Integrity of Melamine Formaldehyde Bonds in Ponderosa Pine Cross-Laminated Timber: Isolating Adhesive Compatibility Effect

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Abstract

The integrity of melamine formaldehyde bonds in prototype cross-laminated timber (CLT) specimens was tested as part of a project on utilization of ponderosa pine (*Pinus ponderosa*) from forest restoration programs in the western United States. Bond integrity tests, block shear, and cyclic delamination are prescribed by ANSI/APA PRG-320 (ANSI/APA 2019) and ANSI 405 (ANSI 2018) to qualify new products. Of these, the cyclic delamination criterion is particularly challenging for layups developed in research labs and pilot plants. Delamination is often blamed on poor compatibility between adhesive and wood species, clamping pressure, or distribution of adhesive, neglecting other potential factors. One of the study objectives was to separate the effect of adhesive compatibility from other potential factors affecting bond integrity in CLT. Bonding integrity tests were conducted on prototype specimens bonded with melamine formaldehyde adhesive. Three types of specimens were studied: (1) specimens harvested from panels fabricated in an industrial CLT plant, (2) specimens harvested from panels fabricated in a pilot-line, and (3) short blocks cross-laminated from 102 by 102-mm sections. The short blocks included sections with juvenile wood and blue stain on bonded surfaces. All samples passed the PRG-320 block shear criteria. All short blocks passed the delamination criterion, demonstrating sufficient adhesive compatibility with the surfaces regardless of heavy presence of blue stain and juvenile wood. Specimens harvested from panels did not meet the delamination criterion. Delaminations developed near preexisting interlaminar gaps observed in prototype panels, which may be related to thickness variation or to inconsistent clamping pressure.

Forest restoration thinning programs, or selective removal of smaller or dead trees from the forest land in order to preserve superior trees, are one of the most effective ways to reduce the risk of catastrophic wildfires (Johnston et al. 2021). These programs are expensive and produce significant amount of low-value small-diameter logs. In Southern Oregon and Northern California such thinning programs generate large volumes of Ponderosa pine (*Pinus ponderosa*, marked as PP from this point on), which has no remarkable market in the region (G. Smith, Collins, personal communication, 2021). It is expected that the high costs of restoration programs may be offset by utilizing the lumber produced from PP logs in structural cross-laminated timber (CLT), a massive engineered wood panel consisting of three or more orthogonally arranged plies of lumber bonded with an adhesive. Custom CLT layups are proposed for use in low-rise modular construction (Bhandari et al. 2023, 2024; Jahedi et al. 2023). However, forest restoration programs tend to target small-diameter logs, which produce low-value lumber with high proportion of juvenile wood. Compared to mature wood, juvenile wood is characterized by substantial presence of knots, high grain angle, higher microfibril angle, and thinner cell walls, which in turn translates to higher rates of shrinkage and swelling (Kretschmann 2010). Differences in shrinkage rates between juvenile and mature wood present in the same piece of lumber is the primary cause for twist, bow, and crook after drying from green state. Lumber

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obtained from dead trees contains substantial amounts of blue stain, which affects the appearance of the lumber but does not significantly reduce the strength of wood (Miller 1980).

In adhesive-bonded engineered wood like CLT the concern is also the effect of presence of juvenile wood and blue stain on the formation of adhesive bonds and the resulting bond integrity. The standard criteria for bond integrity in CLT are stipulated in the North American standard for performance-rated CLT (ANSI/APA PRG 320, 2019) and include the resistance to shear and cyclic delamination. A limited study on cross-laminated lodgepole pine (*Pinus contorta* L.) specimens bonded with polyurethane resin (PUR) demonstrated that blue stain did not affect shear resistance or percentage of wood failure (WF) (Li et al. 2018). The study did not address delamination. Effect of presence of juvenile wood and blue stain on bond integrity in other common combinations of species and adhesive systems remains unknown.

The aim of this study was to assess the integrity of adhesive bonds in cross-laminated PP layups bonded with a two-component melamine–formaldehyde (MF) system.

Overview of bond integrity criteria in CLT standards

The North American standard for performance-rated CLT (ANSI/APA, 2019) introduced in 2012 adapted the procedures for the assessment of adhesive bond integrity and acceptance related criteria from the American Institute of Timber Construction (AITC, 2007) standard for glue-laminated timber, a mass beam product with a long history, but fundamentally different from CLT in that all laminations are bonded parallel to each other. These criteria include resistance of the bonds to short-term shear loads, assessed by block shear tests (ASTM D905-08; ASTM 2013), and to delamination assessed by soak–dry cycles (cyclic delamination tests per PRG320-2019 section 8.2.6; ANSI/APA 2019). These bond integrity qualification criteria were included with no major changes in all subsequent versions of PRG-320 (section 6.3.3, in PRG320-2019; ANSI/APA 2019).

