
Douglas-fir-RF	55.99 [8,120]	B C D	25
Douglas-fir-PU/AEP	54.64 [7,925]	C D E	26
Douglas-fir-RF/Soy	49.54 [7,185]	D E	26
Southern pine-RF/Soy	46.49 [6,743]	E F	24
Keruing-RF/Soy	40.70 [5,903]	F	32

[a]Treatment combinations having the same capital letter are not significantly different following a t-test having a 0.05 level of significance.

[b]COV = coefficient of variation, which equals sample standard deviation expressed as a percentage of the sample mean.

Table 14. — LSMean separation tension test WF, species by adhesive interaction.

Treatment combination	Mean	t-group[a]		COV[b]
	(%)			
Douglas-fir-PU/AEP	92	A		11
Southern pine-PU/AEP	92	A		8
Douglas-fir-RF	91	A		9
Douglas-fir-RF/Soy	90	A		11
Southern pine-RF	88	A		12
Keruing-RF	76	B		22
Southern pine-RF/Soy	74	B		22
Keruing-RF/Soy	67	B	C	33
Keruing-PU/AEP	65		C	24

[a]Treatment combinations having the same capital letter are not significantly different following a t-test having a 0.05 level of significance.
[b]COV = coefficient of variation, which equals sample standard deviation expressed as a percentage of the sample mean.

solids content of about 60 percent. Therefore, the RF adhesive is more performance efficient on a delivered solids basis than the PU/AEP adhesive.

Summary and conclusions

In summary, this research project showed several significant interactions for the response variables studied. The most prevalent interaction, occurring in six of the eight ANOVA procedures, was species by adhesive. Because of its frequency, this interaction appears to be very important. In most of the mean separations, the keruing-RF and keruing-PU/AEP combinations appear at or near the highest flexural and tension strength values of the treatment combination groups. The analyses having a species main effect show keruing to perform well. These analyses also show Douglas-fir and southern pine, while not as high as keruing, to perform well and usually not significantly different from each other. Keruing, southern pine, and Douglas-fir in various combinations with the RF and PU/AEP adhesives seemed to have the best performance after the delamination process. This result would indicate these combinations to be the better adhesive systems while the RF/Soy adhesive system does not perform as well.

Comparative strength values in this study of the finger-jointed lumber to solid lumber of the same species is very limited and qualified. The flexural tests in this study were by two-point loading and not single- (center-) point loading; however, the dry MOR of the RF-bonded finger-jointed lumber averaged 75 percent of the published values of solid wood in this regard (USDA 1999).

Many combinations involving keruing and/or the RF/Soy adhesive appeared to have the least amount of WF. Keruing's inclusion in this observation may be due to the fact that it is much denser (780 kg/m^3), and, therefore, a stronger species in some properties than Douglas-fir or southern pine (550 to 580 kg/m^3).

In conclusion, the overall performance of the RF adhesive bonded finger-jointed lumber appears to be the best in flexural and tensile strength of the adhesive systems evaluated in this study. In addition, keruing seems to be the best species for flexural and tensile strength of the three species evaluated in this study, with southern pine and Douglas-fir both performing well and not significantly different from one another. However, the PU/AEP adhesive could be considered a comparable system in most instances.

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