Report

Cross-Laminated Timber Layup Tests Using Mixed Fir Species

Submitted by

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to the

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Contents

Project Background and Justification

California's 33 million acres of forestland is the largest land-based carbon sink in the state, with trees, shrubs, meadows, and forest soils sequestering carbon from the atmosphere. Decades of fire exclusion/suppression compounded by rising average temperatures and reduced precipitation have dramatically increased the size and intensity of California wildfires and bark beetle infestations, threatening the ability of forests to capture and clean water, serve as long-term carbon sinks, and support native biodiversity. To reverse these trends, system-wide changes in forest management and forest product innovation are imperative. To achieve desired goals, the state must increase the pace and scale of forest management and restoration efforts, build local capacity and strengthen regional collaboration, support forest product innovation, and promote the use of forest products.

Core challenges facing forest management activities include the lack of an economically sustainable demand for smaller diameter trees; trees killed by fire, insects, and/or disease; and woody biomass removed during forest management activities. A lack of demand for this material can result in sub-optimal management of forestlands and biomass to uses that are less economically, socially, or environmentally beneficial than desired.

In 2020-21, the Joint Institute for Wood Products Innovation (Joint Institute) funded an initial testing project that was carried out by the TallWood Design Institute (TDI) at Oregon State University (OSU) to investigate the suitability of white fir sourced from California for use in cross-laminated timber (CLT), a product that is rapidly gaining market share in the US non-residential and commercial building markets. These tests indicated that, while there are some lingering questions regarding delamination, the strength and stiffness characteristics of California white fir CLT are generally adequate for structural use in certain loading situations. As a follow-up to that work, the Joint Institute funded tests that examined the use of white fir in combination with Douglas-fir in the manufacture of 3-ply and 5-ply CLT, the results of which are reported here. This project builds upon the previous work in generating valuable technical data of use to forest industry manufacturing companies in evaluating potential entry into mass timber production. In doing so, it will aid in accelerating development of commercial markets for lesser utilized and restoration timber and assist in urgent efforts to reduce wildfire risk.

TDI, a collaborative organization based at OSU and in partnership with the University of Oregon, was contracted to carry out this project.

Project Team

TDI is one of the nation's first and only interdisciplinary research collaboratives focusing on the advancement of mass timber and structural wood products building solutions. 'Its primary activities are technical testing, timber construction research, and industry-focused education and outreach. Around 30 professors and their students from the OSU Colleges of Forestry and Engineering and the University of Oregon College of Design are involved, in addition to many external collaborators and stakeholders.

Iain Macdonald, TDI Director, served as overall coordinator of this project and principal point of contact for the Joint Institute. Panel layup and fabrication was carried out by Phil Mann, TDI's Technical and Operations Manager, Mark Gerig, Laboratory Technician/Machinist, and Ashley McCann, Undergraduate Lab Assistant. Testing was led by Byrne Miyamoto with the assistance of Mark Gerig, Ashley McCann, and Tyler Deboodt, Faculty Research Associate with the OSU Department of Wood Science and Engineering.

Project Deliverables

The project entailed completing the following deliverables**:**

1. Create a detailed work plan and timeline for project completion, including clear explanation of methods and product layups;
2. Arrange for procurement and transportation of all necessary project materials;
3. Conduct testing as necessary for the evaluation of the prototype mixed species panels against the PRG-320 product standard for CLT, with additional detailed analysis of any delamination effects;
4. Document fabrication and test procedures for product layups, including images and video clips where appropriate;
5. Create a report describing methodologies and results of testing, discussion of anticipated commercial potential for tested CLT configurations, and recommendations for further research and action; and
6. Disseminate project results using appropriate wood products, media, and other information channels. The California Board of Forestry and Fire Protection Joint Institute shall be acknowledged in all information distributed.
7. Test samples will be provided to the Joint Institute as requested.

Methodology

In 2020, 14 units of rough white fir 2x6 material were shipped to our Emmerson Lab from Sierra Pacific Industries in Northern California to be manufactured into CLT, processed into testing specimens, and mechanically tested. The results of that study were submitted to the Joint Institute in June of 2021 and approved by the Board of Forestry (BOF) in December that year, with a follow-up Addendum approved in March 2023. The remnants of that initial shipment of white fir were used in this test in combination with five units of 2x6 Douglas-fir supplied by Roseburg Forest Products.

Study Goals

The goal of the project was to perform a preliminary study of the viability of using white fir in combination with Douglas-fir in CLT. To evaluate the white fir as a potential raw material input for mixed species CLT, the entire process of manufacturing and processing of 3-ply and 5-ply CLT panels was performed at TDI's Emmerson Lab. The Douglas-fir material was used in the panels as the outer face layers to potentially increase the strength of the panels made from white fir. This could potentially lead to a new combination of CLT panels that could be used within a structure. Mechanical testing of the fabricated panels was performed in the College of Forestry's Richardson Hall structural testing lab.

The study consisted of three parts, the first being CLT panels made of Polyurethane (PUR) adhesive and tested following the Standard for Performance-Rate CLT (ANSI/APA PRG 320-2019). PUR was chosen due to its increased use in CLT within the U.S. and lack of Formaldehyde. These tests used six 3-ply CLT panels and six 5-ply CLT panels. The second part of the study was an in-depth analysis of delamination throughout an entire CLT panel, using Melamine Formaldehyde (MF) adhesive. MF is a common adhesive used in the production of CLT within the U.S. and was chosen to understand how a typical adhesive would behave with the white fir/Douglas-fir combination. Two panels of MF adhesive were manufactured for this study, one being a 3-ply panel and the other being a 5-ply panel. The last part of this study was to analyze the compatibility of white fir and Douglas-fir to the 2 types of adhesive. This study used sub samples, manufactured within a small controlled hydraulic press to create optimal specimens to ensure the adhesive compatibility with the wood species.

CLT Panel Fabrication

The manufacturing of the hybrid CLT panels followed a sequence of steps: sorting, milling, adhesive application, layup, pressing, and machining. The hybrid CLT panels used two species, Douglas-fir and white fir, within the panels. The Douglas-fir was used as face laminations, while the white fir was used for the interior laminations. To bond the material, two adhesives were used to create panels. The primary adhesive, which was used for the 12 main panels, was a Henkel PUR. The other adhesive, which was used for the two delamination study panels, was a Hexion MF. The MF panels were manufactured as part of an additional study investigating delamination, found in Appendix A.

Sorting

Except for one partial unit, the white fir material left over from the 2021 Joint Institute project was still wrapped and banded in its original packaging from the mill and had been stored in the lab’s covered, outdoor storage area. The Douglas-fir was shipped directly from Roseburg Forest Products and stored alongside the white fir. The Douglas-fir and white fir both had lumber grades of number 2 and better. Both white and Douglas-fir units were brought inside the lab a minimum of 48 hours before fabrication, with some units spending more time inside prior to sorting and fabrication depending on available floor space and the production schedule. Conditions in the lab were recorded prior to panel pressings with temperatures ranging between 61-63°F, and with relative humidity readings between 23-32%. The individual boards in each unit of lumber were visually inspected for obvious defects such as excessive bow, twist, and wane which could have potentially compromised the glue bond between the panels’ lamellas. Sub-standard boards were rejected.

Milling

Panels for the test were manufactured in two thickness, a 3-ply panel with a nominal thickness of 4.125” and a 5-ply with a nominal thickness of 6.875”. Overall panel dimensions were driven by the press capacity, which was 8’ x 10’.

Prior to machining, five boards of each species were selected at random to have had their moisture content checked with a pin moisture meter (see Table 1). As noted above, the white fir lumber used was rough sawn, while the Douglas-fir was surfaced on 4 sides (S4S), but all material was planed to a nominal dimension of 1.375” x 5.15” based on dimensions used in the previous Joint Institute project performed at TDI. For a few of the 5-ply panels towards the end of the fabrication run, an additional step was added to crosscut some boards for use as 8’ transverse lamellas. A Leadermac LMC 460 4-sided planer was used to dimension the lumber (Figure 1).

Figure 1: Leadermac planer.

Table 1: Average Moisture Content of the Panel Boards at the Given Temperature and Relative Humidity

Panel #	Adhesive	Lamellae	Average White fir MC%	Average Douglas-fir MC%	Temp (F)	RH%
1	MF	3-ply	9.7	15.1	63	32
2	MF	5-ply	11.0	16.5	63	32
1	PUR	3-ply	9.7	14.9	63	27
2	PUR	3-ply	NA	13.6	63	26
3	PUR	3-ply	10.2	12.6	63	36
4	PUR	3-ply	9.6	11.1	63	35
5	PUR	3-ply	8.9	10.0	63	32
6	PUR	3-ply	8.4	12.1	63	29
7	PUR	5-ply	8.6	12.6	63	23
8	PUR	5-ply	8.4	10.7	61	32
9	PUR	5-ply	8.9	11.8	61	31
10	PUR	5-ply	8.3	11.4	63	28
11	PUR	5-ply	9.6	13.9	61	31
12	PUR	5-ply	10.1	14.3	63	31

Adhesive Application

MF Resin Panels:

The two panels (3-ply and 5-ply) intended to be processed into samples for cyclic delamination testing were pressed using Hexion Ecobind 6500 resin with a Wonderbond catalyst. The individual boards were placed on a belt conveyor that passed underneath a curtain of the resin. A custom-made Apquip curtain-type resin applicator designed for two-part resins was used to ensure consistent spread rate throughout the panel. The resin and hardener were stored in a climate-controlled equipment room prior to pressing the 3-ply panel, while the resin and hardener were stored in the system before pressing of the 5-ply panel. In face bond applications, the recommended adhesive spread rate was 70 lbs/1000 ft^2 at temperatures below 80˚F.

PUR Resin Panels:
For the 12 panels using the PUR resin, a shop-made primer misting system was installed at the end of the planer outfeed that applied a PUR primer solution to the top and bottom of the boards as they came out of the planer (Figure 2A). Henkel's (Loctite PR 3105) primer was applied at a rate of 2 g/m^2, according to the manufacturer's instructions. The milled boards were then stacked using stickers of non-absorbent material to allow even airflow, then allowed to dry for a minimum of 10 minutes before resin application.

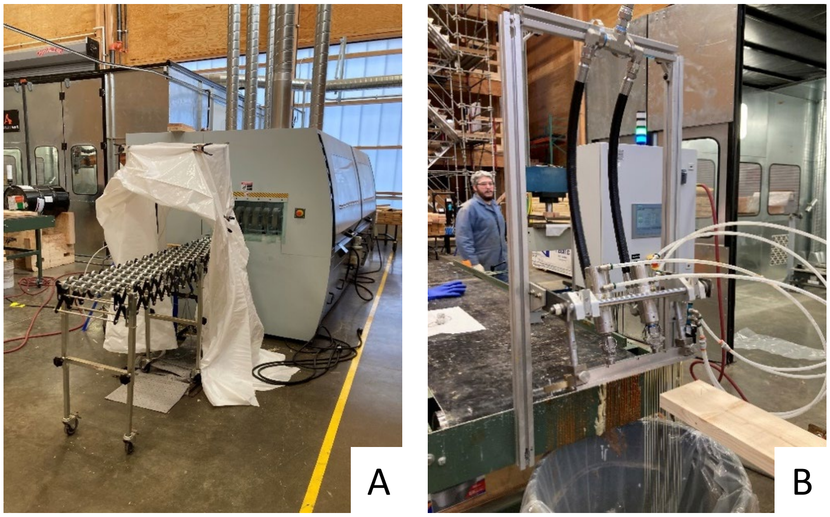


Figure 2: (A) Primer tent on planer outfeed; (B) PUR resin curtain applicator.

The adhesive resin used in the fabrication of the CLT panels was a Henkel, PUR adhesive (Loctite HB X602 Purbond). The recommended spread rate of 28 lbs./1000 ft^2 was verified by weight prior to resin application. As with the MF panels, the individual boards were placed on a belt conveyor that passed underneath a curtain of the resin, ensuring a consistent spread rate throughout the panel (Figure 2B).

Panel Layup

The layup method for both panel types and thicknesses was the same. From the outfeed of the adhesive applicator line, the boards were hand-loaded into the infeed tray of the Minda hydraulic press with 19 (10') boards on the bottom face in the longitudinal axis, 24 (8') boards in the center in the transverse axis, and another 19 (10') boards on the top face in the longitudinal direction in the case of the 3-ply panels. Boards were "flipped" end for end as they came out of the adhesive line to mitigate any possible cumulative effects of inconsistencies in milling or adhesive application.

Pressing

The press used was an 8' x 10' pilot-plant scale cold press, which was equipped with 12 linear actuators applying force to four plate steel platens. Once all the boards were placed in the tray, the press was closed and side pressure was applied parallel to the longitudinal axis using four hydraulic actuators to consolidate the laminae in the press tray. End pressure was applied to most panels using a shop-made caul and a forklift (Figure 3). This procedure could not be used for two 5-ply panels because longitudinal white fir boards that were not cut to length at the mill protruded slightly, preventing uniform contact from the caul.

MF Panels:
The assembly of the MF panels fell within the adhesive manufacturer's guidelines of a maximum total assembly time of 45 minutes and a minimum clamp time of five hours with lumber temperatures of 60-69˚F, with a post-cure time of 24 hours at 60˚F. The clamping pressure required was 125-150 psi with a preferred pressure of 150 psi.

PUR Panels:
The PUR manufacturer recommended a press pressure of 73-116 psi and for this operation the set value of the press was 115 psi. Since the adhesive manufacturer advises longer pressing times for temperatures below 68˚F (Table 1), panels were left in the press until the end of the workday to maximize clamping time, and actual pressing time was a minimum of four hours. Panels were stored in the lab overnight or longer before machining to allow for full curing of the resin.

