Final Report

Cross-Laminated Timber Layup Tests Using Western Wood Products Association (WWPA) White fir Species Group

Submitted by

TallWood Design Institute

to the

Joint Institute for Wood Products Innovation

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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.

This project, commissioned in 2020 by the Joint Institute for Wood Products Innovation, will take the first steps toward creating viable commercial markets for lesser-utilized California fiber by evaluating the suitability of fir harvested from California forests for use in cross-laminated timber.

The TallWood Design Institute (TDI), a collaborative organization based at Oregon State University and in partnership with the University of Oregon, was contracted to carry out this project.

Project Team

The TallWood Design Institute 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. TDI's 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 our work, in addition to a large number of 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 Jörn Dettmer, TDI's previous Technical Manager, Byrne Miyamoto, Structural Testing Coordinator, Collin Barkley, Undergraduate Lab Assistant, and Phillip Mann, our current Technical Manager. Testing was led by Byrne Miyamoto with the assistance of 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 2 product layups, one using white fir species lumber grade 2 and better (both longitudinal and lateral) and one white fir species lumber grade 2 and better and grade 3 and better (#2 for longitudinal, #3 for lateral);
2. Arrange for procurement and transportation of all necessary project materials;
3. Identify the species composition of the lumber used to fabricate the panels, with an estimate of percentages of each specific species to the extent reasonably possible with on-campus resources;
4. Document fabrication and test procedures for product layups, including images and video clips where appropriate;
5. Provide results of testing, 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.

Methodology

Fourteen units of rough white-fir 2x6 material were shipped to our Emmerson Lab from Sierra Pacific Industries in northern California, to be manufactured into cross laminated timber (CLT), processed into testing specimens, and mechanically tested. Eight of these were 10-foot lengths and six were 8-foot lengths. The goal of the project was to perform a preliminary study of the viability of using white fir in CLT, and in addition to evaluate if specific grade differences within the layers would affect the properties of the CLT. To evaluate the white fir as a potential raw material input for CLT, the entire process of manufacturing and processing of 3-ply CLT panels was performed in TDI's Emmerson Lab. Mechanical testing of the fabricated panels was performed in the College of Forestry's Richardson Hall structural testing lab. The material was sorted into two grades, 2 and better (2&btr), and 3 and better (3&btr). Half of the panels were made with a layup consisting of all three layers being 2&btr, while the other half were made with a layup consisting of 2&btr boards on the outside layers and 3&btr boards in the center.

CLT Panel Fabrication

The panel fabrication process consisted of 6 steps: sorting, planing, adhesive application, panel layup, pressing and CNC fabrication.

Sorting

Individual boards in each unit of lumber were visually inspected for obvious deficiencies such as excessive bow and twist, and for the presence of rock chips and other foreign matter. Sub-standard boards were rejected. Hand-scanning was then carried out with a metal detector to locate staples that had been inserted during the lumber wrapping process.

Figure 1: Examples of rejected boards

The boards pictured in Figure 1 were rejected due to extremely poor surface quality and excessive twist.

Once sub-standard boards had been removed, the appropriate number of boards needed for each panel were pulled and placed on carts (Figure 2). 50% of our fabricated CLT test panels consisted of #2&btr throughout the panel, and the remaining panels utilized #2&btr for the outer layers and #3&btr for the middle layer. To manufacture one 8' x 10', 3-ply CLT panel (24) 8' boards and (38) 10' boards (19 boards for each face) were needed. Based on the sorting process approximately 283 boards had to be culled due to defects, which was approximately 2 units of wood.

Figure 2: Boards stacked on carts, ready for planing

Planing

Once all of the material was sorted, it was then taken to be planed and primed to approximately 1.375" in thickness and 5.15" width. A Leadermac LMC 460 planer was used to plane the lumber (Figure 3)

Figure 3: Leadermac Planer (left) and primer setup connected to the outfeed of Planer (right)

At the end of the outfeed of the planer a priming system was set up to apply the adhesive primer (Figure 3). A Henkel primer was applied at a spread rate of 2g/ft^2, according to Henkel's instructions (Loctite PR 3105)[1]. The boards were then allowed to dry for 1-2 hours.

Adhesive Application

We fabricated the CLT panels using a Henkel polyurethane adhesive (Loctite HB X602 Purbond)[2], which was chosen based on its compliance with the California Air Resources Board (CARB) standards. The recommended spread rate of 28 lbs/1000ft^2 was verified by weight prior to resin application. A custom-made Apquip resin applicator was used to ensure consistent spread rate throughout the panel. The individual lumber boards (known as *lamella* in CLT manufacturing) were placed on a belt conveyor that passed underneath a curtain of resin.