In Europe, the product requirements for CLT are stipulated in EN 16351 (Timber structures–cross-laminated timber – requirements; EN 16351; EN 2021), which until 2021 has been used by European mass timber industry in its project versions (prEN 16351; prEN 2015). In contrast to PRG320, EN 16351 allows qualification of CLT bonding integrity, based on block shear as a reference method, with cyclic delamination remaining a nonmandatory option. Both PRG320 and EN 16351 permit tests on square cuts as well as on cylindrical specimens. There are some major differences in the pass/fail criteria as well. In EN 16351, the maximum allowable delamination in each specimen is 10 percent, excluding isolated small gaps and those that are caused by knots touching on the bond line. In PRG-320, the maximum allowable delamination in each specimen is 5 percent. For block shear test, EN 16351 requires a minimum of 1.25 MPa characteristic shear strength in all specimens and a minimum 1.00 MPa shear strength in each glue line, while PRG-320 relies primarily on visual assessment of WF percentage and mandates at a minimum the average of WF in all specimens to be 80 percent, and a minimum of 60 percent WF in each specimen. Shear strength is reported as a secondary criterion in AITC T107 standard to eliminate false high WF marks in specimens that exhibit significantly lower shear strengths compared to the published values for clear wood specimens of the same species.

Review of studies reporting assessment of adhesives and bond integrity in CLT

Two prior Oregon State University (OSU) studies on small-scale, laboratory-made, prototype hybrid CLT panels, one with lodgepole pine cores and Douglas-fir (*Pseudotsuga menziesii*) face layers bonded with PUR and phenol-resorcinol formaldehyde adhesive systems (Larkin 2017), the other on with PP cores and Douglas-fir faces bonded with MF adhesive (Lawrence 2017), met the PRG320 block shear resistance criteria but failed the cyclic delamination criterion. Loose thickness tolerances of laminations processed on a shop-grade planer were hypothesized as a potential cause for delamination (Lawrence 2017), but the study could not effectively separate the effect of compatibility of the adhesive with lumber surface chemistry from fabrication parameters to confirm this hypothesis. The later study included specimens from prototype hybrid panels fabricated at an industrial CLT line, which also failed the delamination tests (Lawrence 2017).

Challenges with meeting the delamination criteria are not uncommon. A review of 20 similar studies reporting assessment of adhesive bond integrity in CLT specimens published between 2015 and 2022 shows that delamination seems to be a persisting challenge in product development work on lab-fabricated CLT specimens. Table 1 presents a summary of the outcomes of block shear and delamination tests in prototype CLT specimens presented by the respective authors in either graphical or tabular format.

Even allowing for the fact that research projects routinely focus on prototypes and novel manufacturing options, where limited success rate may be expected, the comparison of reported failures in block shear test (seven based on PRG320 and three based on EN 16351) to those reporting failures in resistance to delamination test (15 based on PRG320 and 12 based on EN 16351) indicates that the latter appears a substantially more severe criterion. Then the larger proportion of failures reported for delamination tests following PRG320 compared EN 16351 seems to reflect the difference in the qualification delamination thresholds (5% vs. 10% respectively).

Of the papers that discussed potential sources contributing to observed bond integrity failures, 41 percent quote incompatibility between the adhesive and surface chemistry of the lamination species, 64 percent quote fabrication parameters related specifically to adhesive bond formation such as uniformity of adhesive distribution, clamping pressure or press time, and only two hinted at the thickness tolerances in lamstock (Sikora et al. 2015, Lawrence 2017). Improved diagnostics should help in discriminating between cases where the bond integrity failures are caused by adhesive compatibility and issues related directly to the bond formation from preventable issues generated elsewhere in the fabrication process. Therefore, this study had the following objectives:

1. to develop a methodology to separate the effects of adhesive compatibility from thickness variability and other fabrication factors, and
2. to determine the compatibility of MF adhesive system with CLT panels made of PP lumber from logs harvested in restoration programs.

Table 1.—Summary of the reviewed projects reporting bond integrity of prototype CLT laminations.

Project cited	Species	Block shear criterion[a] EN 16351[b] (>1.25 MPa)	Block shear criterion[a] PRG-320[c] (>80% WF)	Delamination criterion[a] EN 16351 (>10%)	Delamination criterion[a] PRG-320 (>5%)
Mohamadzadeh and Hindman 2015	Yellow poplar (*Liriodendron tulipifera*)	Pass	Fail	Pass	Pass
Hindman and Bouldin 2015	Southern pine	Pass	Pass	Fail	Fail
Hovanec 2015	Yellow poplar (*Liriodendron tulipifera*)	N/A[d]	Pass	Pass	Pass/fail[e]
Sikora et al. 2015	Sitka spruce (*Picea sitchensis*)	Pass/fail	Pass	Fail	Fail
Liao et al. 2017	*Eucalyptus urophylla* and *Eucalyptus grandis*	Pass	Pass/fail	Fail	Fail
Larkin 2017	Lodgepole pine (*Pinus contorta*), Douglas-fir (*Pseudotsuga menziesii*)	Pass	Pass/fail	Pass/fail	Pass/fail
Sharifnia and Hindman 2017	Southern yellow pine	Pass	Pass	Not tested	Not tested
Lawrence 2017	Ponderosa pine (*Pinus ponderosa*) Douglas-fir (*Pseudotsuga menziesii*)	Fail	Fail	Fail	Fail
Wang et al. 2018	Hem-fir	Pass	Pass	Pass/Fail	Fail
Dugmore 2018	*Eucalyptus grandis*	Pass	Pass	Fail	Fail
Lu et al. 2018	*Eucalyptus urophylla* and *Eucalyptus grandis*	Pass	Pass/fail	Pass/fail	Pass/fail
Arbelaez et al. 2020	Salvaged Douglas-fir (*Pseudotsuga menziesii*)	Pass	Pass	Fail	Fail
Mohd Yusof et al. 2019	*Acacia mangium*	Fail	Fail	Fail	Fail
Brunetti et al. 2020	Beech (*Fagus sylvatica*) L. and spruce (*Picea abies*)	Pass	Pass/fail	Fail	Fail
Kim 2020	Japanese larch (*Larix kaempferi*), Korean red pine (*Pinus densiflora*)	Pass	Pass	Pass	Pass/fail
Yusoh et al. 2021	Four tropical hardwoods: Batai (*Paraserianthes falcataria*), sesendok (*Endospermum malaccensis*), rubberwood (*Hevea brasiliensis*) and kedondong (*Canarium sp.*)	Pass	Pass	Pass	Fail
Furtini et al. 2021	*Pinus oocarpa, Coffea arabica*	Not tested	Not tested	Pass	Pass
Ma et al. 2021	Sugar maple (*Acer saccharum*), white spruce (*Picea glauca*)	Pass	Pass	Not tested	Not tested
Snow et al. 2021	10 species	N/A	Pass	Pass	Pass
Muñoz et al. 2022	*Gmelina arborea, Tectona grandis*	Not tested	Not tested	Fail	Fail
% of projects reporting failures in one or more specimen groups[f]		19%	39%	67%	88%