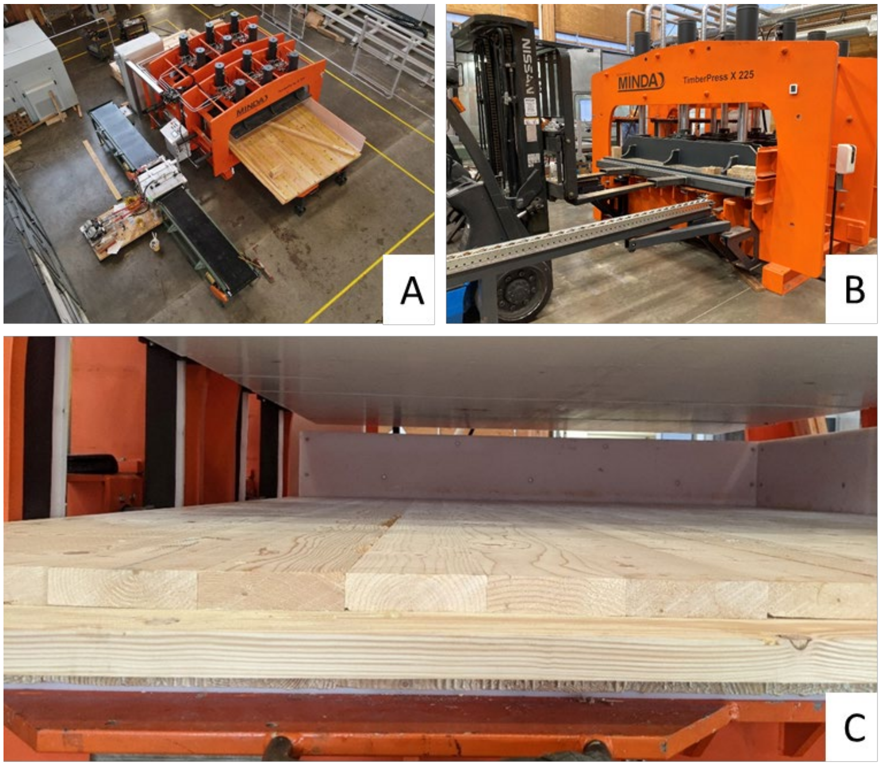
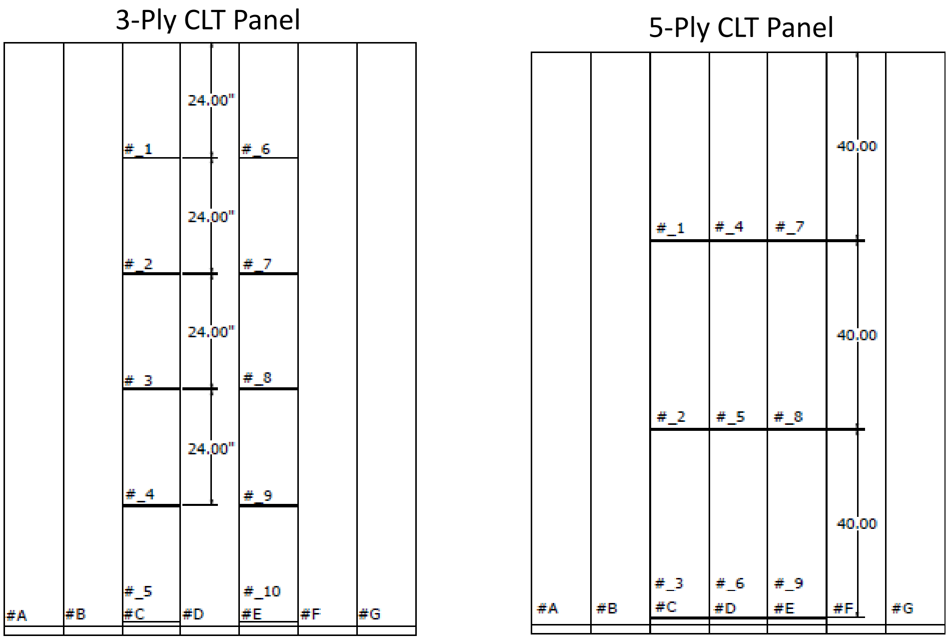


Figure 3: (A) Minda press and Apquip resin applicator; (B) Forklift applied end pressure caul; (C) CLT panel immediately after pressing.

Sample Fabrication

The process of creating sample sections of the manufactured panels for testing purposes was performed on a Biesse Uniteam Ultra, 5-axis, computer numerical control (CNC) machine, which is designed for mass timber material. Each panel was first squared on the CNC with the outer edges trimmed approximately 3 to 6” from the edge. The panels were then ripped into a total of seven 12” x 120” strips, and then labeled with the panel number (1 – 14) and the location of strip within the panel (A – G). Strips A, B, D, F, and G were put aside for long span testing, while strips C and E were cut down further for short span testing, shear block testing, and delamination testing. The cutting pattern can be seen in Figure 4.


3-Ply CLT Panel

5-Ply CLT Panel

Figure 4: Sample cutting list.

Additional Short Block Delamination Study

In addition to the 14 full panels, 12 short block samples were made with MF and PUR with dimensions of 3” x 3” with thicknesses of 4.125” or 6.875” depending on the number of plies used within the panel. The short block specimens consisted of four 5-ply MF adhesive specimens, four 3-ply PUR adhesive specimens, and four 5-ply PUR adhesive specimens. These short blocks were used as a method to validate the adhesive performance between the different wood species avoiding potential effects of thickness lamination variation and excessive twist that can contribute to delamination measured on specimens harvested from larger panels. To ensure that the adhesives would perform on white fir and Douglas-fir boards, the blocks were manufactured with limited defects and tight thickness tolerances to confirm a proper bond. The blocks were manufactured similarly to the full panels, with the boards first being planed to 1.375” x 5.15”, with areas of minimum defects cut to 5.15” x 5.15”. Once the blocks were cut to size, they were placed through the adhesive applicator following the manufacturers stated spread rate. Following the adhesive application, the cut blocks were stacked together alternating grain direction in each layer and placed. The samples were then moved to another laboratory for pressing in a Carver Auto Series press. This move resulted in longer open assembly times than the full panel samples, but were still within the adhesive’s allowable open assembly times. The blocks were then pressed to the manufacturers recommended pressure and time. Due to fabrication constraints, four sample assemblies had to be pressed simultaneously, which may have impacted the evenness of the press force. After the press time was complete the blocks were removed and stored in a climate conditioned room. Before testing, the blocks were trimmed down to a 3” x 3” size in plane. The blocks were then tested following the PRG 320 cyclic delamination test.

Testing

Four tests were performed to observe the panels’ mechanical properties as well as the strength of the adhesive bond between the boards. The first two tests observed the adhesive bond lines, block shear and cyclic delamination tests, using sections cut from different locations within the panel. The second two tests that were performed were flatwise long-span flexure and flat-wise short-span shear tests, which looked at both the bending and shear properties of the panel. Additionally, moisture content and specific gravity were calculated for each panel from sub samples of the shear and cyclic delamination specimens.

Shear Block and Cyclic Delamination Subsampling

The shear block and cyclic delamination specimens were obtained from sections 1, 3, 8, and 10 of the 3-ply panel and sections 1, 5, and 9 of the 5-ply panel (Figure 5). Even though about 45 pairs of delamination and shear block specimens have been harvested from the panels (15 from sections C1, 15 from D5, and 15 from E9), only three pairs from each section were used for qualification of each panel to follow PRG320-2019 sampling scheme (block specimens marked red for delamination tests and blue for block shear tests on the cutup diagram in Figure 5). The results from the remaining blocks were used for better understanding of the representativeness of specimens harvested following the standard.

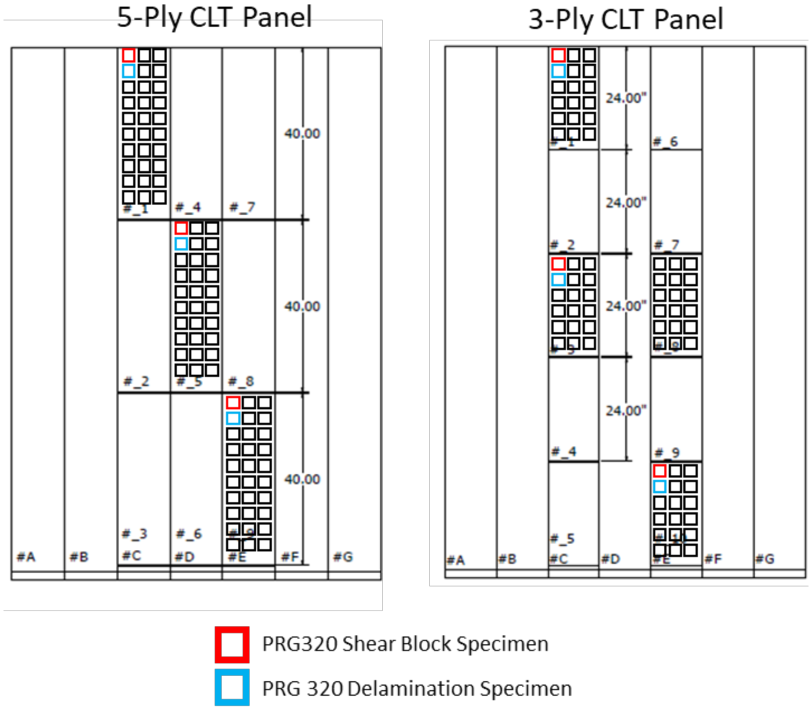


Figure 5: PRG320-2019 subsample locations for shear block and cyclic delamination specimens.

Shear Block Testing

Shear block samples were cut from the 3” x 3” blocks to then be cut into stair stepped samples following the ANSI/APA PRG320-2019 standard, which refers to AITC T107 for specimen geometry and to ASTM D905 test method. The samples were placed into an ASTM D905 shearing tool and loaded at a rate of 0.5 in/min, until failure. Once the sample failed, the bond area was sheared off completely to expose the bond fracture plane. The samples were visually evaluated to determine the percentage of wood vs. adhesive failure.

The three PRG320-2019 panel specimens can be seen in Table 2 and 3 for both the 3-ply and 5-ply, respectively. The tables show the average wood percentage failure and if it passed the standard criteria. PRG320 minimum requirements state that the average wood failure percentage in all specimens combined should be no less than 80% and that each specimen in the sample should have wood failure percent equal or greater than 60%. In addition to the three PRG320 tests, the remaining specimens from each section were tested following the same block shear standard. Each panel contained approximately 16-18 additional delamination specimens (Appendix B).

Table 2: Average 3-Ply Wood Failure %

Panel	Rip	Section	Block	Wood Failure (%)	Pass/Fail
1	C	1	1	87.5	Pass
1	C	3	1	100	Pass
1	E	10	1	95	Pass
2	C	1	1	100	Pass
2	C	3	1	100	Pass
2	E	10	2	90	Pass
3	C	1	3	100	Pass
3	C	3	1	100	Pass
3	E	10	1	85	Pass
4	C	1	1	100	Pass
4	C	3	2	100	Pass
4	E	10	2	100	Pass
5	C	1	3	100	Pass
5	C	3	1	100	Pass
5	E	10	1	100	Pass
6	C	2	1	100	Pass
6	C	3	1	100	Pass
6	E	10	2	100	Pass

Table 3: Average 5-Ply Wood Failure %

Panel	Rip	Section	Block	Wood Failure (%)	Pass/Fail
7	C	1	1	97.5	Pass
7	D	5	1	98.75	Pass
7	E	9	1	100	Pass
8	C	1	1	100	Pass
8	D	5	1	93.75	Pass
8	E	9	1	100	Pass
9	C	1	1	100	Pass
9	D	5	1	97.5	Pass
9	E	9	2	81.25	Pass
10	C	1	1	96.25	Pass
10	D	5	1	100	Pass
10	E	9	1	100	Pass
11	C	1	1	95	Pass
11	D	5	1	100	Pass
11	E	9	1	97.5	Pass
12	C	1	2	87.5	Pass
12	D	5	1	82.5	Pass
12	E	9	1	100	Pass

All 12 panels passed the PRG320-2019 shear block criteria, with the minimum average wood failure percent for all panels being 81.25%.

Cyclic Delamination

Delamination specimens were cut from section 1, 3, 8, and 10 for 3-ply and sections 1, 5, and 9 for 5-ply. These sections were cut and processed into 3” x 3” specimens, with thicknesses of 4.125” or 6.875” depending on the number of plies ieused within the panel. The cyclic delamination test was performed following the ANSI/APA PRG320-2019 section 8.2.6 for cyclic delamination. From the specimens cut, blocks with visible knots and interlamination edge gaps near the specimen’s edge were excluded from testing. The sample size for each panel ranged from 18-21 specimens, depending on how many were excluded.

The testing utilized a single soak-dry cycle, using a pressure/vacuum vessel and an air circulating oven. The testing procedure began by recording the initial weights of the samples before placing them into the vessel. The samples were submerged in water and then had a vacuum force applied for 30 minutes at approximately 12.3 psi. Once the 30-minute vacuum had elapsed, the vessel was then pressurized for two hours at approximately 75 psi. After the pressure cycle was complete, the specimens were removed from the vessel and placed into an air circulating oven at 160°F. The specimens would remain in the oven until they reached approximately 115% of the sample’s initial weights.

Once the specimens were dry, they were analyzed for delamination. The bond line of each specimen was examined for any delamination and then marked and measured. A percentage was calculated based on the measured delamination and the total length of the all the bond lines. The standard specifies that the criteria for each panel requires that the average delamination of all bond lines in each specimen must not exceed 5%. In the event that the average delamination of all bond lines in a specimen exceeds 5% but does not exceed 10%, a second specimen may be tested. If a second test was required, the next consecutive block was chosen.

Tables 4 and 5 display the results of the three PRG320 specimens for each panel, denoting whether the specimens passed or failed the standard’s criteria. Furthermore, all remaining specimens from each section underwent testing according to the same cyclic delamination standard. Each panel included around 16-18 additional delamination specimens (Appendix B).

Table 4: 3-Ply Delamination Samples

Panel	Rip	Section	Block	Pass/Fail
1	C	1	3	Pass
1	C	3	1	Pass
1	E	10	2	Pass
2	C	1	1	Pass
2	C	3	1	Pass
2	E	10	2	Pass
3	C	1	3	Pass
3	C	3	1	Pass
3	E	10	2	Pass
4	C	1	1	Pass
4	C	3	1	Fail
4	E	10	2	Pass
5	C	1	1	Pass
5	C	3	1	Pass
5	E	10	2	Pass
6	C	2	1	Pass
6	C	3	1	Pass
6	E	10	2	Pass

Table 5: 5-Ply Delamination Samples

Panel	Rip	Section	Block	Pass/Fail
7	C	1	1	Pass
7	D	5	1	Pass
7	E	9	1	Pass
8	C	1	1	Pass
8	D	5	1	Pass
8	E	9	2	Pass
9	C	1	1	Pass
9	D	5	4	Pass
9	E	9	8	Pass
10	C	1	1	Pass
10	D	5	4	Pass
10	E	9	1	Pass
11	C	1	1	Pass
11	D	5	1	Pass
11	E	9	2	Pass
12	C	1	1	Pass
12	D	5	1	Pass
12	E	9	2	Pass

The results revealed that panel 4 did not meet the standard criteria due to delamination. The specimen that led to the panels' failure exhibited delamination exceeding the allowable 5% threshold, and it exceeded the 10% allowance for retesting.

The data for the short block delamination samples can be found in Table 6. The short blocks had a total of 12 specimens made and underwent the same testing criteria as the standard delamination samples that were performed in the above tests.