Figure 4: Resin Applicator

Panel Layup

From the outfeed of the adhesive applicator the boards were then hand-laid into the infeed tray of the Minda hydraulic press with 19 (10') boards on the bottom face in the strong direction, 24 (8') boards in the center in the weak direction, and another 19 (10') boards on the top face in the strong direction. The layup process was typically completed within 25 – 30 minutes, well within the 60-minute open time of the Henkel polyurethane adhesive (Loctite HB X602 Purbond)[2].

Table 1: CLT Panel Layup Characteristics

Layer	Board Quantity	Board Dimensions
Top	24	10’ x 5.15” x 1.375”
Middle	19	8’ x 5.15” x 1.375”
Bottom	24	10’ x 5.15” x 1.375”

Pressing

Once all the boards were placed in the press, the press was closed and set for the required pressure of the PUR adhesive, which was 120 psi (Figure 1c). The press used was a custom-built Minda CLT press which is equipped with 12 linear actuators (Figures 5 and 6). Figure 7 shows a completed panel exiting the press.

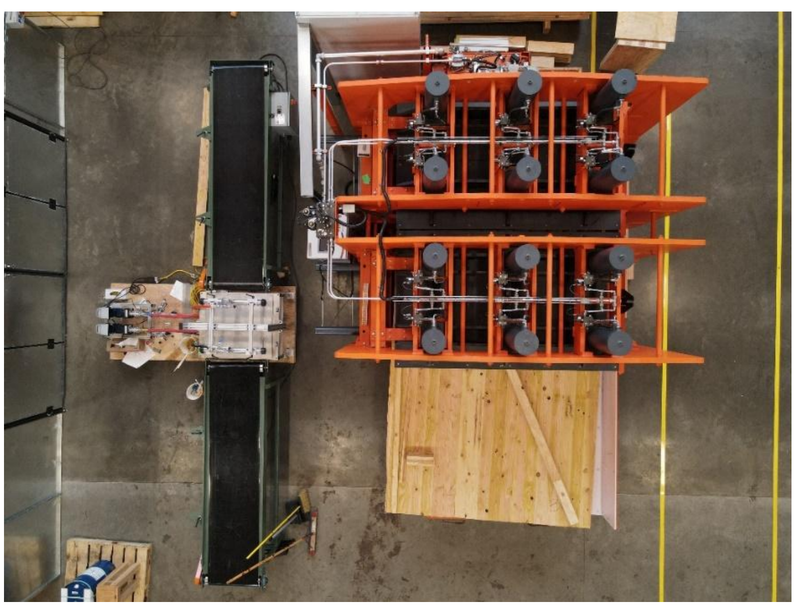

Figure 5: Apquip resin applicator (Left) and Minda press (Right)

Figure 6: Apquip resin applicator and Minda press

Figure 7: CLT panel immediately after pressing

The close time for the press was approximately 4 hours. The approximate time taken to complete the entire process to create one panel was around 6-7 hours.

In the process of manufacturing, 2 panels had to be culled. The first panel was culled due to a malfunction with the primer system, causing the boards to be improperly primed. The second panel was culled due to an inaccurate glue spread in half the panel, due to a lack of adhesive in the system when pressing. Both of these defects were generally attributable to teething troubles with these new pieces of equipment.

CNC Fabrication

The processing of the CLT panels was performed on a Biesse Uniteam UT-9 five-axis computer numerical control (CNC) machine (Figure 8).

Figure 8: (Left) CNC panels about to be lifted into CNC, (Center) CNC performing ripping operation on panels, and (Right) CNC performing cross-cutting of panels

Each panel was ripped into a total of 7 (12” x 120”) strips and then labeled with the panel number (1-14) and the location of 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 9.

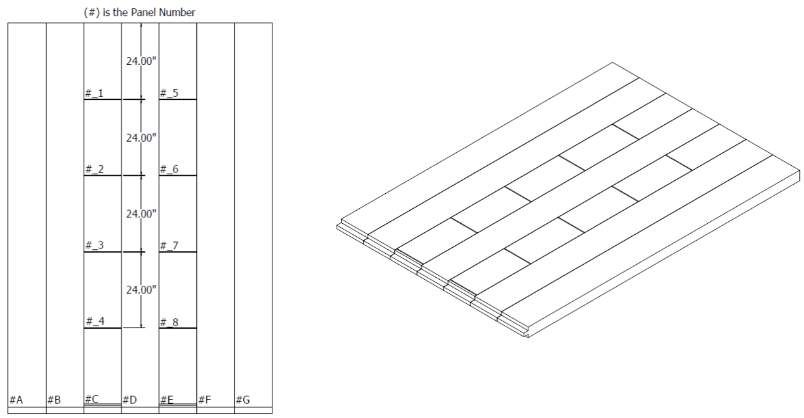

Figure 9: Panel cutting layout.