[a] Based on data presented in the graphs and tables.
[b] EN 16351 = per EN 16351. 2021. Timber structures - Cross laminated timber – Requirements, Ref. No. EN 16351:2021 E
[c] PRG-320 = per American National Standards Institute/APA-The Engineered Wood Association 2019 standard for performance-rated cross laminated timber.
[d] Presented data not sufficient to make decisions on whether the criterion have been passed or failed.
[e] Projects included tests on groups of specimens fabricated with different factors and at least one of the groups met the criterion.
[f] Including all papers in the column except N/A or "not tested." The projects marked as "pass/fail" counted reporting failures. Each project was counted as one entry regardless of how many samples were tested.

Materials and Methods

The approach involved standard PRG-320 bond integrity tests conducted on prototype cross-laminated specimens bonded with the two-component MF adhesive and fabricated at three different scales: (1) harvested from full-scale CLT panels produced in an industrial manufacturing line, (2) harvested from pilot-plant–scale CLT panels produced at OSU, and (3) fabricated as lab-scale "short-block" specimens, or small square sections of planed laminations arranged in cross-laminated blocks.

While the first two types were standard delamination specimens harvested from CLT billets including multiple laminations in each layer, the short-block specimens were assembled by cross-laminating individual square sections of laminations, precluding the effect of imperfect contact due to thickness variation within layers that might occur in larger CLT billets. That way the effect of chemical compatibility between the MF adhesive system and the surfaces of PP laminations, adhesive component mixing ratios, spread rate, and curing dynamics can be effectively separated from that of thickness variation, which is much harder to control in prototype lab conditions. The short-block specimens included layers with juvenile wood and blue stain on bonded surfaces. All types of specimens were tested for resistance to delamination and block shear following PRG320-2019 procedures (sections 8.2.4-6) and assessed against the standard criteria (sections 6.3.3 a and b).

Materials

The material was nominal 2 by 6 PP lumber harvested, processed, and kiln-dried by the Collins lumber company, located in Lakeview, Oregon, performing contract forest restoration programs in Southern Oregon and Northern California. About 76 percent of the donated lumber (32.5 thousand board feet; MBF) was visually graded by the company following Western Wood Products Association grading rules (WWPA 2017) and fell in the following grades: No. 1 (3%), No. 2 (48%), and No. 3 (25%). The remaining 24 percent of the lumber, produced mostly from dead trees, was delivered ungraded. A more detailed description of the test material is provided in a related publication (Jahedi et al. 2022).

All laminations were planed within 48 hours prior to the CLT production following the adhesive manufacturer's guideline and PRG320-2019 requirement.

PRG-320 standard specifies the maximum acceptable thickness variation along CLT laminations at ±0.30 mm and ±0.20 mm when measured across the width of the lamination at every 305 mm along the piece (ANSI/APA, 2019). However, thickness variations in prototype or commercial CLT laminations are rarely reported.

In this study, lumber designated for the production of test layups was surface planed on four sides on an industrial grade planer (LeaderMac, Blaine, Washington) with adjustable compression rollers to straighten pieces with moderate twist or bow. Pieces with excessive twist, cup or bow (about 0.5% of the total) were excluded to avoid overplaning. The planer was fitted with new cutting blades and fine-tuned before the process.

Thickness variation was measured on a sample of 12 straight boards planed to the target thickness of 34.29 mm. The thickness was measured on both edges at 36 points along each of these pieces using a ±0.01-mm caliper (864 measured points in total). The average deviation of all measured points from the target thickness was −0.01 mm (with a standard deviation of 0.09 mm and a maximum deviation of 0.53 mm).

In absence of a PRG320 specific definition of thickness tolerance, in this study, thickness variation in laminations is defined as the difference between the maximum and minimum thicknesses measured along one edge or on opposite edges of a piece. Thickness variation along the lamination exceeding the 0.30-mm tolerance was detected in 7 of the 12 pieces (58%) (average variation was 0.01 mm with a standard deviation of 0.09 mm, and the maximum variation of 0.83 mm). Thickness variation across the lamination exceeding the 0.20-mm tolerance was detected in 8 of the 12 pieces (67%, average variation was 0.04 mm with a standard deviation of 0.11 mm, and the maximum measured variation of 0.41 mm).