Table 6: Short Block Delamination Test Samples

Sample ID	Adhesive	Laminations	Total Delam %	Pass/Fail
MF-5-1	MF	5	0%	Pass
MF-5-2	MF	5	0%	Pass
MF-5-3	MF	5	0%	Pass
MF-5-4	MF	5	0%	Pass
PUR-5-1	PUR	5	0%	Pass
PUR-5-2	PUR	5	0%	Pass
PUR-5-3	PUR	5	1%	Pass
PUR-5-4	PUR	5	0%	Pass
PUR-3-1	PUR	3	0%	Pass
PUR-3-2	PUR	3	0%	Pass
PUR-3-3	PUR	3	7%	Fail
PUR-3-4	PUR	3	2%	Pass

The short block delamination blocks had all MF specimens, and all 5-ply PUR specimen passed the PRG320 criteria. However, among the 3-ply PUR specimens, one specimen exhibited a total delamination of 7%, surpassing the 5% threshold. It's worth noting that although this specimen exceeded the 5% limit, it remained below the 10% threshold for retesting, which implies that it would qualify for retesting as stated in the standard.

Long-Span Flexure

The long-span flexure test specimens used the 12” x 120” strips that were cut from each panel. The samples were tested in 3rd-point bending following the ASTM D198-15 Standard Test Methods of Static Tests of Lumber in Structural Sizes. The samples were tested as a total span of 114” with a mid-span of 38” (1/3 of the total span). The total span and mid-span deflections were measured with string potentiometers, which were attached to a deflection measuring apparatus (Figure 6). Due to limitations of the press, the 5-ply CLT was not able to meet the span/depth ratio of 30 times the specimen depth. The total sample size for the 5-ply and 3-ply were 22 specimens and 30 specimens, respectively.

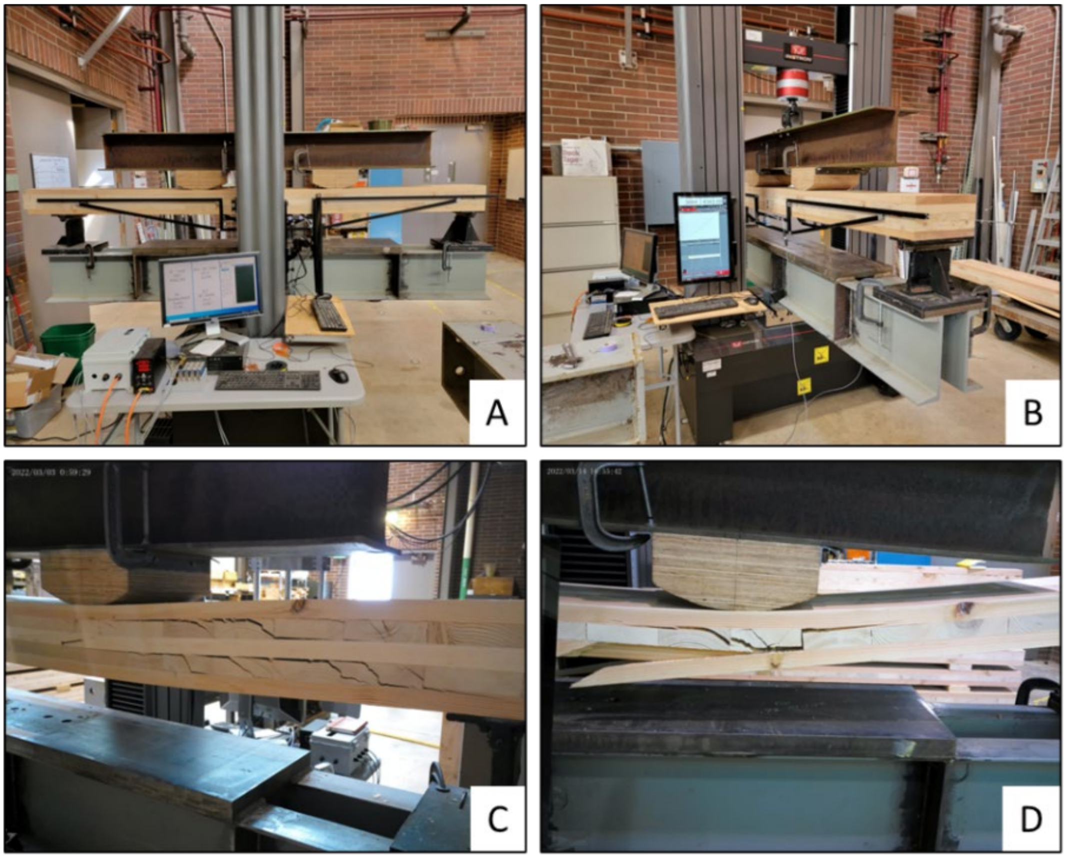


Figure 6: (A&B) Long-Span Flexure Test setup; (C) 5-ply sample failure (shear failure, due to 10 ft span); (D) 3-ply sample failure (expected failure in tension).

The samples were tested at a rate of 0.25 in/minute until failure and had deflections, load, and failure type recorded. The recorded data was then used to calculate the Modulus of Rupture (MOR), the Modulus of Elasticity (MOE), E_{app}, Effective Moment Capacity, and Effective Stiffness.

Formula 1 is the calculation for the MOR (psi):

$$MOR = \frac{P_{max}\, l}{bd^2}$$

Where P_{max} is the max load (lbf), l is the testing span (in), b is the width of the sample (in), and d is the thickness of the sample (in).

Formula 2 is the calculation used to find the MOE (E_{app})(psi):

$$MOE = \frac{Pll_{sf}^2}{4bd^3\Delta_{sf}}$$

Where P_{max} is the max load (lbf), l is the testing span (in), l_{sf} is the span between the two loading points, that is, shear-free deflection (in), b is the width of the sample (in), d is the thickness of the sample(in), and Δ_{sf} is the change in deflection within the shear-free span corresponding to the load (in).

Formula 3 is the calculation used to find the Effective Moment Capacity (FbS)(lbf-ft):

$$Moment\ Capacity\ = \frac{MOR * \frac{bd^2}{6}}{12}$$

Where MOR is the modulus of rupture (psi), b is the width of the sample (in), and d is the thickness of the sample(in).

Formula 4 is the calculation used to find the Effective Stiffness (EI)(10^6 lbf-in2):

$$Effective\ Stiffness\ = MOE * I$$

Where MOE is the modulus of elasticity (psi) and I is the moment of inertia.

Tables 7 and 8 illustrate the data summary for both the 3-ply and 5-ply CLT. In the tables the averages for the panels' Max Load, Modulus of Rupture, Modulus of Elasticity, Moment Capacity, and Effective Stiffness are shown.

Table 7: Panel Averages 3-Ply Cross Laminated Timber DF-WF

Panel #	Max Load (lbs)	Modulus of Rupture (psi)	Moment Capacity (lbf-ft)/ft	Modulus of Elasticity (psi)	Effective Stiffness (10^6 lbf-in^2)/ft
1	10,829	6,046	17,146	1,665,426	116.9E+6
2	10,433	5,825	16,518	1,486,279	104.3E+6
3	9,466	5,285	14,987	1,533,271	107.6E+6
4	9,061	5,059	14,346	1,486,696	104.4E+6
5	9,713	5,423	15,379	1,418,896	99.6E+6
6	9,043	5,049	14,318	1,368,730	96.1E+6

Table 8: Panel Averages 5-Ply Cross Laminated Timber DF-WF

Panel #	Max Load (lbs)	Modulus of Rupture (psi)	Moment Capacity (lbf-ft)/ft	Modulus of Elasticity (psi)	Effective Stiffness (10^6 lbf-in^2)/ft
7	20,322	4,085	32,177	1,527,339	496.3E+6
8	19,546	3,929	30,949	1,526,925	496.2E+6
9	20,874	4,196	33,051	1,431,432	465.1E+6
10	17,158	3,449	27,167	1,282,079	416.6E+6
11	20,415	4,103	32,324	1,419,111	461.1E+6
12	20,221	4,064	32,017	1,426,746	463.6E+6

Within the ANSI/APA PRG320-2019 section 8.5.3.2 the panels would need to meet certain criteria to be able to be qualified under a V2 grade. The effective stiffness of the panels would need to equal or exceed the published flatwise bending stiffness of 95 x 10^6 lbf-in^2 for the 3-ply. For the moment capacity the panels would need to equal or exceed the published bending moment capacity times 2.1, which would be 4263 lbf-ft for the 3-ply.

The overall average effective stiffness for all the 3-ply panels was 96 x 10^6 lbf-in^2. The panel's effective stiffnesses met the V2 grade published in the PRG320 standard. The total average moment capacity for all the 3-ply panels was 14,318 lbf-ft. The 3-ply panel's moment capacity met the V2 grade published in the PRG320 standard.

Due to the limitations of the press size, the 5-ply samples could not be manufactured to the test length of 17 feet. As a result, the 5-ply samples could not be directly compared to the PRG320. The short lengths of the 5-ply samples caused shear failures during the test rather than a flexural/tension failure within the sample (Figure 5).

Short-Span Shear

The short-span shear test specimens used 12" x 23" strips from the 3-ply panels and 12" x 38" strips from the 5-ply panels. The samples were tested in center point bending following the ASTM D198-15 Standard Test Methods of Static Tests of Lumber in Structural Sizes (Figure 7). The testing used a span to depth ratio of 5.1:1, making spans of approximately 21" and 35" for 3-ply and 5-ply samples, respectively. The total sample size for both thicknesses were 35 specimens, with a grand total of 70 specimens tested.

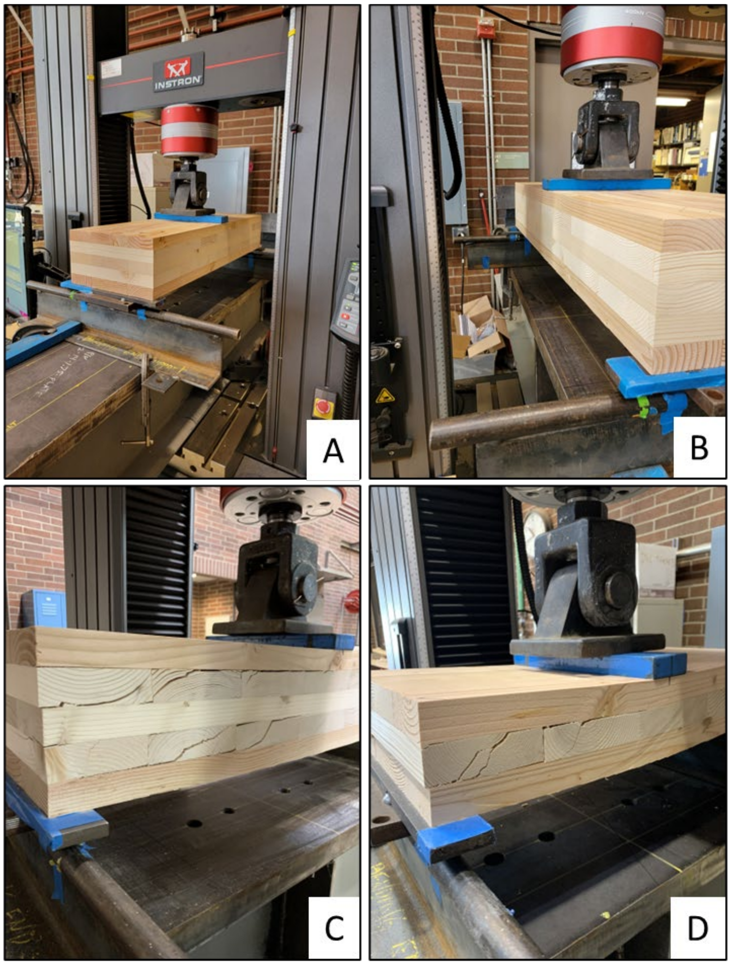


Figure 7: (A&B) Short-span shear test setup; (C) 5-ply shear failure; (D) 3-ply shear failure.

The samples were tested at a rate of 0.1 in./minute until failure, and had the actuator deflection, load, and failure type recorded. The recorded data was then used to calculate the shear stress (f_v) and the shear capacity in the minor direction.

Formula 5 is the calculation for the shear stress (Psi):

$$f_v = \frac{3P_{max}}{4bd}$$

Where Pmax is the max load, b is the width of the sample, and d is the thickness of the sample.

Formula 6 is the calculation for the planar (rolling) shear stress of the lamination in the CLT minor direction ($F_{s,minor}$):

$$F_{s,minor} = \frac{f_v}{3}$$

Where f_v is the shear stress in Psi.

Formula 7 is the calculation for the shear capacity in the minor direction (V_{s0}):

$$V_{s0} = F_{s,minor}\frac{2A_{gross,0}}{3}$$

Where $F_{s,\ minor}$ is the planar shear stress in the minor direction and $A_{gross,\ 0}$ is the gross cross-sectional area of the sample.

Table 9 and 10 illustrate the results of the flexure test. Both Tables 9 and 10 show the samples ID, Max Load, Shear Stress, and Shear Capacity can be found.

Table 9: Panel Averages 3-Ply Cross Laminated Timber DF-WF

Panel #	Max Load (lbf)	Shear Stress (psi)	Shear Capacity (Minor) (lbf/ft of width)
1	22,011	353	3,668
2	22,042	353	3,674
3	21,461	344	3,577
4	21,129	337	3,521
5	23,782	377	3,964
6	23,990	380	3,998

Table 10: Panel Averages 5-Ply Cross Laminated Timber DF-WF

Panel #	Max Load (lbf)	Shear Stress (psi)	Shear Capacity (Minor) (lbf/ft of width)
7	25,499	243	4,250
8	25,630	244	4,272
9	24,929	237	4,155
10	25,513	243	4,252
11	25,064	238	4,177
12	25,404	242	4,234

Similarly to the long-span bending tests, the short-span shear test follows the PRG320 section 8.5.4.2 criteria that the panels would need to equal or exceed the published shear capacity times 2.1. The published shear capacity times 2.1 for a V2 grade would be 1040 lbf/ft of width for the 3-ply and 3129 lbf/ft of width for the 5-ply.

The overall average shear capacity for all the 3-ply panels and 5-ply panels was 3733 lbf/ft of width and 4236 lbf/ft of width, respectively. Both panel types of shear capacity met the V2 grade published in the PRG320 standard.

Moisture Content and Specific Gravity

The specimens for both moisture content (MC%) and specific gravity (SG), also known as relative density, were taken from the 3” X 3” blocks that were cut from the short sections of the panel. A total of six specimens per panel were used to calculate both properties, MC% and SG. The specimens were tested following the ASTM Standards D4442 and D2395 for obtaining MC%and SG (ASTM 2020 & ASTM 2022). The specimens were placed into an oven set at 103°C for approximately 48 hours. After the 48 hours of drying were complete, the samples were removed and had their weights and dimensions recorded immediately. Below are the formulas for MC%and SG.