Testing

Mechanical testing was performed on the processed samples to analyze the mechanical properties of the panel and to evaluate the integrity of the adhesive bonds. The first two tests (Shear Block and Cyclic Delamination) looked at the bond strength of the adhesive to the wood by mechanically testing the bond line (Shear Block) as well as performing advanced weathering of the samples (Cyclic Delamination). In addition to the mechanical testing, the physical properties of the CLT were measured to obtain the moisture content of the samples just prior to testing and to find the specific gravity of the White-fir CLT.

Shear Block

Shear Block samples were cut from the 3” x 3” blocks to then be cut into stair step samples as seen in Figure 10a and 10b. The Samples were tested following the AITC Test Method for Structural Glued Laminated Timber. The samples were placed into a shear testing apparatus (Figure 10c) and loaded at a rate of 0.025 in/min, until failure. Once the sample failed the bond area was sheared off completely to expose the bonded area. The samples were visually evaluated to determine the failure type and the percentage of wood vs. adhesive failure.

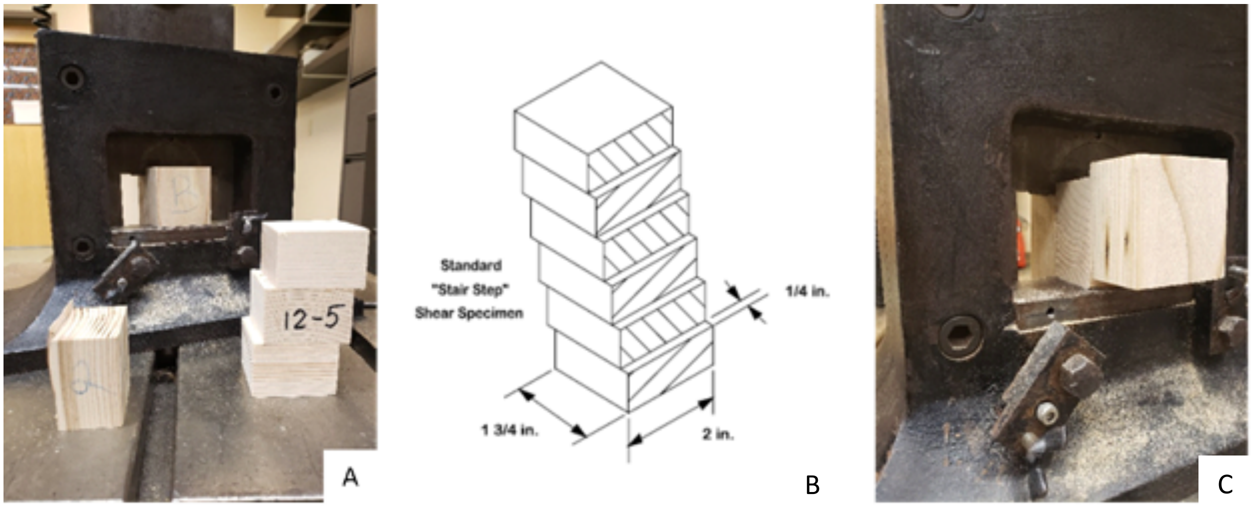

Figure 10: (A) Shear block sample next to testing apparatus, (B) Typical shear block diagram, and (C) Shear block sample in testing apparatus

The sample averages can be seen in Table 2, while the full results can be seen in Appendix A. The table shows the averages for the panels' max load, shear stress, and wood vs. adhesive percentage failure.

Table 2: Shear Block Averages

ID	Grade	Stat	Max Load (lbf)	Shear Strength (PSI)	Wood Failure (%)
1_3	2	Mean	1903.63	475.91	91.43
		StDev	668.84	167.21	25.75
		COV	0.35	0.35	0.28
2_7	2	Mean	1316.77	329.19	87.27
		StDev	444.49	111.12	23.54
		COV	0.34	0.34	0.27
4_1	2	Mean	2061.70	515.43	89.55
		StDev	816.97	204.24	25.63
		COV	0.40	0.40	0.29
5_3	2	Mean	1800.88	450.22	97.50
		StDev	690.18	172.54	8.34
		COV	0.38	0.38	0.09
9_1	3	Mean	1642.63	410.66	74.36
		StDev	650.19	162.55	34.89

		COV	0.40	0.40	0.47
10_3	3	Mean	1610.90	402.73	93.90
		StDev	440.75	110.19	14.53
		COV	0.27	0.27	0.15
12_5	3	Mean	1478.37	369.59	87.50
		StDev	547.88	136.97	25.30
		COV	0.37	0.37	0.29

The shear blocks had a total average of approximately 420 PSI with an average wood failure of 90%. The PRG 320 minimum requirements state that the percentage of samples that experience wood failure versus adhesive bond failure should be no less than 80%. In total 27 out of 146 samples failed to reach the 80% mark. Most of the failed samples contained knots, and these are likely to have negatively affected adhesive penetration.