The goal of thickness measurements was to achieve a general assessment of the variations based on a sample of the population used for manufacturing. Laminations that were measured for thickness variations and showed variation higher than allowed by PRG320 tolerances were not included in the production of test specimens, we should assume that the 12 measured laminations were representative of the geometrical variations in all planed laminations used for the fabrication of the test material. Consequently, we should allow that more than 50 percent of these laminations would not pass the PRG320 thickness tolerances despite aggressive planing on a pilot-scale industrial planer. Thickness tolerances in laminations planed for panels fabricated by the industrial partner have not been measured.

This finding highlights the challenge the research labs, either using shop planers or even pilot-scale semi-industrial planers, may face in producing laminations of consistent thickness and may support the hypothesis that poor control of thickness variation may be responsible for some of the delaminations reported in studies collected in Table 1.

Fabrication of block shear and delamination specimens

Three types of cross-laminated specimens were fabricated for the assessment of bond integrity:

1. Specimens sampled from five-ply 3.0 by 5.5-m (10 by 18-ft) prototype CLT panels, with random assignment of grades in the layup, laminated in the industrial CLT production line at DR Johnson Wood Innovations in Riddle, Oregon (marked IP, 20 specimens).
2. Specimens sampled from five-ply 2.4 by 3.0-m (8 by 10-ft) prototype CLT panels, with random assignment of grades in the layup, laminated at the pilot plant in the A.A. Red Emmerson Advanced Wood Products Laboratory at OSU in Corvallis, Oregon (marked LP, 47 specimens).
3. Short block specimens assembled from three 102 by 102-mm (4 by 4-in) cross-laminated knot-free and straight-grained sections of planed laminations, fabricated in laboratory following manufacturer's prescribed spread rate, press cycle timing, and cured under 0.68 MPa (consistent with the pressure used to fabricate billets from which LP and IP specimens were harvested). Once cured, the blocks were trimmed to standard block shear and delamination specimen dimensions. The effects of thickness variations were eliminated by laying up small sections individually so that the laminations did not bridge across blocks. The clamping plates were equipped with a rubber mat to ensure that the compression force was distributed evenly among the specimens. Two types of the short-block specimens were fabricated:
    - one with blue stain covering more than half of the bonded surface (marked SBB, 27 specimens);
    - the other with high content of juvenile wood, some including the pith on the bonded surfaces, but with no trace of blue stain (marked SBJ, 14 specimens).

In all samples, two-component MF adhesive systems (MF system 1263/9563; AkzoNobel, Amsterdam, Netherlands) were used. Fabrication parameters were selected following adhesive manufacturer's guideline (Table 2). Resin and hardener components were applied on the lamination surfaces separately at ratio of 100:100 and mixed when the surfaces were pressed together. Spread rates were adjusted depending on the environment temperature. Press cycle timing (open, close, and press time) varied slightly depending on the degree of automation available for each scale of fabrication.

In case of IP and LP samples, automated adhesive applicators with adjustable spread rates were used, in which the resin and hardener were applied in continuous parallel beads on one side of the bonding surface and mixed together once the layup was assembled and pressed. For SBB and SBJ samples, beads of resin and hardener were applied manually with syringes separately, one on the bottom and the other on the top face of the bond area and mixed together when layers were put in contact to form the block layup. The spread rate was controlled by applying a measured amount of the resin and the hardener while the square lamination sections were resting on a ±0.01-g Mettler Teledo PB1502-S scale. Besides the clamping pressure, other fabrication factors for IP samples made in an industrial plant were not shared.

Pressed specimens were then fabricated in a room with average temperature of 23°C ± 3°C and 45 ± 3 percent relative humidity. The LP and IP delamination and block shear

Table 2.—Summary of fabrication factors.

Sample	Plies	Ambient temperature (°C)	Spread rate (g/m^2)	Resin to hardener ratio	Close assembly time (min)	Press time (h)	Pressure (MPa)	Curing time (h)[a]
SBB[c]	3	23 ± 3	344–374[b]	100:100	30	24	0.68	0
SBJ	3	23 ± 3	344–374[b]	100:100	30	24	0.68	0
LP	5	23 ± 3	340	100:100	40	3	0.68	13
IP	5	n/n[c]	n/n	n/n	n/n	n/n	0.68	n/n

[a] Curing time refers to the conventional method of keeping the panels under reduced pressure (0.2 MPa) to stabilize the bonding.

[b] The prescribed spread rate for this fabrication conditions was 344 g/m^2. Since adhesive was applied manually, the amount exceeded for some bonds.

[c] SBB = short block with blue stain covering more than half of the bonded surface; SBJ = short block with juvenile wood, some including the pith on the bonded surfaces, but with no trace of blue stain; LP = prototype panel laminated at the pilot plant in the A.A. Red Emmerson Advanced Wood Products Laboratory; IP = prototype panel laminated in the industrial CLT production line at DR Johnson Wood Innovations; n/n = The company did not share this information with authors.

specimens were harvested from two corners and the center of the CLT panels following guidelines in PRG320-2019 section 8.2.4. Then specimens were trimmed to final standard block shear and delamination specimens, following the same guidelines (ANSI/APA 2019). As much as possible, sections with knots, wane, and holes were trimmed off to separate the effect of adhesive compatibility from that of natural wood defects.