Formula 8 is the calculation for MC%*:*

$$MC\% \;= \frac{m_{wet} - m_{dry}}{m_{dry}} \times 100$$

Where m_{wet} is the original mass and m_{dry} is the oven dry mass in grams

Formula 9 is the calculation for Oven-dry SG:

$$S_o = \frac{Km_o}{V_o}$$

Where So is oven dry SG, K constant determined by units used to measure mass and volume, m_o is the oven-dry mass, and V_o is the oven-dry volume.

Table 11 represents the average six specimens per panel tested for MC% and SG. The table illustrates the wet (m_{wet}) and dry mass (m_{dry}) in pounds for each panel as well as the calculated MC%as a percentage and the SG.

Table 11: Average Mass, Moisture Content, and Specific Gravity for Each Panel

Panel (#)	# Plies (#)	m_{wet} (lbs)	m_{dry} (lbs)	Moisture Content (%)	Specific Gravity (unitless)
1	3	0.66	0.60	9.18	0.49
2	3	0.63	0.58	8.77	0.48
3	3	0.59	0.54	8.37	0.45
4	3	0.59	0.55	8.26	0.45
5	3	0.61	0.56	8.30	0.46
6	3	0.64	0.59	8.21	0.47
7	5	0.92	0.84	9.72	0.41
8	5	1.03	0.94	9.74	0.45
9	5	0.99	0.90	9.86	0.43
10	5	0.99	0.91	9.80	0.44
11	5	0.95	0.86	9.31	0.42
12	5	0.96	0.88	9.52	0.42

The total average MC% and SG for the 3-ply panels was 8.85% and 0.47, respectively. While the total average MC% and SG for the 5-ply panels was 9.66% and 0.43, respectively.

In comparison to a solid white fir 3-ply CLT panel, the hybrid white fir/Douglas-fir 3-ply panel had a specific gravity of 0.47, while a white fir panel had a SG of 0.4 (TallWood Design Institute 2023). This increase in SG is due to the addition of Douglas-fir into the panel, since Douglas-fir has a higher SG (0.48) than white fir (0.39) (Ross 2010).

Conclusions

Both the 5-ply and 3-ply CLT panels were fabricated using a combination of Douglas-fir lumber and white fir lumber, with a variety of mechanical and physical tests performed on the panels. The panel layup was comprised of Douglas-fir nominal 2 x 6 material for the face lamella and all white fir nominal 2 x 6 material for the core. Once pressed, the panels were cut into the proper sample dimensions and then tested.

The shear block specimens had wood failure above 80%, indicating that a proper bond was formed within all panels. The cyclic delamination specimens following the PRG320 criteria indicated that panel 4 would not pass the standard due to a large amount of delamination within the specimen found in section 3 of the panel. All other panels passed the PRG320 criteria for delamination. The assessment is based on sparse sampling scheme of three specimens per panel as required by the PRG320-2019 standard. For this study, block shear and delamination specimens were harvested and tested for better understanding of the consistency of bond integrity. These specimens show some block shear and delamination failures that would have not been detected using the standard sampling scheme.

The mechanical properties of the mixed Douglas-fir and white fir CLT exceeded the published values stated in ANSI/APA PRG320 for a V2 Grade. Both the flexure properties as well as the shear properties were calculated and compared to the ANSI/APA PRG320 tabulated values with the effective stiffness directly compared, and the moment and shear capacity compared to 2.1 times the tabulated values. As mentioned in the previous sections, the 5-ply long-span flexural samples could not meet the span-to-depth ratio since the laboratory press was limited to 10’.

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Appendix A: Delamination Diagnostics Study

This appendix describes a sub-study conducted in order to investigate the potential causes for the lingering questions regarding delamination in the CLT specimens fabricated on the Emmerson Lab pilot-line. Both the initial study reported in the current project described in June 2021 and 2023 Addendum, and the current project described in the main body of this report, revealed nontrivial numbers of specimens failing the PRG320-2019 delamination test criteria. In the current study, specimens with delamination exceeding 5% were found in samples harvested from medium-scale panels fabricated on the pilot line AND in one of the short block specimens fabricated in support of diagnosis of the root causes of the issue.

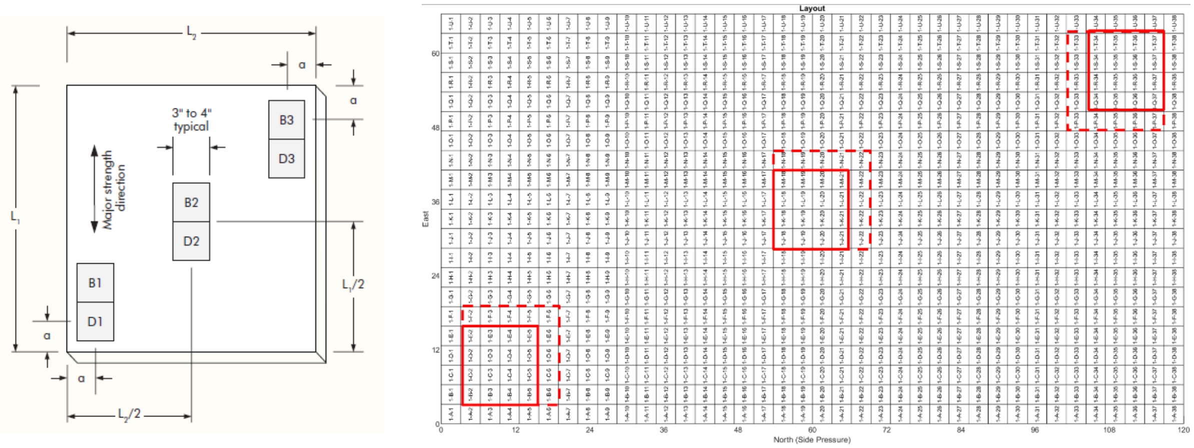
Adhesive bond integrity depends on many factors which include:

a) chemical compatibility between the adhesive system and surface chemistry of laminations;
b) moisture content of laminations (which is important for the chemistry of the adhesive bond formation and for the prospect of dimensional stability of laminations);
c) tight and consistent thickness tolerances in laminations within the same layer;
d) lamination surface activation (surface planing within a prescribed time interval of layup operation);
e) presence of inhomogeneities on the bonded surfaces of laminations (knots, tool marks, contaminations, skips);
f) presence of interlamination gaps in the delamination specimens (PRG320 2019 allows excluding delamination specimens containing more than one such gap);
g) in two-part adhesives a resin:hardener mixing ratio appropriate for the temperature and humidity of ambient air during the pressing operation;
h) adhesive spread rates;
i) pressing cycle timing (open time, closed time, and press time);
j) clamping pressure; and
k) un-pressed curing time.

In addition, the potential for detecting localized bond integrity issues in large CLT panels depends on a sampling scheme which should be adequate for the stochastic characteristic of the issue.

The standard PRG320 sampling scheme may leave very different options harvesting the delamination specimens from large industrial-sized panels compared to pilot-scale panels or small lab-scale cross laminated billets Appendix A Figure 1.

Except for the fundamental chemical compatibility between the adhesive system and the surface chemistry of the laminations (the intended target of the bond integrity tests), all other factors are related to the fabrication process and should be possible to account for and control, at least to some extent. Most of the factors listed above (d-j) are relatively easy to control and have been carefully accounted for, and documented, in this study. Two factors posing persistent challenges in lab- and pilot-line scale operations conducting most of the product prototyping research are adequate control of the variability of moisture content and thickness in laminations (b and c in the list above)[1].



Appendix A Figure 8. Standard PRG320 sampling scheme for delamination specimens allows more options in small lab-scale billets (left) than in larger test panels (right).

It should be also noted that the prescribed sampling scheme for bond integrity testing is often taken for granted. ANSI/APA PRG320 requires just three sets of block shear and delamination specimens per prequalification billet and a minimum of two specimens per shift for subsequent quality assurance. The areas of sampling are assigned in a way that leaves few options in small billets, but leaves substantial freedom in harvesting test specimens from larger panels (Appendix A Figure 1). The standard does not support the prescribed sampling scheme with any external reference or rationale and we are not aware of any empirical or theoretical study to back the scheme.

The goal of this sub-study was to conduct a comprehensive diagnostic of the bond integrity issues in the pilot-scale prototypes used in the main study, as revealed by failures in standard cyclic delamination tests (per ANSI/APA PRG320-2019). The specific objectives were to:

1. assess the adequacy of the standard specimen sampling scheme,
2. determine the actual extent of bond integrity issues in panels fabricated on Emmerson pilot-line;
3. determine the effect of the presence of knots and inter-lamination gaps (as well as the combination of both) in the delamination specimens on the outcome of the cyclic delamination tests.

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[1] Jahedi S., L. Muszyński, M. Riggio, S. Bhandari (2023): Integrity of Melamine Formaldehyde Bonds in Ponderosa Pine Cross-Laminated Timber. Isolating Adhesive Compatibility Effect, Forest Project Journal. In print

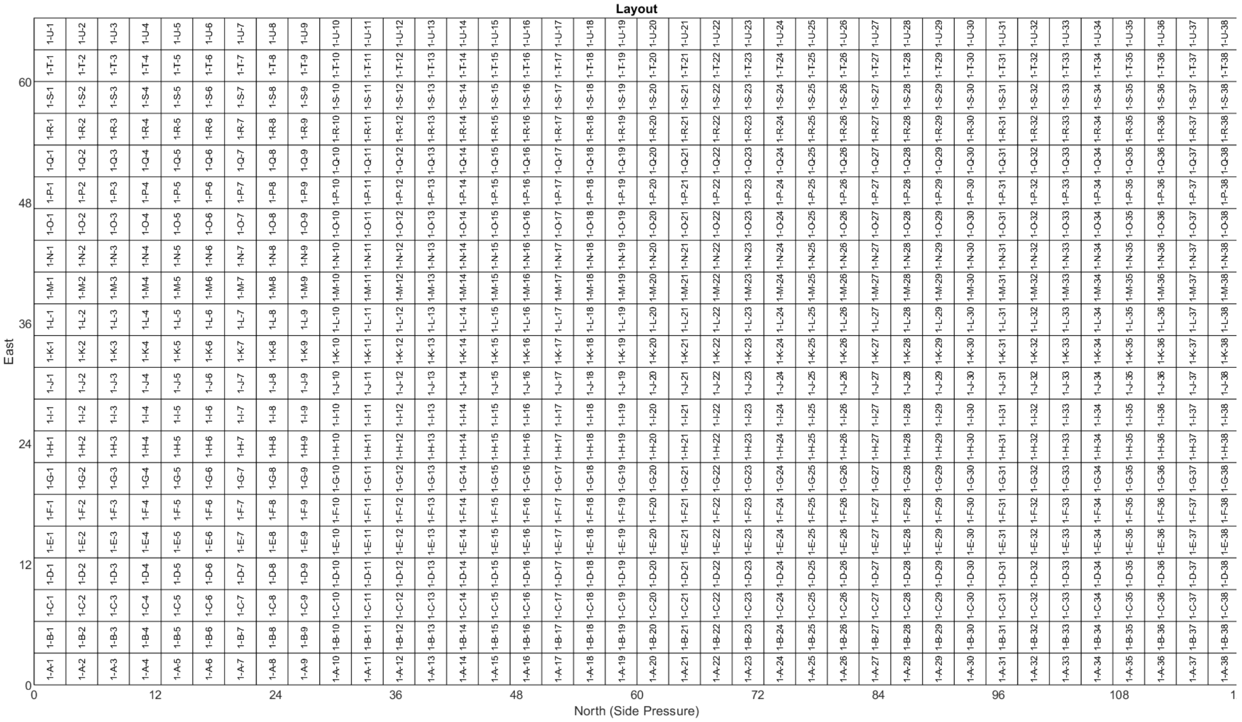
The general approach was to dissect two representative pilot-line scale panels (one 3-ply and one 5-ply) into standard delamination blocks, inspect all blocks for presence of inhomogeneities thought to affect bond integrity (items e and f in the list above), and examine correlations with actual outcomes of the standard cyclic delamination tests. The outcomes of this procedure presented as a “delamination map” on the contour of the test panels allowed for the assessment of the extent and topography of the issue. The delamination map was then compared with the known positions of knots and interlamination gaps to determine correlations and a potential for causation. The map was also used to assess the adequacy of the prescribed standard sampling scheme.

Materials and methods used to fabricate the two test panels for this sub-study are described in the main body of the report (in section CLT Panel Fabrication, referred to as panels # 1 and 2 bonded with MF adhesive in Table 1, and subsequently referred to as *MF panels)*.

Apart from the adhesive system used for these two panels, the main difference from other panels described in the main body of this report is specimen fabrication. Each panel was fabricated using the CNC described in the Fabrication section. The panels were ripped into 3” wide by 10’ long sections and then cross cut into 3”x3” specimens. Each specimen was labeled based on the panel and location within the panel, using 1 and 2 to represent the 3-ply panel and 5-ply panel, respectively. Following the panel identification, letters (A-U) were used to represent the 10’ ripped sections, followed by numbers (1-38) to represent the crosscut sections.

The complete cutting scheme for both panels is shown in Appendix Figure 2. In line with original marking and cutup sequence, the horizontal strips are referred to as columns and are marked with letters (A, B, C,… through U) while the vertical strips are referred to as rows and are marked with numerals (1, 2, 3, …, through 38).

All specimens harvested that way were subjected to the PRG320-2019 delamination test as described in the main body of this report (sub-section Cyclic Delamination).