Cyclic Delamination

Delamination samples were cut from the 12” x 25” samples and processed into 3” x 3” cubes to be tested. The cyclic delamination test was performed following the AITC T110-2007 for cyclic delamination. There were two sample types that were tested, the first being 5 blocks from 6 random panels at different locations. The second sample type was from panel 1, strip E, and block 8. Figure 11 shows the exact locations from which the samples were taken.

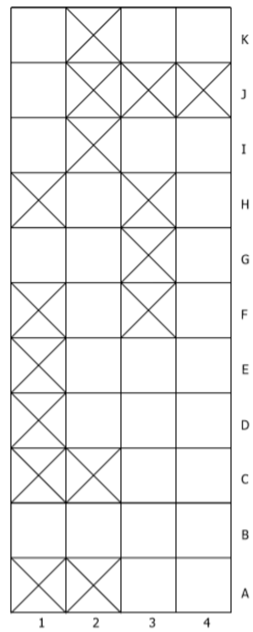

Figure 11: Delamination sample group 2 from Panel 1, strip E, Block 8

The testing utilized a single soak-dry cycle, using a pressure/vacuum vessel and an air circulating oven (Figure 12). The testing procedure began by recording the initial weights of the samples before placing them into the vessel. The samples were then 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 2 hours at approximately 75 psi. After the pressure cycle was complete the samples were removed from the vessel and placed into an air circulating oven at 160°F. The samples would remain in the oven until they reached approximately 15% of the sample's initial weights. The drying process took approximately 10 to 15 hours for the samples to dry down to 15% of their initial weight.

Figure 12: (a) Vacuum/Pressure Vessel, (b) Air Circulating Oven with Samples, and (c) Top: Samples after soaking, Bottom: Samples after drying

Once the samples were dry, they were analyzed for delamination. The bond line of each sample was examined for any delamination and then marked and measured. Samples that contained defects such as knots were omitted from the totals, as per the guidelines in the PRG-320 standard. A percentage was calculated based on the measured delamination and the total length of the bond line. The averages for the panels can be seen in Table 3. In the table the samples' average delamination percentage for the top and bottom bond lines is shown. The full results for each specimen and each bond line can be seen in Appendix B.

Table 3: Cyclic Delamination Averages

ID	Stat	% Top Bond Line	% Bottom Bond Line
2_7	Mean	9.6	0.0
	StDev	0.5	0.0
	COV	0.1	0.0
4_1	Mean	0.0	0.0
	StDev	0.0	0.0
	COV	0.0	0.0
5_3	Mean	11.4	0.0
	StDev	11.8	0.0
	COV	1.0	0.0
9_1	Mean	8.9	1.1
	StDev	15.6	2.3
	COV	1.8	2.2
10_3	Mean	5.0	1.8
	StDev	5.8	3.5
	COV	1.2	2.0
12_5	Mean	12.5	11.2
	StDev	19.1	18.2
	COV	1.5	1.6
1_E_8	Mean	3.4	2.9
	StDev	6.6	5.7
	COV	1.9	1.6

The delamination test saw approximately 28% of the samples fail, with 10 out of the 36 samples not passing and 11 samples omitted for defects. The PRG 320 standard states that the percentage of samples that delaminate should not exceed 5%. Many of the omitted samples had failed due to delamination at the knots.

Moisture Content and Specific Gravity

The moisture content and specific gravity samples were cut from the off cuts of both the shear block and delamination samples. The specimens were cut to approximately 2” x 4.5” and had their initial weight and volume recorded. The samples were tested following the ASTM Standards D4442 and D2395 for obtaining moisture content and specific gravity. The samples 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 moisture content and specific gravity.

Moisture Content:

$$MC\% = \frac{A - B}{B} \times 100$$

Where A is the original mass and B is the oven dry mass in grams

Oven-dry Specific Gravity:

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

Where So is oven dry specific gravity, K constant determined by units used to measure mass and volume, mo is the oven-dry mass, and Vo is the oven-dry volume.

The average moisture content of the CLT was approximately 10.8% when tested, with a specific gravity of approximately 0.4. The full set of data can be seen in Appendix E, showing both the moisture content and specific gravity values.

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 center deflection of the samples was measured with a Linear Variable Differential Transformer (LVDT) attached to a yoke that spanned the entire sample (Figure 13). The samples were tested at a rate of 0.25 in/minute until failure, and had the actuator deflection, center deflection, load, and failure type recorded.