Delamination test

The cyclic delamination procedure followed PRG-320 2019 guidelines (section 8.2.6). A Mettler Teledo PB1502-S scale was used to monitor the weight of specimens. All specimens were carefully inspected for preexisting bond issues. While none were found in SBB or SBJ specimens, interlaminar gaps have been found in eight, about 17 percent, of the LP specimens and in four, 20%, of the IP specimens (Fig. 1). On average, interlaminar gaps covered 0.55 percent of the bond line perimeter of LP and 0.71 percent of the IP bending specimens.

The specimens were marked, submerged in water in a 1.7-m^3 vessel, and subjected to a vacuum-pressure soak cycle consisting of a 70 ± 20 kPa vacuum stage for 30 minutes, followed by a 520 ± 20 kPa pressure stage for 2 hours. The saturated specimens were then placed in an oven with air circulation and constant temperature set to 70.0°C ± 0.1°C for about 13 hours until their weight was reduced to about 110 to 115 percent of their original weight before soaking.

After drying, the bond lines on four sides of the CLT blocks were inspected using a microscopic camera (Jiusion Magnification Endoscope, 640 by 480 pixels resolution). Images of areas with suspected delamination were taken for further analysis and to discriminate between delaminations and shallow WFs.

PRG-320 defines delamination as a separation in bonding due to failure of the adhesive, either caused by poor bonding or low strength of the adhesive itself (Fig. 2). Wood fibers attached to the adhesive layer indicate a shallow WF and do not count as delamination (Fig. 3). The length of delamination was determined to ±1 mm.

Delamination was calculated by dividing the sum of delamination lengths plus the preexisting interlaminar gaps by the sum of bond-line perimeter in all bond planes, and represented as a percentage. A sample meets the PRG-320 criteria if delamination in all specimens falls below 5 percent.

Block shear test

Tests for the resistance to shear followed the ASTM D905 block shear test method referred by PRG-320 2019 (section 8.2.5). Figure 4 shows the standard step specimen and test setup for block shear test. The dimensions of the bonding surfaces were measured using a ±0.01-mm caliper. An Instron universal testing machine, equipped with a 10-kN capacity load cell and accuracy of ±0.4 N, was used to load each bond surface to failure. The ultimate load was recorded.

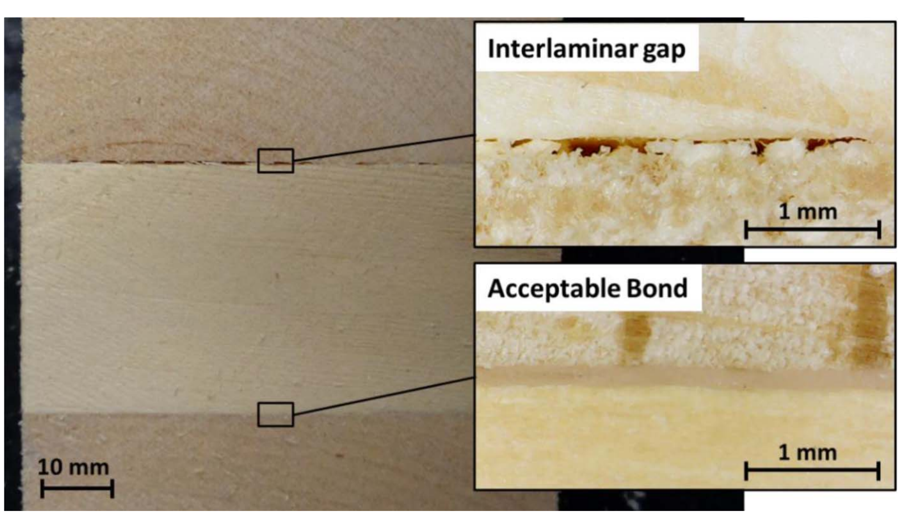

Figure 1.—Examples of interlaminar gaps found in the specimens prior to tests compared to an acceptable bond.

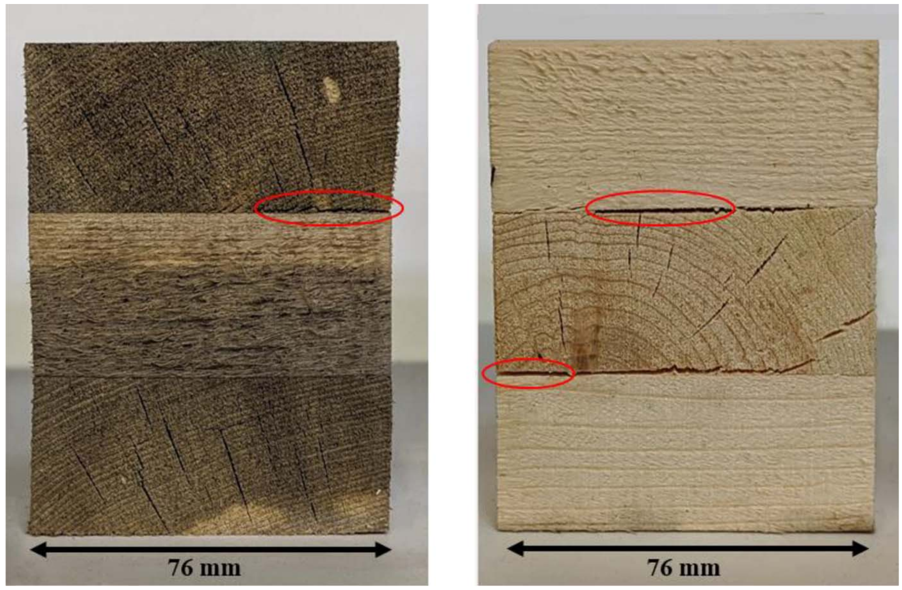

Figure 2.—Examples of delaminated specimen on a macro scale. (Left) Short block with blue stain covering more than half of the bonded surface. (Right) Short block with juvenile wood, some including the pith on the bonded surfaces, but with no trace of blue stain.