1-U-1	1-U-2	1-U-3	1-U-4	1-U-5	1-U-6	1-U-7	1-U-8	1-U-9	1-U-10	1-U-11	1-U-12	1-U-13	1-U-14	1-U-15	1-U-16	1-U-17	1-U-18	1-U-19	1-U-20	1-U-21	1-U-22	1-U-23	1-U-24	1-U-25	1-U-26	1-U-27	1-U-28	1-U-29	1-U-30	1-U-31	1-U-32	1-U-33	1-U-34	1-U-35	1-U-36	1-U-37	1-U-38
1-T-1	1-T-2	1-T-3	1-T-4	1-T-5	1-T-6	1-T-7	1-T-8	1-T-9	1-T-10	1-T-11	1-T-12	1-T-13	1-T-14	1-T-15	1-T-16	1-T-17	1-T-18	1-T-19	1-T-20	1-T-21	1-T-22	1-T-23	1-T-24	1-T-25	1-T-26	1-T-27	1-T-28	1-T-29	1-T-30	1-T-31	1-T-32	1-T-33	1-T-34	1-T-35	1-T-36	1-T-37	1-T-38
1-S-1	1-S-2	1-S-3	1-S-4	1-S-5	1-S-6	1-S-7	1-S-8	1-S-9	1-S-10	1-S-11	1-S-12	1-S-13	1-S-14	1-S-15	1-S-16	1-S-17	1-S-18	1-S-19	1-S-20	1-S-21	1-S-22	1-S-23	1-S-24	1-S-25	1-S-26	1-S-27	1-S-28	1-S-29	1-S-30	1-S-31	1-S-32	1-S-33	1-S-34	1-S-35	1-S-36	1-S-37	1-S-38
1-R-1	1-R-2	1-R-3	1-R-4	1-R-5	1-R-6	1-R-7	1-R-8	1-R-9	1-R-10	1-R-11	1-R-12	1-R-13	1-R-14	1-R-15	1-R-16	1-R-17	1-R-18	1-R-19	1-R-20	1-R-21	1-R-22	1-R-23	1-R-24	1-R-25	1-R-26	1-R-27	1-R-28	1-R-29	1-R-30	1-R-31	1-R-32	1-R-33	1-R-34	1-R-35	1-R-36	1-R-37	1-R-38
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1-P-1	1-P-2	1-P-3	1-P-4	1-P-5	1-P-6	1-P-7	1-P-8	1-P-9	1-P-10	1-P-11	1-P-12	1-P-13	1-P-14	1-P-15	1-P-16	1-P-17	1-P-18	1-P-19	1-P-20	1-P-21	1-P-22	1-P-23	1-P-24	1-P-25	1-P-26	1-P-27	1-P-28	1-P-29	1-P-30	1-P-31	1-P-32	1-P-33	1-P-34	1-P-35	1-P-36	1-P-37	1-P-38
1-O-1	1-O-2	1-O-3	1-O-4	1-O-5	1-O-6	1-O-7	1-O-8	1-O-9	1-O-10	1-O-11	1-O-12	1-O-13	1-O-14	1-O-15	1-O-16	1-O-17	1-O-18	1-O-19	1-O-20	1-O-21	1-O-22	1-O-23	1-O-24	1-O-25	1-O-26	1-O-27	1-O-28	1-O-29	1-O-30	1-O-31	1-O-32	1-O-33	1-O-34	1-O-35	1-O-36	1-O-37	1-O-38
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1-M-1	1-M-2	1-M-3	1-M-4	1-M-5	1-M-6	1-M-7	1-M-8	1-M-9	1-M-10	1-M-11	1-M-12	1-M-13	1-M-14	1-M-15	1-M-16	1-M-17	1-M-18	1-M-19	1-M-20	1-M-21	1-M-22	1-M-23	1-M-24	1-M-25	1-M-26	1-M-27	1-M-28	1-M-29	1-M-30	1-M-31	1-M-32	1-M-33	1-M-34	1-M-35	1-M-36	1-M-37	1-M-38
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1-K-1	1-K-2	1-K-3	1-K-4	1-K-5	1-K-6	1-K-7	1-K-8	1-K-9	1-K-10	1-K-11	1-K-12	1-K-13	1-K-14	1-K-15	1-K-16	1-K-17	1-K-18	1-K-19	1-K-20	1-K-21	1-K-22	1-K-23	1-K-24	1-K-25	1-K-26	1-K-27	1-K-28	1-K-29	1-K-30	1-K-31	1-K-32	1-K-33	1-K-34	1-K-35	1-K-36	1-K-37	1-K-38
1-J-1	1-J-2	1-J-3	1-J-4	1-J-5	1-J-6	1-J-7	1-J-8	1-J-9	1-J-10	1-J-11	1-J-12	1-J-13	1-J-14	1-J-15	1-J-16	1-J-17	1-J-18	1-J-19	1-J-20	1-J-21	1-J-22	1-J-23	1-J-24	1-J-25	1-J-26	1-J-27	1-J-28	1-J-29	1-J-30	1-J-31	1-J-32	1-J-33	1-J-34	1-J-35	1-J-36	1-J-37	1-J-38
1-I-1	1-I-2	1-I-3	1-I-4	1-I-5	1-I-6	1-I-7	1-I-8	1-I-9	1-I-10	1-I-11	1-I-12	1-I-13	1-I-14	1-I-15	1-I-16	1-I-17	1-I-18	1-I-19	1-I-20	1-I-21	1-I-22	1-I-23	1-I-24	1-I-25	1-I-26	1-I-27	1-I-28	1-I-29	1-I-30	1-I-31	1-I-32	1-I-33	1-I-34	1-I-35	1-I-36	1-I-37	1-I-38
1-H-1	1-H-2	1-H-3	1-H-4	1-H-5	1-H-6	1-H-7	1-H-8	1-H-9	1-H-10	1-H-11	1-H-12	1-H-13	1-H-14	1-H-15	1-H-16	1-H-17	1-H-18	1-H-19	1-H-20	1-H-21	1-H-22	1-H-23	1-H-24	1-H-25	1-H-26	1-H-27	1-H-28	1-H-29	1-H-30	1-H-31	1-H-32	1-H-33	1-H-34	1-H-35	1-H-36	1-H-37	1-H-38
1-G-1	1-G-2	1-G-3	1-G-4	1-G-5	1-G-6	1-G-7	1-G-8	1-G-9	1-G-10	1-G-11	1-G-12	1-G-13	1-G-14	1-G-15	1-G-16	1-G-17	1-G-18	1-G-19	1-G-20	1-G-21	1-G-22	1-G-23	1-G-24	1-G-25	1-G-26	1-G-27	1-G-28	1-G-29	1-G-30	1-G-31	1-G-32	1-G-33	1-G-34	1-G-35	1-G-36	1-G-37	1-G-38
1-F-1	1-F-2	1-F-3	1-F-4	1-F-5	1-F-6	1-F-7	1-F-8	1-F-9	1-F-10	1-F-11	1-F-12	1-F-13	1-F-14	1-F-15	1-F-16	1-F-17	1-F-18	1-F-19	1-F-20	1-F-21	1-F-22	1-F-23	1-F-24	1-F-25	1-F-26	1-F-27	1-F-28	1-F-29	1-F-30	1-F-31	1-F-32	1-F-33	1-F-34	1-F-35	1-F-36	1-F-37	1-F-38
1-E-1	1-E-2	1-E-3	1-E-4	1-E-5	1-E-6	1-E-7	1-E-8	1-E-9	1-E-10	1-E-11	1-E-12	1-E-13	1-E-14	1-E-15	1-E-16	1-E-17	1-E-18	1-E-19	1-E-20	1-E-21	1-E-22	1-E-23	1-E-24	1-E-25	1-E-26	1-E-27	1-E-28	1-E-29	1-E-30	1-E-31	1-E-32	1-E-33	1-E-34	1-E-35	1-E-36	1-E-37	1-E-38
1-D-1	1-D-2	1-D-3	1-D-4	1-D-5	1-D-6	1-D-7	1-D-8	1-D-9	1-D-10	1-D-11	1-D-12	1-D-13	1-D-14	1-D-15	1-D-16	1-D-17	1-D-18	1-D-19	1-D-20	1-D-21	1-D-22	1-D-23	1-D-24	1-D-25	1-D-26	1-D-27	1-D-28	1-D-29	1-D-30	1-D-31	1-D-32	1-D-33	1-D-34	1-D-35	1-D-36	1-D-37	1-D-38
1-C-1	1-C-2	1-C-3	1-C-4	1-C-5	1-C-6	1-C-7	1-C-8	1-C-9	1-C-10	1-C-11	1-C-12	1-C-13	1-C-14	1-C-15	1-C-16	1-C-17	1-C-18	1-C-19	1-C-20	1-C-21	1-C-22	1-C-23	1-C-24	1-C-25	1-C-26	1-C-27	1-C-28	1-C-29	1-C-30	1-C-31	1-C-32	1-C-33	1-C-34	1-C-35	1-C-36	1-C-37	1-C-38
1-B-1	1-B-2	1-B-3	1-B-4	1-B-5	1-B-6	1-B-7	1-B-8	1-B-9	1-B-10	1-B-11	1-B-12	1-B-13	1-B-14	1-B-15	1-B-16	1-B-17	1-B-18	1-B-19	1-B-20	1-B-21	1-B-22	1-B-23	1-B-24	1-B-25	1-B-26	1-B-27	1-B-28	1-B-29	1-B-30	1-B-31	1-B-32	1-B-33	1-B-34	1-B-35	1-B-36	1-B-37	1-B-38
1-A-1	1-A-2	1-A-3	1-A-4	1-A-5	1-A-6	1-A-7	1-A-8	1-A-9	1-A-10	1-A-11	1-A-12	1-A-13	1-A-14	1-A-15	1-A-16	1-A-17	1-A-18	1-A-19	1-A-20	1-A-21	1-A-22	1-A-23	1-A-24	1-A-25	1-A-26	1-A-27	1-A-28	1-A-29	1-A-30	1-A-31	1-A-32	1-A-33	1-A-34	1-A-35	1-A-36	1-A-37	1-A-38

Appendix Figure 9. Sub-study panel cutup scheme. In line with original marking in the subsequent text, the horizontal strips are referred to as columns (A, B, C,…) while the vertical strips are referred to as rows (1, 2, 3, …).

In addition to the assessment of the delamination, each specimen was marked for presence of knots and interlamination haps, with identification of the affected layers and bond lines.

Analysis

The data for the delamination was organized into binary values to understand the effects of defects (knots and bondline splits) on the delamination of a CLT panel. The samples were classified by face and bondline, with "yes" or "no" indicators for defects, and "pass" or "fail" indicators for delamination. The delamination data was then converted to "0" and "1" for "pass" and "fail," respectively. The defect data was then condensed to indicate if an entire sample had a "knot" or "split" with either a "4" or "8," respectively. If the sample did not contain a defect, a value of "0" was listed. The values for knots, splits, and delamination were added together to create an identification value. An example and legend are shown in Appendix Table 1 for the identification vales.

Appendix Table 12 Identification Numbers for Specimens’ Categorization of Defects

No Knots/Knots (0,4)	+	No Splits/Splits (0,8)	+	Pass/Fail (0,1)	=	ID	Legend
0	+	0	+	0	=	0	Passes with no defects
0	+	0	+	1	=	1	Fails with no defects
4	+	0	+	0	=	4	Passes with only knots present
4	+	0	+	1	=	5	Fails with only knots present
0	+	8	+	0	=	8	Passes with only splits present
0	+	8	+	1	=	9	Fails with only splits present
4	+	8	+	0	=	12	Passes with both knots and splits
4	+	8	+	1	=	13	Fails with both knots and splits

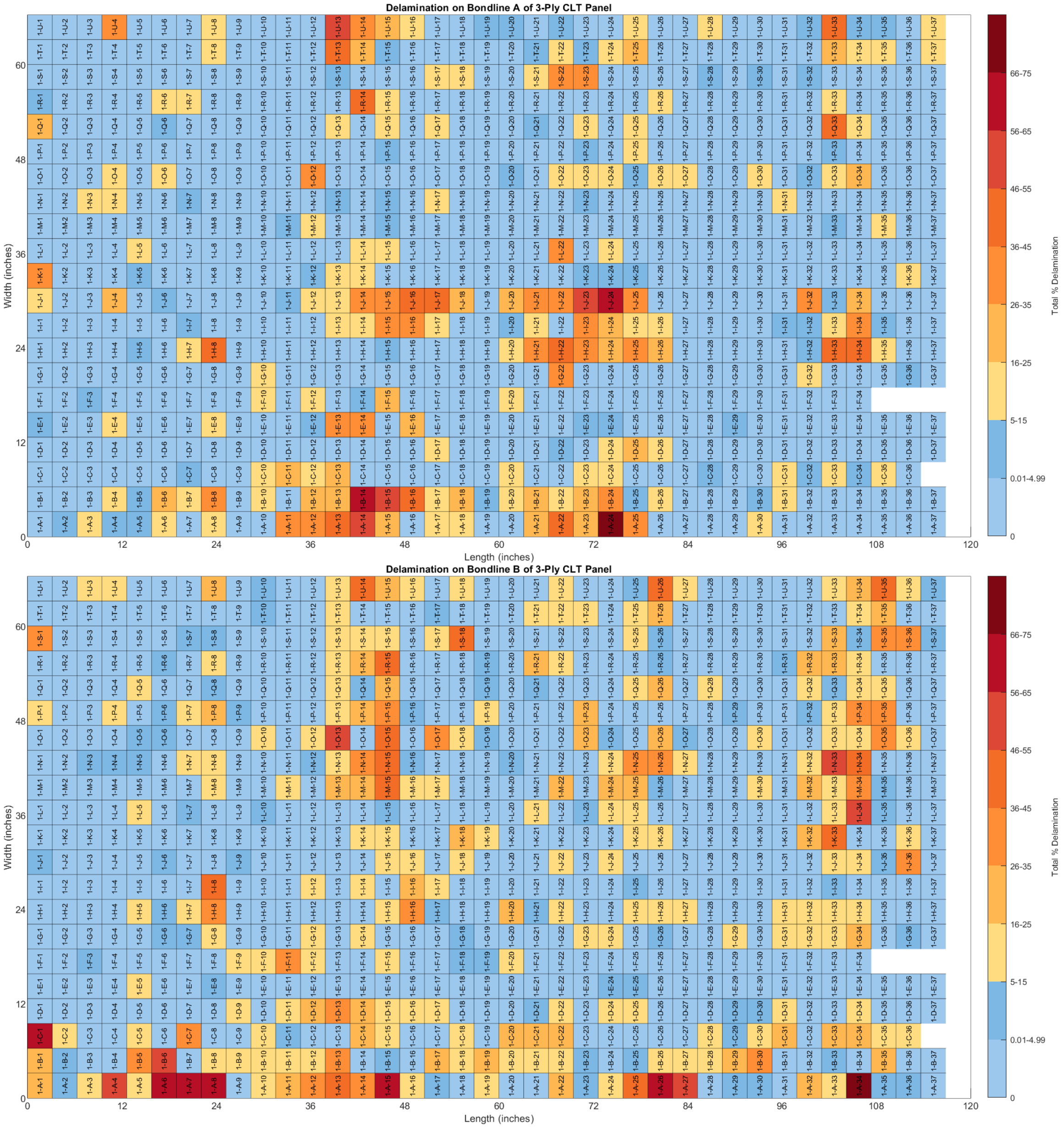
Once the sample’s ID was indicated, each ID was counted and placed into a table for both 3-ply and 5-ply. With the count table totals for each category also displayed.

The data was analyzed with graphical representations of the delamination within the entire panel. Along with the visual representation, a statistical analysis was performed on the data investigating significant differences within the panel’s rows. The assumptions of these tests were verified using a Shapiro-Wilk test to evaluate normality and a Fligner-Killeen test to evaluate equal variance at $\alpha = 0.05$. Due to the delamination values not meeting the assumption of normality, a Kruskal-Wallis rank sum test was chosen.

The Kruskal-Wallis test is a non-parametric test method, which is a common alternative to a one-way analysis of variance (ANOVA) when assumptions are violated. This method ranks the delamination values from the highest to lowest in all rows and uses the ranks in a one-way ANOVA to tell if there is any significant difference between the rows. The delamination for each row was analyzed first with a Kruskal Wallis test (Kruskal test, $\alpha = 0.05$) to determine if there was a significant difference between all the rows, followed by a Kruskal multiple comparison’s (kruskalmc) test (kruskalmc, $\alpha = 0.05$) to identify which rows were significant to one another. After completing the analysis for the rows, the same statistical analysis was performed on the columns.