Figure 13: (A) Test Specimen, (B) Test specimen after bridge is removed, and (C) Tension failure of Specimen.

The recorded data was then used to calculate the Modulus of Rupture (MOR) and the Modulus of Elasticity (MOE), E_{app}. Formula 1 is the calculation for the MOR:

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

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 or E_{app}:

$$MOE = \frac{23Pl^3}{108bd^3\Delta}$$

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

Tables 4 and 5 illustrate the data summary for the flexure test for both lumber grades. In the tables the averages for the panels' Max Load, Modulus of Rupture, and Modulus of Elasticity are shown.

Table 4: Grades 2 and Better Long-Span 3rd Point Flexure Averages

Grade: 2 and better				
Panel	Stat	Max Load (lbf)	MOR (PSI)	MOE (PSI)
1	Mean	6942	3876	1647306
1	StDev	1333	744	596351
1	COV	0.19	0.19	0.36
2	Mean	8707	4861	1349292
2	StDev	872	487	107725
2	COV	0.10	0.10	0.08
4	Mean	7785	4346	1344306
4	StDev	1758	981	81979
4	COV	0.23	0.23	0.06
5	Mean	9145	5106	1351920
5	StDev	1476	824	127561
5	COV	0.16	0.16	0.09
11	Mean	9622	5372	1406123
11	StDev	1193	666	117778
11	COV	0.12	0.12	0.08
13	Mean	8086	4515	1176865
13	StDev	1312	733	90655
13	COV	0.16	0.16	0.08

Table 5: Grades 3 and Better Long-Span 3rd Point Flexure Averages

Grade: 3 and better				
Panel	Stat	Max Load (lbf)	MOR (PSI)	MOE (PSI)
6	Mean	8013	4474	1238021
6	StDev	1405	784	120353
6	COV	0.18	0.18	0.10
7	Mean	8792	4909	1382913
7	StDev	2480	1384	123520
7	COV	0.28	0.28	0.09
8	Mean	9290	5187	1447185
8	StDev	1672	934	52875
8	COV	0.18	0.18	0.04
9	Mean	9583	5350	1426448

9	StDev	1456	813	92066
9	COV	0.15	0.15	0.06
10	Mean	9637	5381	1352204
10	StDev	2324	1298	98586
10	COV	0.24	0.24	0.07
12	Mean	8645	4827	1313649
12	StDev	1589	887	105420
12	COV	0.18	0.18	0.08

The average MOR came to be approximately 4850 PSI, while the average MOE was approximately 1,259,710 PSI for all the CLT panels. When comparing data to other studies, Douglas-fir and Radiata Pine had MOR values of 5035 PSI and 3770 PSI, respectively, as well as MOE values of 1,260,378 PSI and 1,147,684 PSI, respectively (Wang et al. & Concu et al.). When comparing the averages of the MOR and MOE of the 2&BTR and 3&BTR there seemed to be little difference. **A Statistical analysis should be conducted for further investigation.**

Short-Span Flexure

The short-span flexure test specimens used the 12” x 24” strips that were cut from each panel. The samples were tested in center point bending following the ASTM D198-15 Standard Test Methods of Static Tests of Lumber in Structural Sizes. The testing used a span to depth ratio of 5.3:1, making a span of 22”. The samples were tested at a rate of 0.1 in/minute until failure, and had the actuator deflection, load, and failure type recorded.