Upon completion of testing, the WF percentage was assessed on both sides of the fractured bond surfaces. Since the MF adhesive is transparent under natural light, as it can be noticed in Figure 5a, ultraviolet (UV) light was used to make the adhesive visible as shown in Figure 5b. VSC8000/HS digital imaging and a multiwavelength illumination device was used to analyze the samples. After preliminary scans, the best wood-versus-adhesive contrast was obtained by 312-nm UV light. Subsequently, this wavelength was used for the analysis of all fractured surfaces with a 4.8-megapixel camera set to a fixed exposure time (1 s) and with the auto light adjustment function turned off.

The images were processed using a modified version of a dedicated ImageJ script (Sept 2015), in which a light intensity threshold was used to count pixels identified as an adhesive failure and calculate the WF (Fig. 5c). The minimum WF percentage of two sides of a bond surface was picked as the representative WF of the bond surface. The optimal light intensity threshold for separating visible wood and adhesive surfaces was determined by comparing the traces of adhesive visible to the eye armed with a loupe with those detected automatically in the processed images in a training set of 20 specimens.

Results

Cyclic delamination test

The histogram in Figure 6 shows the distribution of delamination rates in restoration-program PP CLT specimens tested for cyclic delamination. All short-block specimens within SBB and SBJ samples fabricated blocks without bridging between adjacent laminations in a layer and met the PRG-320 delamination criteria. In specimens harvested from larger panels, four specimens in the LP samples and three in the IP samples exceeded the 5 percent delamination, failing the PRG-320 criterion. If compared to the EN 16351 delamination requirements, three LP specimens still failed, but all IP specimens passed the criterion (Table 4).

The interlaminar gaps were marked on the specimens prior to the soak–dry cycle. Examination of the marked sections of the bond lines revealed that all specimens failing the delamination criterion had preexisting interlaminar gaps. In most cases, the delaminations developed on either end of the marked interlaminar gaps.

Block shear test

Both IP and LP samples met the PRG-320 criterion. The average WF of all specimens within a sample are summarized

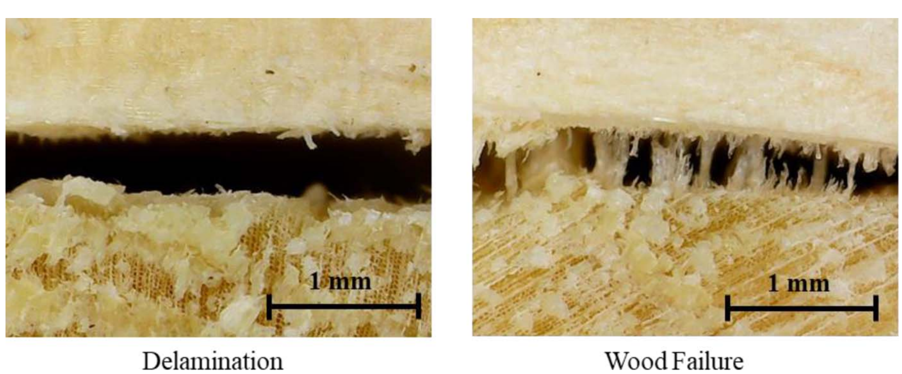

Figure 3.—Images of (left) delamination and (right) wood failure.

Figure 4.—Block shear test setup.

in Table 3. None of the specimens in either sample fell below 60 percent WF.

The cumulative distribution of the shear strengths determined in all bonding surfaces is shown in Figure 7. As the CLT plies are arranged orthogonally, the wood–adhesive interphase of the bond can fail on either side of the bond plane producing either a rolling shear (or shear in the plane perpendicular to the grains), in shear parallel to the grains or in a combination of these two.

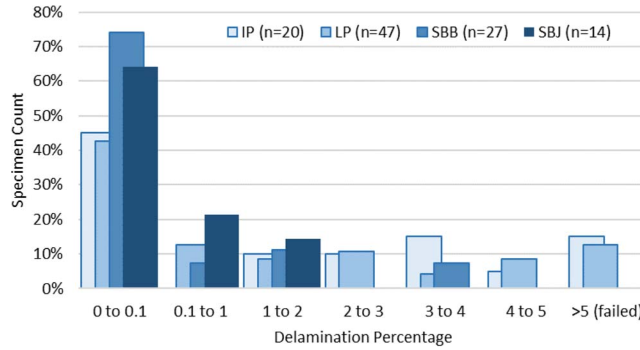

Figure 6.—Histogram results of cyclic delamination test of all sample samples. Number of specimens in each sample include: 20 IP, 47 LP, 27 SBB, and 14 SBJ. IP = prototype panel laminated in the industrial CLT production line at DR Johnson Wood Innovations; SBB = short block with blue stain covering more than half of the bonded surface; SBJ = short block with juvenile wood, some including the pith on the bonded surfaces, but with no trace of blue stain; LP = prototype panel laminated at the pilot plant in the A.A. Red Emmerson Advanced Wood Products Laboratory.