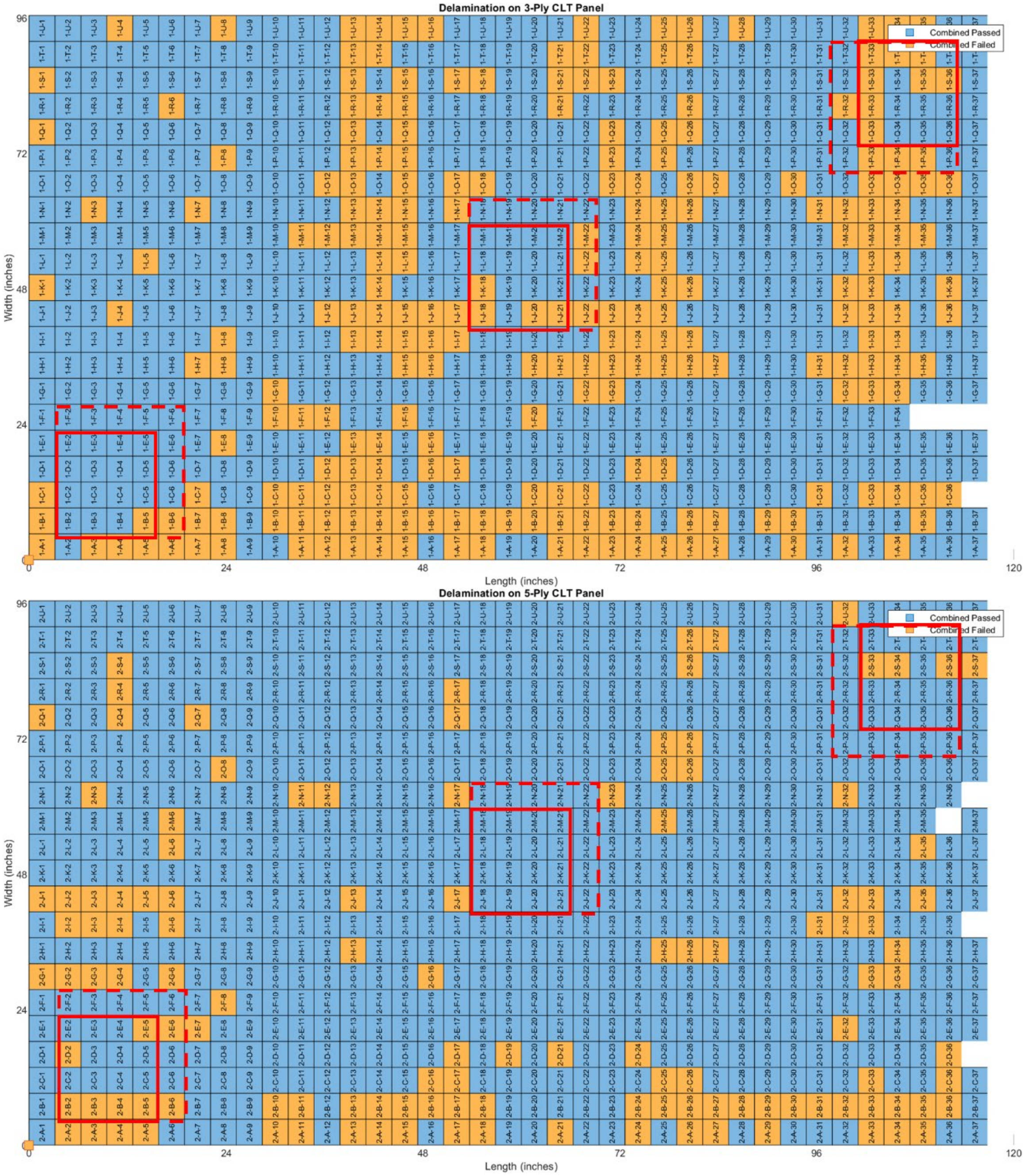
Results

The results of PRG320-2019 delamination tests for all block specimens obtained from 3-ply panel are summarized in Appendix Figure *3*. The color-coded maps show levels of delamination recorded in two bond planes of individual specimens. The shades of blue indicate acceptable (passing) level of delamination in that bond line (within 5%).



Appendix Figure 10. Color coded delamination map for two bond planes in 3-ply MF panel. Color scale reflects the percent of delamination in each block measured after PRG320-2019 PRG delamination test (shades of blue show acceptable level of delamination or pass).

However, it is the average delamination in these two bond planes, or in four bond planes in 5-ply panel, that decides whether or not the specimen is considered passing or failing the PRG320 delamination criterion. Distributions of specimens failing the PRG320-2019 delamination criterion in the 3-ply and 5-ply MF panels are shown in Appendix Figure 4.



Appendix Figure 11. Distribution of specimens failing PRG320-2019 delamination criterion in 3-ply (top) and 5-ply (bottom) MF panels with possible sampling areas marked as solid and dashed red rectangles.

Effectiveness of the Standard Sampling Scheme

While both panels show disappointing numbers of specimens failing the PRG320-2019 delamination criteria, examination of the content of the possible sampling areas marked on the panel maps as solid and dashed rectangles show that whether the issue is captured or not in the standard sampling scheme is a matter of chance.

The probability for detecting a delamination issue in this sampling scheme is further affected by the standard requirement to exclude delamination specimens with edge joints or inter-lamination gaps in layers oriented along a panel's major strength direction. It is also common practice to avoid specimens with edge bong or gap or with larger knots touching the bond-line in all layers. Such practice is believed to increase the chance of passing the delamination test criteria.

Further, the standard permits sampling of a replacement of a delamination specimen in case the average delamination of all bond lines in a specimen exceeds 5% but is not more than 10%.

Therefore, the PRG320 sampling scheme favors larger panels, and the related practice makes it possible to pass large panels with extensive potential for delamination. It is much more difficult to miss a delamination issue in small lab-fabricated billets.

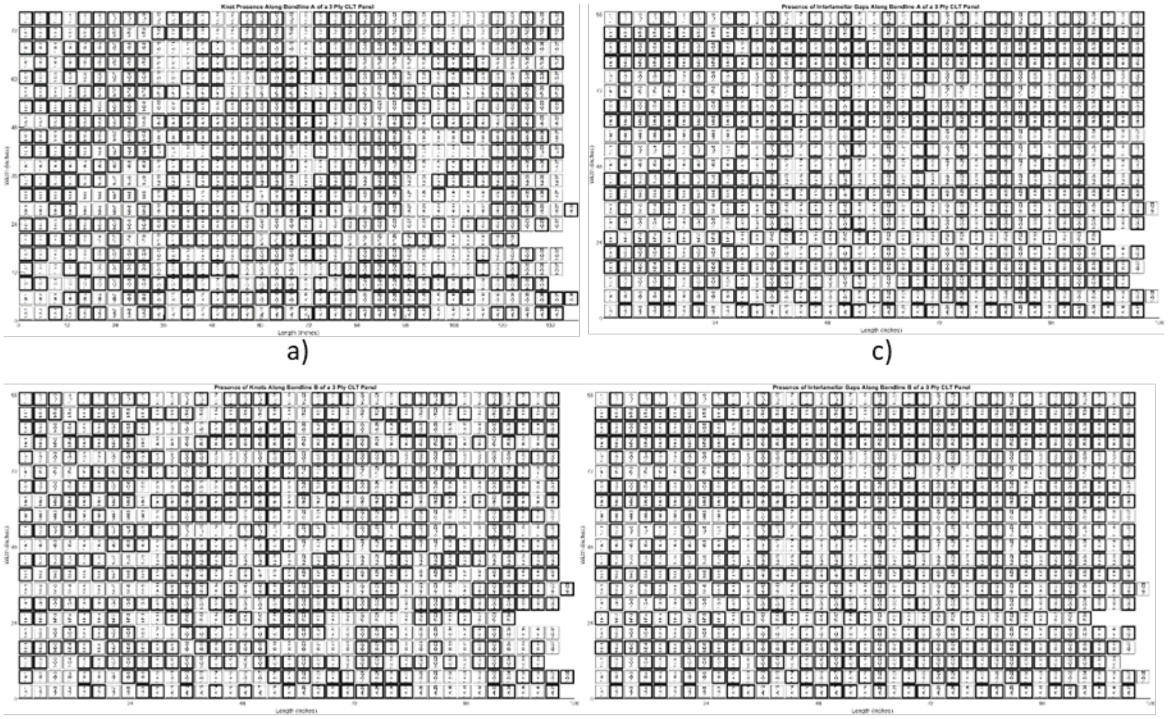
It should be stressed; however, that the standard cyclic delamination test is a harsh procedure and that PRG320-2019 passing criteria are the stringiest in the world. Potential for delamination in the cyclic delamination test indicates weaker bonds, but not preexisting delamination in finished panels.

Effect of Inter-Lamination Gaps and Knots in Delamination Specimens

While the presence of gaps between the edges of adjacent laminations within the same layer (inter-lamination gaps) and knots touching the bond lines in delamination specimens are widely believed to impair the resistance to delamination, there is little empirical evidence available to support such hypothesis. Both are unavoidable and common features in CLT. Appendix Figure *5* shows the distribution of knots (a and b) and inter-lamination gaps (c and d) touching bond planes A (a and c) and B (b and d) of a 3-ply MF panel. This is quite representative for the distributions of these features in 5-ply MF panels (not shown here). In fact, the specimens including either a knot touching a bond plane or an inter-lamination gap (or both) substantially outnumbers the clear specimens sought for the standard delamination tests: more than 10:1 in 3-ply panel (bottom row in Appendix Table 2) and over 30:1 in the 5-ply panel (bottom row in Appendix Table 3).

A quick inspection of Appendix Figure 4 and the summary columns showing numbers of passing and failing specimens in Appendix Table 2 and, proves that 70% (in 3-ply panel) to 80% (in 5-ply panel) of the specimens with these features passed the PRG320-2019 delamination test.

Comparison of absolute numbers and proportions of specimens passing and failing the PRG320-2019 delamination tests in 3-ply (a) and 5-oly (b) MF panels by categories: clear specimens (A), specimens with knots touching a bond plane (B), specimens with inter-lamination gaps (C), and with both knots and gaps (D), based on 775 delamination specimens harvested from each panel are shown in the middle sections of Appendix Table 2 and 3 and in Appendix Figure *6*.



a) c)

b) d)

Appendix Figure 12. Distribution of knots (a and b) and inter-lamination gaps (c and d) touching bond planes A (a and c) and B (b and d) of a 3-ply MF panel.

Appendix Table 13 Presence of Knots Touching Bond Plane and Inter Lamination Gaps (Splits) in Specimens Harvested from 3-Ply MF Panel

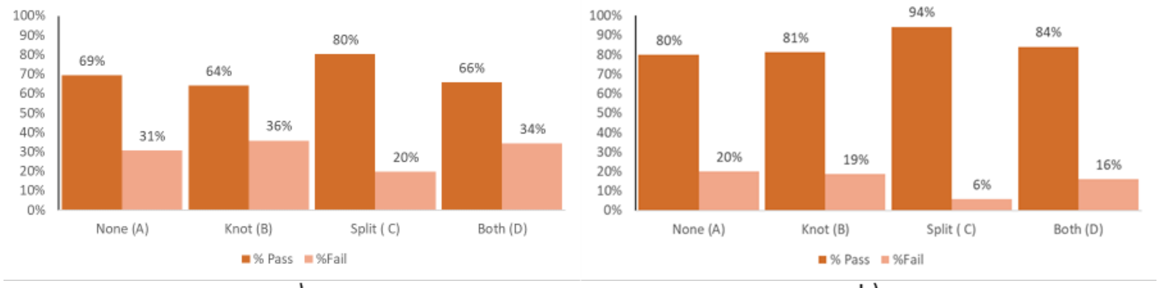
Pass/Fail	Features Observed in Delamination Specimens Harvested from 3-Ply MF Panel				Total
	None	Knot	Split	Both	
Pass	43	104	98	282	527
Fail	19	58	24	147	248
totals	62	162	122	429	775

Appendix Table 14 Presence of Knots Touching Bond Plane and Inter-Lamination Gaps (Splits) in Specimens Harvested from 5-Ply MF Panel

Pass/Fail	Features Observed in Delamination Specimens Harvested from 5-Ply MF Panel				Total
	None	Knot	Split	Both	
Pass	20	148	33	448	649
Fail	5	34	2	85	126
totals	25	182	35	533	775

If the clear specimens (free of the presence of knots touching any of the bond planes and inter-lamination gaps) may be considered a reference standard, then we must conclude that in the 3-ply panel, 31% of all specimens did not meet the PRG320-2019 delamination criteria and in the 5-ply panel, about 20% of all specimens did not meet the PRG320-2019 delamination criteria.

Nonparametric Kruskal-Wallis test performed at 0.95 confidence level on the groups represented in the columns of Appendix Table 2 and 3 show that specimens containing knots were just as likely to fail delamination test in both 3-ply and 5-ply panels and splits were significantly less likely to fail. Specimens containing both knots and splits were again just as likely to fail delamination tests as the clear specimens.



a) b)

Appendix Figure 13. Comparison of proportions of specimens passing and failing the PRG320-2019 delamination tests in 3-ply (a) and 5-ply (b) MF panels by categories: clear specimens (A), specimens with knots touching a bond plane (B), specimens with inter-lamination gaps (C), and with both knots and gaps (D). (Based on n=775 in both panels).

This observation flies against the widely held beliefs that seem to guide the PRG320 standard sampling procedures and common practice described above. That conclusion prompts the question of other potential sources of the delamination seen in the MF specimens.

Other Diagnostic Clues

Excessive moisture content: The first culprit must be the excessive moisture content of laminations revealed in Table 1 of the main report. PRG320-2019 product standard and the adhesive manufacturer guidelines require that the moisture content of laminations at the time of glue application is between 9% and 15% moisture content. While the white fir lumber had been air drying in OSU covered storage for about a year, the Douglas-fir lumber arrived freshly milled. The MF panel fabrication was rushed first in the coolest, dampest part of the year with no chance to dry out. The average moisture values for the MF panels (15.1% for 3-ply panels and 16.5% for 5-ply panel) summarized in that table are based on measurements performed on five boards of each species that were selected at random to have their moisture content checked with a pin moisture meter prior to planing. Unlike commercial manufacturing lines, labs and pilot-plants are not equipped for continuous measurement of surface moisture content of all laminations being processed for fabrication. Therefore, it is likely that there were Douglas-fir laminations with even higher moisture contents used in the fabrication of these two panels.