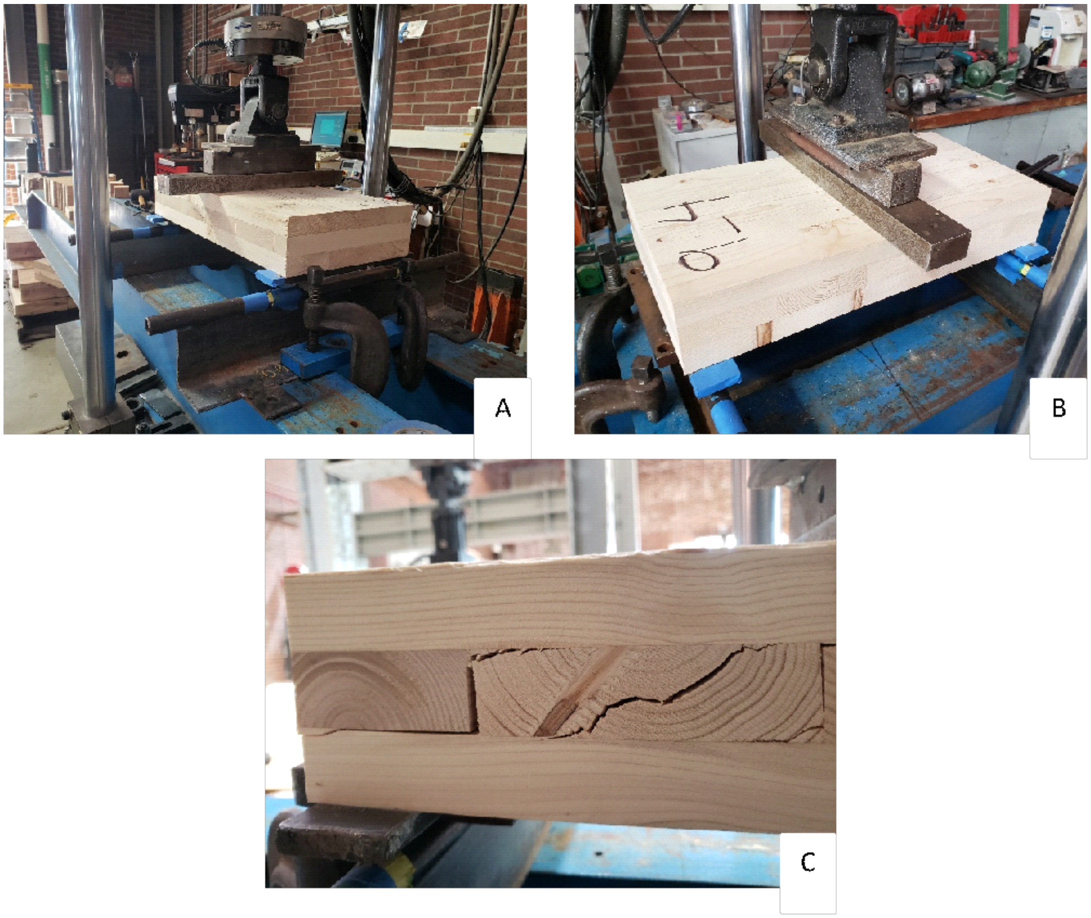

Figure 14: (A) and (B) short span testing setup side and top view, respectively. (C) Typical sample failure, failing in shear

The recorded data was then used to calculate the shear strength, f_v. Formula 3 is the calculation for the shear stress:

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

Where P_{max} is the max load, b is the width of the sample, and d is the thickness of the sample.

Table 6 and 7 illustrates the results of the flexure test. In the table the samples ID, Max Load, Shear Stress, and failure type are logged.

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Table 6: Grades 2 and Better Short-Span 3-Point Flexure Averages

2 and better			
Panel	Stat	Max Load (lbf)	Fv (PSI)
1	Mean	19953	302
	StDev	1125	17
	COV	0.06	0.06
2	Mean	20608	312
	StDev	2464	37
	COV	0.12	0.12
4	Mean	20351	308
	StDev	6408	97
	COV	0.31	0.31
5	Mean	21262	322
	StDev	3363	51
	COV	0.16	0.16
11	Mean	22544	342
	StDev	1214	18
	COV	0.05	0.05
13	Mean	21349	323
	StDev	759	11
	COV	0.04	0.04

Table7: Grades 3 and Better Short-Span 3-Point Flexure Averages

3 and better			
Panel	Stat	Max Load (lbf)	Fv (PSI)
3	Mean	16701	253
	StDev	1441	22
	COV	0.09	0.09
6	Mean	20542	311
	StDev	797	12
	COV	0.04	0.04
7	Mean	19148	290
	StDev	497	8
	COV	0.03	0.03
10	Mean	22853	346
	StDev	1336	20
	COV	0.06	0.06
12	Mean	19328	293

	StDev	2764	42
	COV	0.14	0.14

The overall average for the short-span shear strength was approximately 308 PSI with a coefficient of variation of approximately 14%. The samples all failed in shear near or at the bond line, with many showing rolling shear as seen in Figure 13c. Similarly to the long-span testing, the two different grades showed little difference in their average shear strength, with 2&btr at 319 PSI and 3&btr at 296 PSI.

Conclusions

3-ply CLT panels were fabricated using lumber from the white-fir species group and a variety of mechanical and physical testing was performed. The white-fir material required a significant amount of sorting to allow for proper planing, and during this sorting process boards with excessive twist, bow, and knots were rejected. Once pressed, the panels were cut into the proper sample dimensions and then tested.

The physical testing (shear block and delamination) showed there was reasonably good adhesive bonding with 72% of the delamination samples passing. By limiting the number of defects within the boards, better adhesive properties can be achieved, since knots and other defects can cause improper adhesive penetration. This was also seen in the shear block testing, with the samples that did not pass the inspection failing at knots.