Bonds on all specimen surfaces were visually inspected to determine the failure mode. On the graph in Figure 7, bonds that failed predominantly in rolling shear are marked with plus signs (66% of all bonds tested). The data were compared with literature values of shear strength parallel to grain and rolling shear strength in clear PP wood (Bendtsen 1976, Kretschmann 2010), shown in the graph as dotted vertical lines. Most of the test data fell in between these two values, which indicates that the cross-laminated block shear specimens tended to fail due to a combination of shear parallel to the grain and rolling shear. One of the specimens with shear strength significantly lower

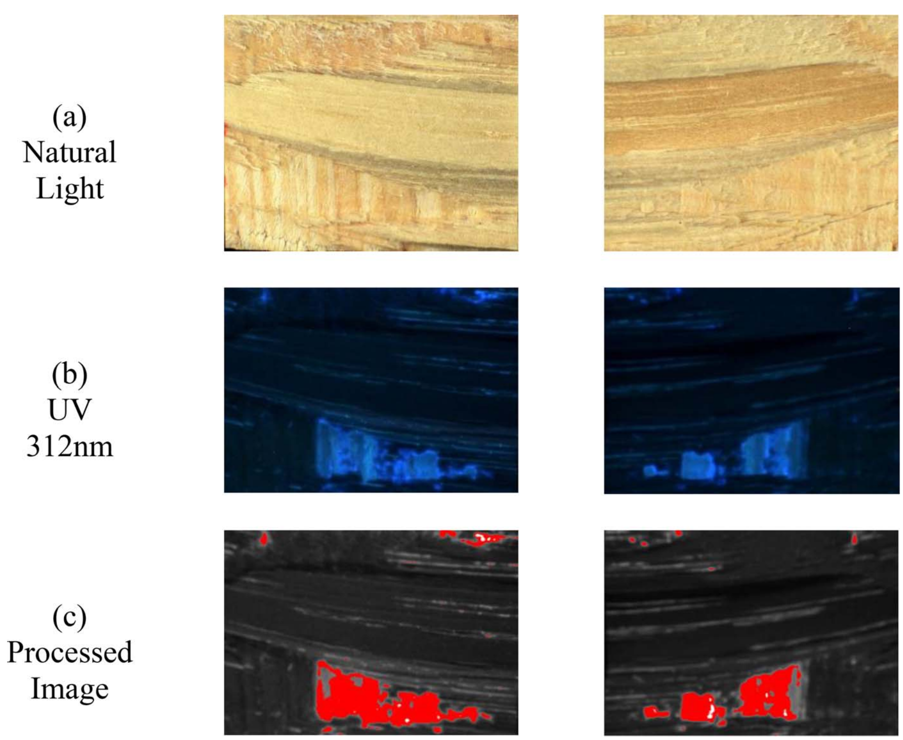

Figure 5.—Images captured from bonding surface of block shear specimens and the processed image after passing through contrast threshold.

Table 3.—Summary of block shear test results and comparison to the standard criteria.

	Tested samples		Standard criteria	
	LP	IP	PRG-320	EN 16351
No. of specimens	36 total	35 total	3 per panel	3 per panel
Average WF[a] of all specimens	90%	89%	80%	N/A[b]
Above 60% WF specimens	100%	100%	95%	N/A[b]
Characteristic shear strength	2.69 MPa	2.72 MPa	N/A[b]	1.25 MPa
Minimum shear strength	2.20 MPa	2.12 MPa	N/A[b]	1.00 MPa

[a] WF = wood failure. See Tables 1 and 2 for other abbreviation definitions.
[b] N/A = criterion not applicable in given standard.

than the benchmark rolling shear strength of clear PP wood was removed from the wood failure data pool (in accordance with AITC T-107).

The characteristic shear strength of the samples was calculated by finding the fifth percentile tolerance limit of the data, 2.69 MPa for the LP sample and 2.72 MPa for the IP sample, exceeding the EN 16351 minimum characteristic value of 1.25 MPa. None of the bonds fell below 1.0 MPa shear strength, meaning that both samples have met the EN 16351 criteria (Table 3).

In Table 4, the results of cyclic delamination and block shear tests for all samples are compared to the bond integrity requirements of PRG-320 and EN 16351 standards.

Discussion

All tested cross-laminated samples passed both PRG-320 and EN 16351 block shear criteria. No significant difference between IP and LP samples was found (based on one-way analysis of variance with confidence level of 0.95). However, four specimens in the LP sample and three in the IP sample exceeded the 5 percent delamination and consequently failed to meet the PRG-320 criterion. Evidence suggests that interlaminar gaps found in the specimens prior to the soak–dry cycle might have triggered excessive delamination, although not all specimens with preexisting interlamiar gaps failed. While in the particular example shown in Figure 1 the interlaminar gap might appear as a result of starved bond, dried adhesive clumps observed in these bond lines prove adhesive squeeze-out a sign of good adhesive transfer from one side to the bonded area to another. One possible cause for these preexisting interlaminar gaps might be the thickness variations in LP laminations detected in a random sample of the planed material that exceeded the PRG 320 tolerances. It is possible, but not certain at this point, that presence of the moderate twist and bow in the lumber allowed in the test material contributed to increasing the thickness variations even further. It is also possible that using higher clamping pressure might have mitigated that effect. Clamping pressure of 0.69 MPa was selected following guidelines of adhesive manufacturer.