The potential effect of using surface Douglas-fir laminations with excessive moisture content might had been two-fold:

1. The excessive moisture on the surface of the laminations might had created sub-standard conditions for the chemical curing of the two-part MF adhesive.
2. Subsequent drying of the surface Douglas-fir layers of the panels stored in the lab with conditions equivalent to 6% equilibrium moisture content might have generated a substantial shear stress in the adjacent bond planes and possibly compromised the bond integrity.

However, neither of these could be easily detected before the tests, nor be tracked back to in the analysis of the specimens after the standard delamination tests. Consequently, the magnitude of this effect cannot be easily proven and must remain a working hypothesis to be resolved in another study.

Effect of the side ram: The pilot-plant CLT press is equipped with a series of horizontal actuators to operate side rams, which are used to tighten up the layup and reduce interlamination gaps by pushing the longitudinal laminations closer together. The side pressure must be applied when the top platens are closing on the layup (to prevent buckling of the longer laminations within the layer) but before the full vertical pressure is applied and the friction between the layers becomes too difficult to overcome. Visual inspection of the delamination maps in Appendix Figure 3 and in Appendix Figure 4 reveal conspicuous concentration of specimens failing the PRG320-2019 delamination test along the bottom edge of the panels, which is the side of the ram. It is possible, though difficult to prove, that a subtle miscoordination between the timing of the vertical and horizontal pressure ramps in the press program led to some level of disruption in the longitudinal layer that could not be later corrected by the vertical pressure. This issue may be resolved by fine tuning the press program.

Thickness variation of laminations within layers: PRG320-2019 product standard requires all laminations within a layer to be planed to tight thickness tolerances (within 0.2 mm in the direction across a lamination and within 0.3 mm along. While all laminations were planed to a target thickness in a semi-industrial 4-side Leadermac planer, measurements on 12 randomly selected pieces of lumber performed in one of the preceding studies revealed that these tolerances are difficult to achieve.[2] The working hypothesis of that study was that it may be generally difficult to replicate thickness consistency in lamellas fabricated in commercial CLT operations in small to medium prototype CLT billets fabricated in lab shops or even pilot-scale plants. This hypothesis is difficult to prove, because continuous accurate measurement of thickness variation of laminations after planing is notoriously difficult and it is rarely practiced in industrial lines. There are no publicly available data bases with records of thickness variation in commercial operations that could serve as reference data for the assessment of discrete measurements performed on randomly selected sample of laminations in research lab operations.

The importance of tight thickness tolerances in cross laminated laminations is often underestimated. Even moderate variations in thickness between individual laminations within the same layer leads to variations in actual pressure in lamination cross-intersections. Thickness variation within one layer tends to propagate along the lamination that is either thinner or thicker than others and result in uneven clamping pressure of that layer. Things get quickly complicated when layers with lose thickness tolerances are cross laminated. The effect is schematically illustrated in Appendix Figure 7.

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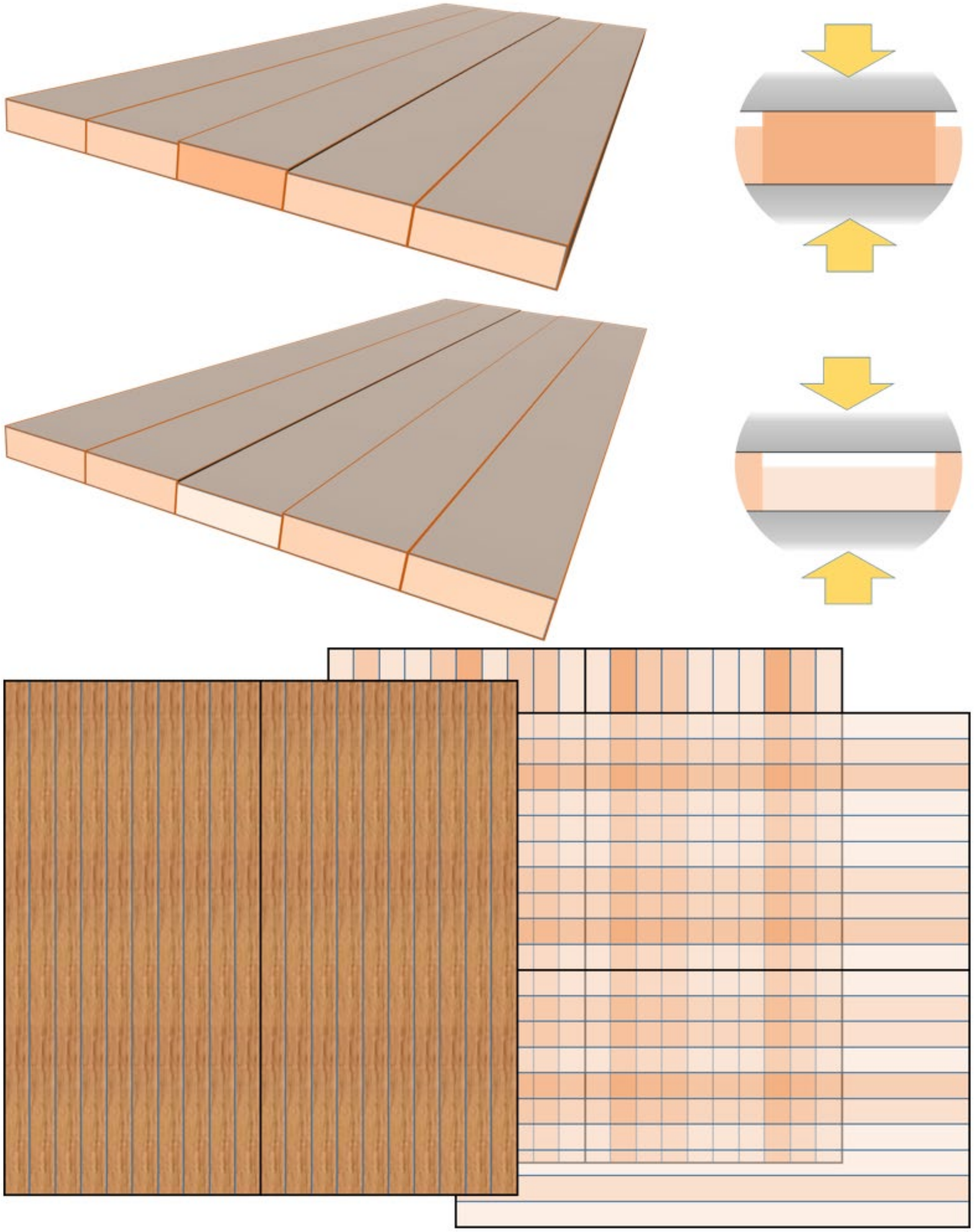
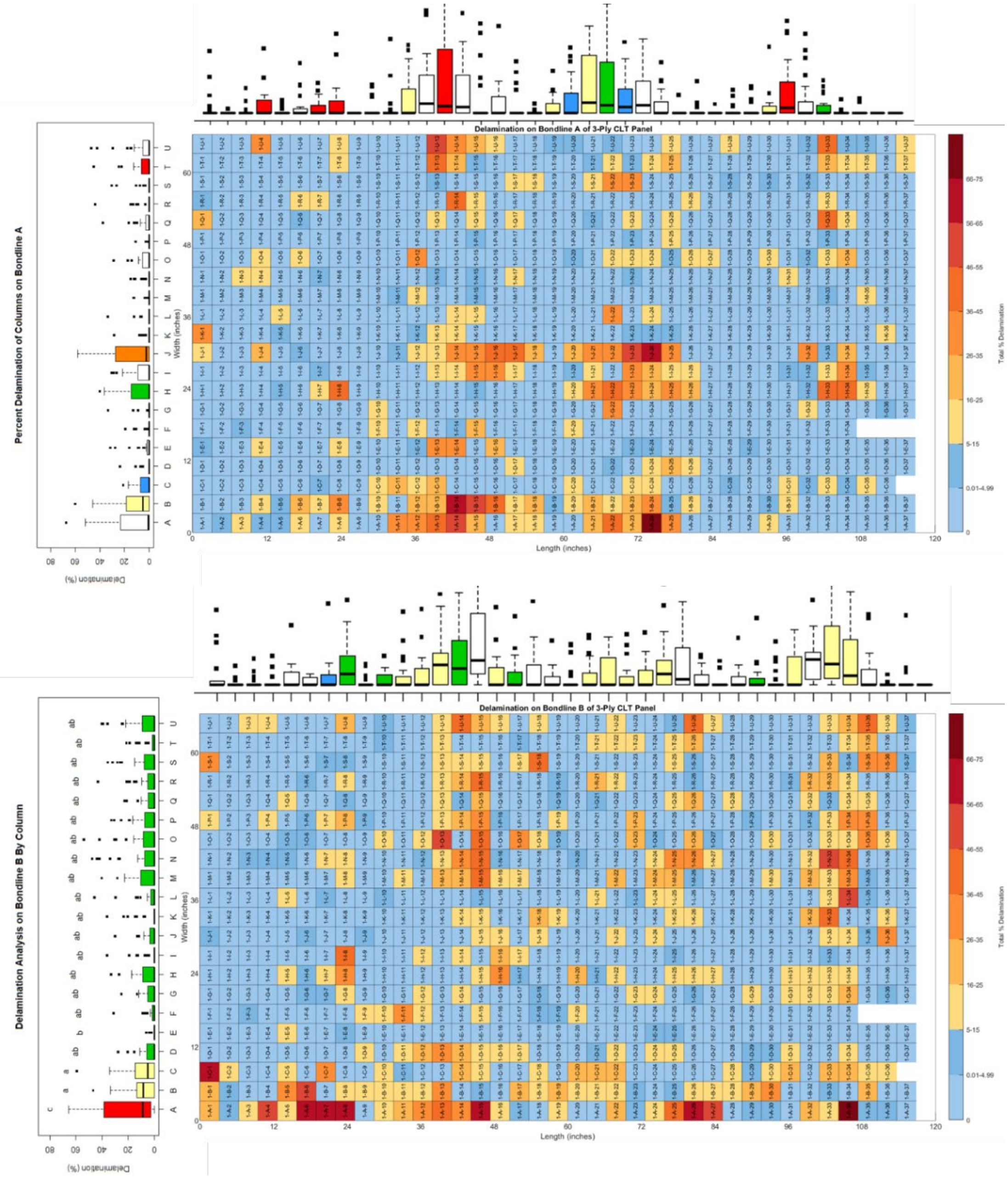
[2] Jahedi S., L. Muszyński, M. Riggio, S. Bhandari (2023): Integrity of Melamine Formaldehyde Bonds in Ponderosa Pine Cross-Laminated Timber. Isolating Adhesive Compatibility Effect, Forest Products Journal. In print



Appendix Figure 14. Schematic diagram illustrating propagation of thickness variation along the lamination within one layer and a potential for bridging when layers with variable lamination thicknesses are cross laminated.

Careful visual examination of delamination in individual bond planes in Appendix Figure 3, reveals that delaminations away from the rammed edge tend to form constellations aligned along individual pieces running either the longitudinal or transverse direction.

This observation is corroborated by the analysis of the frequency of delaminations within these layers shown in Appendix Figure 8.



Appendix Figure 15. Distribution of frequency of delamination within individual bond planes in 3-ply MF panels within horizontal and vertical strips. Alignment along individual laminations may be an indication of an effect of lamination thickness variation.

While this is not definite proof, it is nevertheless a clue indicating a potential role of lamination thickness variation in the delamination failures found in the MF panels.

The effect of lamination thickness variation in CLT is subject of a parallel study funded by USDA ARS grant.[3]

Conclusions

Based on the sub-study presented in this Appendix, we conclude that the sampling schedule for block shear and delamination specimens required by ASTM/APA PRG320-2019 does not guarantee detection of delamination issues in medium and large panels.

It may also be concluded that the presence of knots touching the bond plane, inter-lamination gaps, or a combination of both does not significantly affect the potential for delamination failures in CLT specimens.

Finally, the study pointed at three hypothetical sources of excessive delamination in the CLT specimens that are related to the limitations of the pilot-line scale fabrication process of the pieces, rather than to the fundamental chemical compatibility between the adhesive systems and the surface chemistry of the laminations. Therefore, the delamination issues detected in this study should not be interpreted negatively regarding the prospect of utilization of white fir or hybrid Douglas-fir/white fir layups in commercial CLT panels.

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[3] L. Muszynski, J. Nairn, F. Rezaei (2023): Understanding the effect of lamination thickness variations on bond integrity and panel properties in CLT. USDA ARS-CoF TDI program. (requested: $189,000/24 mo, : $165,375/36 mo)

Appendix B: Additional Shear Block and Cyclic Delamination Specimen Data

Percent Delamination for 3-Ply Panels

Panel	Rip	Section	Block	Total %	Pass/Fail
1	C	3	1	4%	Pass
1	C	3	3	0%	Pass
1	C	3	4	9%	Fail
1	C	3	6	0%	Pass
1	C	3	7	19%	Fail
1	C	1	1	0%	Pass
1	C	1	3	0%	Pass
1	C	1	6	0%	Pass
1	C	1	7	0%	Pass
1	C	1	9	0%	Pass
1	E	8	1	0%	Pass
1	E	8	2	0%	Pass
1	E	8	5	3%	Pass
1	E	8	8	0%	Pass
1	E	8	9	0%	Pass
1	E	10	2	0%	Pass
1	E	10	4	0%	Pass
1	E	10	5	0%	Pass
1	E	10	6	0%	Pass
1	E	10	8	0%	Pass
2	C	3	1	0%	Pass
2	C	3	6	0%	Pass
2	C	3	7	13%	Fail
2	C	3	8	4%	Pass
2	C	3	9	0%	Pass
2	E	8	2	6%	Fail
2	E	8	3	0%	Pass
2	E	8	4	0%	Pass
2	E	8	5	0%	Pass
2	E	8	8	0%	Pass
2	E	10	2	0%	Pass
2	E	10	3	0%	Pass
2	E	10	5	0%	Pass
2	E	10	8	0%	Pass
2	E	10	9	0%	Pass
2	C	1	1	0%	Pass
2	C	1	2	0%	Pass
2	C	1	5	0%	Pass
2	C	1	6	5%	Fail
2	C	1	7	25%	Fail
3	E	8	4	0%	Pass