The mechanical properties of the white-fir CLT showed to be similar to those obtained in prior studies performed on Douglas-fir and radiata pine. The tested samples had similar averages to that of an V1 panel as specified in the PRG 320 and failed in the typical failure mode of tension and shear.

We recommend that further investigation be conducted on the manufacturing of white-fir into CLT, by looking at other potential adhesives, as well as using white-fir that is sorted based on its mechanical properties by using machine stress ratings (MSR). Other steps that could be considered would be to have a commercial CLT manufacturer produce test panels and compare data from the lab fabrication and the commercial fabrication. Within commercial fabrication of CLT panels there are other factors that may affect the results. These include the finger jointing process, open/close times being reduced for higher efficiency, and automated assembly rather than hand layup.

Project Challenges

This project was impacted by a number of challenges that resulted in some scaling back of deliverables and schedule delays. Firstly, the project commenced during a series of wildfires, unprecedented in scale, that affected California, Oregon and Washington in August to October 2020. The fires meant that plans to collect samples from the working forests from which lumber was sourced had to be shelved. This, in turn, meant that it was not possible to use the USDA Wood Identification and Screening Center facilities at Oregon State University to analyze the precise species composition of the purchased lumber. TDI staff conferred with JIWPI regarding this issue and it was decided to move ahead with the testing without performing the species breakdown analysis.

COVID 19 also caused supply chain delays which impacted the project. TDI was in the process of designing a custom-made adhesive application system in early 2020, and this was a vital piece of equipment for ensuring accurate spread of adhesive across the CLT panel layers. The lead time for this equipment was delayed both by the wildfires (the supplier's facility in Southern Oregon was evacuated for several days) as well as by parts delays caused by business shutdowns related to COVID-19. As a result, the equipment was delivered and installed several months later than planned, and the TDI technical team had less time than was expected to calibrate, configure and test the new system prior to the start of the project. This did result in some teething troubles that caused two panels to be rejected, as is described elsewhere in this report.

Research activities were also temporarily halted several times during the period from September 2020 to February 2021 due to some students and staff of TDI and the OSU College of Forestry testing positive for COVID-19. This necessitated quarantining of key technical staff involved in fabricating the panels and conducting the tests. During these periods no technical work in our labs was possible.

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Appendices

Appendix A: Shear Block Test Results

ID	Grade	#	Side	Max Load (lbf)	Shear Strength (PSI)	Glue Failure (%)
1_3	2	1	A	1341	335	0
1_3	2	1	B	1227	307	0
1_3	2	2	A	1598	400	0
1_3	2	2	B	2455	614	95
1_3	2	3	A	1152	288	0
1_3	2	3	B	2186	547	0
1_3	2	4	A	1776	444	0
1_3	2	4	B	2968	742	0
1_3	2	5	A	1543	386	0
1_3	2	5	B	1361	340	0
1_3	2	6	A	1683	421	25
1_3	2	6	B	1488	372	0
1_3	2	7	A	2744	686	0
1_3	2	7	B	3128	782	0
2_7	2	1	A	2852	713	25
2_7	2	1	B	1084	271	0
2_7	2	2	A	1212	303	0
2_7	2	2	B	915	229	0
2_7	2	3	A	1572	393	0
2_7	2	3	B	1139	285	0
2_7	2	4	A	1466	366	95
2_7	2	4	B	1363	341	30
2_7	2	5	A	1218	305	0
2_7	2	5	B	830	208	25
2_7	2	6	A	1363	341	0
2_7	2	6	B	1615	404	50
2_7	2	7	A	1489	372	0
2_7	2	7	B	1116	279	0
2_7	2	8	A	1699	425	0
2_7	2	8	B	1528	382	0
2_7	2	9	A	1013	253	0
2_7	2	9	B	709	177	0
2_7	2	10	A	1642	411	0
2_7	2	10	B	1182	295	25
2_7	2	11	A	1115	279	0