It was also observed that all the LP specimens with delamination rates exceeding 5 percent were harvested from the center of the panels, while all specimens harvested from the corners of the panels passed PRG320 delamination criteria. Similar failures in laminates examined in parallel projects drew the attention to the possibility of uneven clamping pressure distribution due to the insufficient rigidity of the retractable tray used in the pilot plant press, which might have deflected under high pressures. Confirmation of such hypothesis requires further investigations. The combined effect of uneven clamping pressure and excessive lamination thickness variations after planing might

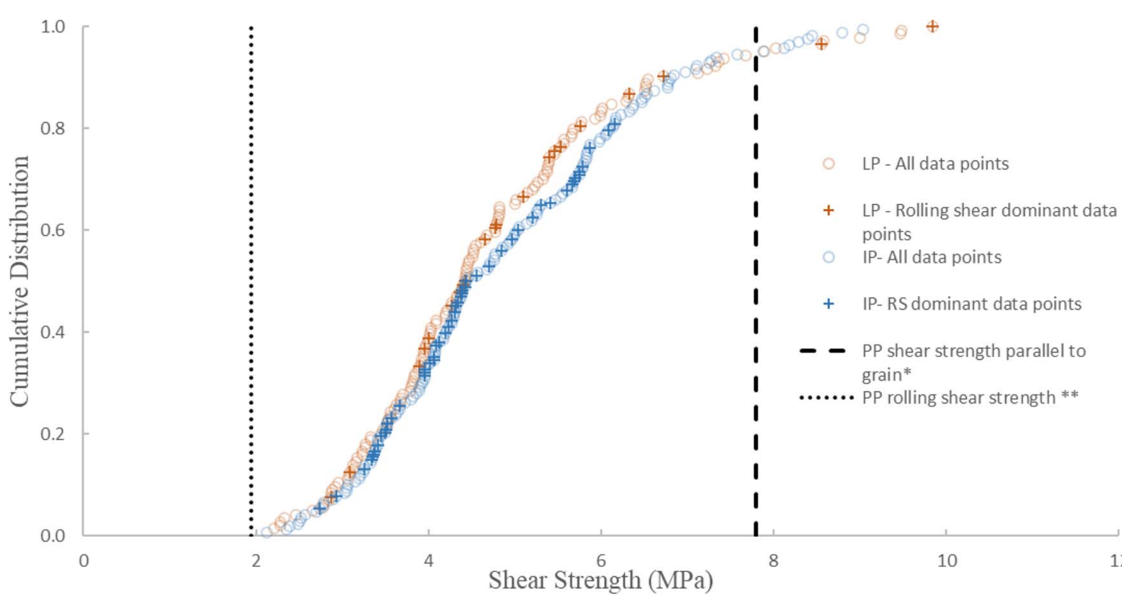

Figure 7.—Cumulative distribution of shear strength of specimens.

Table 4.—Test results compared to pass and fail criteria of American and European standards.

	Delamination requirements		Block shear requirements	
	PRG-320[a]	EN 16351	PRG-320	EN 16351
Sample	All specimens <5%	All specimens <10%	$>WF_{avg.}$	>1.25 MPa[b] >1.0 MPa[c]
SBB	Pass	Pass	Not tested	Not tested
SBJ	Pass	Pass	Not tested	Not tested
LP	Fail (4 out of 47)[d]	Fail (3 out of 47)[b]	Pass	Pass
IP	Fail (3 out of 20)[d]	Pass	Pass	Pass

[a] See footnotes in Tables 1, 2, and 3 for abbreviation definitions.
[b] Characteristic strength value per EN 16351.
[c] All bonds.
[d] Number of specimens failed compared to the total number of specimens tested in that sample.

explain the presence of interlaminar gaps in LP samples, but not in the IP specimens sampled from panels produced on the industrial line.

Given all that other parameters of creating the adhesive bonds were equal, the fact that all short CLT blocks (SBB and SBJ) passed PRG320 delamination criteria demonstrated good compatibility between MF adhesive and PP lumber from restoration forest programs despite substantial presence of blue stain or juvenile wood. This approach allowed effective separation of the effect of adhesive compatibility to the bonded lamination surfaces from issues related to other fabrication factors, substantially enhancing the diagnostics. However, at this point, identification of the specific fabrication issue resulting in areas of poor bonding remains a challenge.

Resistance to delamination is likely to remain a challenging criterion for projects focused on CLT product development with new combinations of adhesive systems and wood species. Future study should focus on simple methods for effective isolation of effects of other fabrication parameters, such as thickness variation in laminations, adhesive spread rate, clamping pressure, closed assembly time, and adhesive chemistry.

Conclusions

In this study a method of enhancing diagnostics of adhesive bond integrity failures in CLT was proposed in which the effects of adhesive compatibility were separated from other fabrication issues.

The short-block method was used to diagnose potential causes of delamination failures in prototype CLT panels in which PP laminations from logs harvested in forest restoration programs were bonded with MF adhesive.

Results of delamination tests on short-block specimens allow us to conclude that MF adhesive systems are compatible with restoration-program PP, regardless of the presence and amount of blue stain and juvenile wood, even though the material sampled from the large-scale, prototype panels failed to meet the delamination criterion.

While the specific cause for the existence of the interlaminar gaps detected in specimens harvested from large-scale CLT specimens used in this study could not be specifically identified, partial evidence collected on the pilot-scale fabricated panels pointed at either wide thickness variation in laminations, or inconsistent clamping pressure, or a combination of both. There were not enough data to speculate on the cause of interlaminar gaps in industrially made CLT panels.

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