Panel	Rip	Section	Block	Total	Pass/Fail
3	E	8	7	0%	Pass
3	E	8	8	0%	Pass
3	E	8	9	0%	Pass
3	C	3	1	0%	Pass
3	C	3	2	0%	Pass
3	C	3	4	0%	Pass
3	C	3	7	22%	Fail
3	C	3	8	0%	Pass
3	C	1	1	3%	Pass
3	C	1	3	0%	Pass
3	C	1	4	0%	Pass
3	C	1	7	0%	Pass
3	C	1	9	0%	Pass
3	E	10	2	0%	Pass
3	E	10	3	0%	Pass
3	E	10	5	2%	Pass
3	E	10	6	0%	Pass
3	E	10	8	0%	Pass
4	C	3	1	13%	Fail
4	C	3	4	0%	Pass
4	C	3	5	0%	Pass
4	C	3	7	0%	Pass
4	C	3	9	0%	Pass
4	E	10	2	0%	Pass
4	E	10	5	0%	Pass
4	E	10	6	0%	Pass
4	E	10	7	0%	Pass
4	E	10	9	0%	Pass
4	E	8	2	0%	Pass
4	E	8	4	0%	Pass
4	E	8	5	0%	Pass
4	E	8	6	0%	Pass
4	E	8	8	0%	Pass
4	C	1	1	0%	Pass
4	C	1	4	0%	Pass
4	C	1	5	0%	Pass
4	C	1	6	0%	Pass
4	C	1	7	0%	Pass
5	E	10	2	0%	Pass
5	E	10	3	0%	Pass
5	E	10	5	0%	Pass
5	E	10	8	0%	Pass
5	E	10	9	0%	Pass

Panel	Rip	Section	Block	Total	Pass/Fail
5	C	3	4	0%	Pass
5	C	3	7	0%	Pass
5	C	3	8	4%	Pass
5	C	3	9	0%	Pass
5	E	8	2	0%	Pass
5	E	8	4	0%	Pass
5	E	8	5	0%	Pass
5	E	8	6	0%	Pass
5	E	8	8	0%	Pass
5	C	1	1	0%	Pass
5	C	1	3	0%	Pass
5	C	1	4	0%	Pass
5	C	1	6	1%	Pass
5	C	1	9	0%	Pass
6	E	10	2	0%	Pass
6	E	10	5	0%	Pass
6	E	10	6	0%	Pass
6	E	10	7	0%	Pass
6	E	10	8	0%	Pass
6	C	3	1	0%	Pass
6	C	3	2	0%	Pass
6	C	3	3	4%	Pass
6	C	3	5	0%	Pass
6	C	3	7	0%	Pass
6	C	1	1	4%	Pass
6	C	1	2	0%	Pass
6	C	1	4	0%	Pass
6	C	1	7	0%	Pass
6	C	1	8	0%	Pass
6	E	8	1	0%	Pass
6	E	8	2	13%	Fail
6	E	8	5	0%	Pass
6	E	8	7	0%	Pass
6	E	8	8	25%	Fail

Percent Delamination for 5-Ply Panels

Panel	Rip	Section	Block	Total	Pass/Fail
7	D	5	7	8%	Fail
7	D	5	8	0%	Pass
7	D	5	9	0%	Pass
7	D	5	1	0%	Pass
7	D	5	2	0%	Pass
7	D	5	3	0%	Pass
7	D	5	4	0%	Pass
7	D	5	5	0%	Pass
7	D	5	6	0%	Pass
7	D	5	13	0%	Pass
7	C	1	1	0%	Pass
7	C	1	4	0%	Pass
7	C	1	5	0%	Pass
7	C	1	7	0%	Pass
7	C	1	10	0%	Pass
7	C	1	13	0%	Pass
7	E	9	1	0%	Pass
7	E	9	5	0%	Pass
7	E	9	6	0%	Pass
7	E	9	8	0%	Pass
7	E	9	11	0%	Pass
7	E	9	14	0%	Pass
8	D	5	1	0%	Pass
8	D	5	2	0%	Pass
8	D	5	3	0%	Pass
8	D	5	7	0%	Pass
8	D	5	8	0%	Pass
8	D	5	9	0%	Pass
8	E	9	2	0%	Pass
8	E	9	3	0%	Pass
8	E	9	5	0%	Pass
8	E	9	8	2%	Pass
8	E	9	11	0%	Pass
8	E	9	12	8%	Fail
8	C	1	1	0%	Pass
8	C	1	4	0%	Pass
8	C	1	5	0%	Pass
8	C	1	10	0%	Pass
8	C	1	13	0%	Pass
8	C	1	14	5%	Pass
9	D	5	13	0%	Pass
9	D	5	14	0%	Pass

Panel	Rip	Section	Block	Total	Pass/Fail
9	D	5	15	0%	Pass
9	D	5	4	0%	Pass
9	D	5	5	13%	Fail
9	D	5	6	0%	Pass
9	C	1	1	0%	Pass
9	C	1	3	0%	Pass
9	C	1	4	0%	Pass
9	C	1	7	0%	Pass
9	C	1	10	0%	Pass
9	C	1	14	0%	Pass
9	E	9	8	0%	Pass
9	E	9	10	0%	Pass
9	E	9	11	25%	Fail
9	E	9	12	0%	Pass
9	E	9	13	0%	Pass
9	E	9	14	0%	Pass
10	E	9	1	0%	Pass
10	E	9	2	0%	Pass
10	E	9	3	0%	Pass
10	D	5	4	0%	Pass
10	D	5	5	0%	Pass
10	D	5	6	0%	Pass
10	D	5	10	0%	Pass
10	D	5	12	2%	Pass
10	D	5	13	0%	Pass
10	D	5	15	0%	Pass
10	C	1	1	0%	Pass
10	C	1	2	0%	Pass
10	C	1	5	3%	Pass
10	C	1	10	0%	Pass
10	C	1	13	0%	Pass
10	C	1	14	0%	Pass
10	E	9	9	0%	Pass
10	E	9	14	0%	Pass
10	E	9	15	0%	Pass
11	D	5	10	0%	Pass
11	D	5	11	0%	Pass
11	D	5	12	13%	Fail
11	D	5	4	0%	Pass
11	D	5	5	0%	Pass
11	D	5	6	0%	Pass
11	C	1	1	1%	Pass
11	C	1	2	0%	Pass

Panel	Rip	Section	Block	Total	Pass/Fail
11	C	1	3	0%	Pass
11	C	1	7	0%	Pass
11	C	1	8	0%	Pass
11	C	1	9	0%	Pass
11	C	1	13	0%	Pass
11	C	1	14	0%	Pass
11	C	1	15	0%	Pass
11	C	1	10	0%	Pass
11	C	1	11	0%	Pass
11	C	1	12	0%	Pass
11	D	5	1	0%	Pass
11	D	5	6	0%	Pass
11	D	5	7	0%	Pass
11	D	5	9	0%	Pass
11	D	5	13	0%	Pass
11	D	5	15	0%	Pass
11	E	9	2	0%	Pass
11	E	9	3	8%	Fail
11	E	9	6	0%	Pass
11	E	9	7	0%	Pass
11	E	9	11	0%	Pass
11	E	9	12	0%	Pass
12	D	5	13	0%	Pass
12	D	5	14	0%	Pass
12	D	5	15	0%	Pass
12	D	5	1	0%	Pass
12	D	5	4	0%	Pass
12	D	5	7	0%	Pass
12	D	5	10	0%	Pass
12	D	5	11	0%	Pass
12	D	5	12	0%	Pass
12	C	1	1	3%	Pass
12	C	1	2	0%	Pass
12	C	1	4	0%	Pass
12	C	1	5	2%	Pass
12	C	1	10	0%	Pass
12	C	1	14	0%	Pass
12	E	9	2	0%	Pass
12	E	9	8	0%	Pass
12	E	9	9	0%	Pass
12	E	9	11	0%	Pass
12	E	9	12	0%	Pass
12	E	9	14	0%	Pass

Percent Wood Failure for 3-Ply Block Shear

Panel	Rip	Section	Block	Wood Failure %
1	C	1	1	87.5
1	C	1	2	100
1	C	1	3	52.5
1	C	1	6	87.5
1	C	1	7	82.5
1	C	1	8	70
1	C	1	9	100
1	C	1	10	87.5
1	C	1	11	100
1	C	1	12	85
1	C	3	1	100
1	C	3	2	100
1	C	3	3	97.5
1	C	3	4	95
1	C	3	6	87.5
1	C	3	7	90
1	C	3	8	100
1	C	3	9	100
1	C	3	10	100
1	C	3	11	95
1	C	3	12	95
1	E	3	2	100
1	E	3	3	75
1	E	3	8	100
1	E	3	9	100
1	E	3	10	95
1	E	10	1	95
1	E	10	2	100
1	E	10	3	100
1	E	10	6	95
1	E	10	8	87.5
1	E	10	9	75
2	C	1	1	100
2	C	1	3	100
2	C	1	4	100
2	C	1	6	100
2	C	1	7	100
2	C	1	9	100
2	C	1	10	100
2	C	1	11	75
2	C	1	12	87.5
2	C	3	1	100

Panel	Rip	Section	Block	Wood Failure %
2	C	3	3	90
2	C	3	4	100
2	C	3	9	100
2	C	3	10	60
2	C	3	11	100
2	C	3	12	75
2	E	3	2	100
2	E	3	3	100
2	E	3	5	80
2	E	3	6	50
2	E	3	8	100
2	E	3	9	95
2	E	3	12	97.5
2	E	10	2	90
2	E	10	3	87.5
2	E	10	5	100
2	E	10	6	87.5
2	E	10	8	100
2	E	10	9	92.5
3	C	1	3	100
3	C	1	4	100
3	C	1	6	100
3	C	1	7	100
3	C	1	9	75
3	C	1	10	100
3	C	1	11	100
3	C	1	12	100
3	C	3	1	100
3	C	3	4	75
3	C	3	6	100
3	C	3	7	100
3	C	3	9	100
3	C	3	10	100
3	C	3	11	100
3	C	3	12	100
3	E	3	1	87.5
3	E	3	2	90
3	E	3	3	75
3	E	3	4	62.5
3	E	3	7	87.5
3	E	3	12	90
3	E	10	1	87.5
3	E	10	2	100
3	E	10	3	95

Panel	Rip	Section	Block	Wood Failure %
3	E	10	4	90
3	E	10	6	95
3	E	10	7	87.5
3	E	10	8	100
4	C	1	1	100
4	C	1	3	100
4	C	1	4	100
4	C	1	6	100
4	C	1	7	100
4	C	1	9	100
4	C	1	10	100
4	C	1	11	100
4	C	1	12	100
4	C	3	1	62.5
4	C	3	2	100
4	C	3	3	100
4	C	3	4	100
4	C	3	7	100
4	C	3	9	87.5
4	C	3	10	100
4	C	3	11	100
4	C	3	12	75
4	E	3	2	62.5
4	E	3	3	95
4	E	3	5	75
4	E	3	6	100
4	E	3	8	100
4	E	3	9	70
4	E	3	10	100
4	E	3	12	100
4	E	10	2	100
4	E	10	3	100
4	E	10	8	87.5
4	E	10	9	95
4	E	10	10	100
5	C	1	3	100
5	C	1	6	90
5	C	1	7	100
5	C	1	11	100
5	C	1	12	100
5	C	3	10	100
5	C	3	11	100
5	C	3	12	75
5	E	3	1	100

Panel	Rip	Section	Block	Wood Failure %
5	E	3	3	100
5	E	3	5	100
5	E	3	6	100
5	E	3	9	100
5	E	3	10	100
5	E	10	1	100
5	E	10	2	100
5	E	10	3	100
5	E	10	7	100
5	E	10	9	100
5	E	10	10	100
5	E	10	12	100
6	C	1	1	100
6	C	1	2	75
6	C	1	3	100
6	C	1	4	100
6	C	1	6	100
6	C	1	9	100
6	C	1	11	100
6	C	1	12	100
6	C	3	1	100
6	C	3	3	100
6	C	3	4	75
6	C	3	6	100
6	C	3	7	100
6	C	3	9	87.5
6	C	3	10	95
6	C	3	11	100
6	C	3	12	100
6	E	3	2	75
6	E	3	5	100
6	E	3	8	75
6	E	3	9	100
6	E	10	2	100
6	E	10	3	87.5
6	E	10	5	70
6	E	10	8	87.5

Percent Wood Failure for 5-Ply Block Shear

Panel	Rip	Section	Block	Wood Failure %
7	C	1	1	97.5
7	C	1	2	83.75
7	C	1	3	87.5
7	C	1	4	97.5
7	C	1	5	95
7	C	1	6	87.5
7	D	5	1	98.75
7	D	5	2	100
7	D	5	3	100
7	D	5	4	100
7	D	5	5	100
7	D	5	6	82.5
7	E	9	1	100
7	E	9	2	92.5
7	E	9	3	100
7	E	9	4	92.5
7	E	9	5	87.5
7	E	9	6	100
8	C	1	1	100
8	C	1	2	100
8	C	1	3	93.75
8	C	1	4	75
8	C	1	5	100
8	C	1	6	97.5
8	D	5	1	93.75
8	D	5	2	87.5
8	D	5	3	100
8	D	5	4	87.5
8	D	5	5	87.5
8	D	5	6	100
8	E	9	1	100
8	E	9	2	93.75
8	E	9	3	86.25
8	E	9	4	87.5
8	E	9	5	50.325
8	E	9	6	82.5
9	C	1	1	100
9	C	1	2	90
9	C	1	3	100
9	C	1	4	100
9	C	1	5	70
9	C	1	6	97.5

Panel	Rip	Section	Block	Wood Failure %
9	D	5	1	97.5
9	D	5	2	100
9	D	5	3	90
9	D	5	4	82.5
9	D	5	5	75
9	D	5	6	78.75
9	E	9	1	75
9	E	9	2	81.25
9	E	9	3	100
9	E	9	4	100
9	E	9	5	97.5
9	E	9	6	75
10	C	1	1	96.25
10	C	1	2	100
10	C	1	3	100
10	C	1	4	100
10	C	1	5	100
10	C	1	6	100
10	D	5	1	100
10	D	5	2	92.5
10	D	5	3	96.25
10	D	5	4	98.75
10	D	5	5	100
10	D	5	6	100
10	E	9	1	100
10	E	9	2	100
10	E	9	3	100
10	E	9	4	100
10	E	9	5	100
10	E	9	6	100
11	C	1	1	95
11	C	1	2	95
11	C	1	3	100
11	C	1	4	85
11	C	1	5	100
11	C	1	6	100
11	D	5	1	100
11	D	5	2	100
11	D	5	3	100
11	D	5	4	100
11	D	5	5	100
11	D	5	6	100
11	E	9	1	97.5
11	E	9	2	90

Panel	Rip	Section	Block	Wood Failure %
11	E	9	3	100
11	E	9	4	100
11	E	9	5	100
11	E	9	6	100
12	C	1	1	50.125
12	C	1	2	87.5
12	C	1	3	100
12	C	1	4	100
12	C	1	5	95
12	C	1	6	100
12	D	5	1	91.25
12	D	5	2	100
12	D	5	3	100
12	D	5	4	100
12	D	5	5	100
12	D	5	6	100
12	E	9	1	100
12	E	9	2	100
12	E	9	3	100
12	E	9	4	85
12	E	9	5	100
12	E	9	6	100