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2_7	2	11	B	847	212	30
4_1	2	1	A	2988	747	0
4_1	2	1	B	1924	481	10
4_1	2	2	A	2430	607	0
4_1	2	2	B	1294	324	0
4_1	2	3	A	2737	684	10
4_1	2	3	B	2579	645	0
4_1	2	4	A	2204	551	0
4_1	2	4	B	1466	367	0
4_1	2	5	A	1847	462	5
4_1	2	5	B	764	191	85
4_1	2	6	A	3607	902	25
4_1	2	6	B	2917	729	0
4_1	2	7	A	1805	451	5
4_1	2	7	B	1608	402	0
4_1	2	8	A	2957	739	0
4_1	2	8	B	1381	345	0
4_1	2	9	A	602	150	90
4_1	2	9	B	980	245	0
4_1	2	10	A	2868	717	0
4_1	2	10	B	2092	523	0
4_1	2	11	A	1461	365	0
4_1	2	11	B	2846	712	0
5_3	2	1	A	1642	411	0
5_3	2	1	B	1432	358	0
5_3	2	2	A	2456	614	0
5_3	2	2	B	1052	263	0
5_3	2	3	A	1967	492	0
5_3	2	3	B	1331	333	10
5_3	2	4	A	2762	691	40
5_3	2	4	B	2233	558	5
5_3	2	5	A	1594	399	0
5_3	2	5	B	1600	400	0
5_3	2	6	A	3868	967	0
5_3	2	6	B	2577	644	0
5_3	2	7	A	1381	345	0
5_3	2	7	B	1079	270	0
5_3	2	8	A	990	248	0
5_3	2	8	B	1173	293	0
5_3	2	9	A	2473	618	0
5_3	2	9	B	2018	505	0

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5_3	2	10	A	2217	554	5
5_3	2	10	B	1872	468	0
5_3	2	11	A	1245	311	0
5_3	2	11	B	1000	250	0
5_3	2	12	A	1468	367	0
5_3	2	12	B	1789	447	0
9_1	3	1	A	2147	537	25
9_1	3	1	B	1691	423	0
9_1	3	2	A	1026	257	70
9_1	3	2	B	1825	456	70
9_1	3	3	A	1725	431	0
9_1	3	3	B	1369	342	0
9_1	3	4	A	1921	480	15
9_1	3	4	B	765	191	95
9_1	3	5	A	248	62	99
9_1	3	5	B	1822	455	55
9_1	3	6	A	1881	470	0
9_1	3	6	B	1353	338	0
9_1	3	7	A	1547	387	20
9_1	3	7	B	1216	304	0
9_1	3	8	A	3144	786	0
9_1	3	8	B	1894	473	0
9_1	3	9	A	1688	422	10
9_1	3	9	B	2205	551	0
9_1	3	10	A	2820	705	0
9_1	3	10	B	754	189	80
9_1	3	11	A	1813	453	0
9_1	3	11	B	1285	321	25
10_3	3	1	A	1051	263	0
10_3	3	1	B	897	224	0
10_3	3	2	A	1430	357	10
10_3	3	2	B	1589	397	0
10_3	3	3	A	2584	646	0
10_3	3	3	B	2229	557	0
10_3	3	4	A	1955	489	0
10_3	3	4	B	1168	292	50
10_3	3	5	A	1178	294	0
10_3	3	5	B	1658	415	10
10_3	3	6	A	2327	582	45
10_3	3	6	B	1598	400	0
10_3	3	7	A	1897	474	0

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10_3	3	7	B	1527	382	2
10_3	3	9	A	1204	301	0
10_3	3	9	B	1454	363	0
10_3	3	10	A	1402	350	0
10_3	3	10	B	1891	473	5
10_3	3	11	A	1799	450	0
10_3	3	11	B	1380	345	0
12_5	3	1	A	1783	446	0
12_5	3	1	B	1509	377	0
12_5	3	2	A	1351	338	0
12_5	3	2	B	1414	354	0
12_5	3	3	A	497	124	60
12_5	3	3	B	1376	344	0
12_5	3	4	A	1260	315	0
12_5	3	4	B	1006	251	75
12_5	3	5	A	2273	568	0
12_5	3	5	B	816	204	0
12_5	3	6	A	1151	288	0
12_5	3	6	B	919	230	70
12_5	3	7	A	1253	313	0
12_5	3	7	B	941	235	0
12_5	3	8	A	2494	623	0
12_5	3	8	B	2738	685	0
12_5	3	9	A	1902	476	5
12_5	3	9	B	1559	390	50
12_5	3	10	A	1366	342	0
12_5	3	10	B	1887	472	15
12_5	3	11	A	1260	315	0
12_5	3	11	B	1769	442	0

Appendix B: Delamination Test Results

ID	#	BL1	BL2	BL3	BL4	BL5	BL6	BL7	BL8	% Top BL	% Bottom BL
2_7	1	0	0	37	0	0	0	0	0	9.3	0.0
2_7	5	0	0	17	0	23	0	0	0	10.0	0.0
4_1	1	0	0	0	0	0	0	0	0	0.0	0.0
4_1	2	0	0	0	0	0	0	0	0	0.0	0.0
4_1	3	0	0	0	0	0	0	0	0	0.0	0.0
4_1	4	0	0	0	0	0	0	0	0	0.0	0.0
4_1	5	0	0	0	0	0	0	0	0	0.0	0.0
5_3	1	12	0	0	0	0	0	0	0	3.0	0.0
5_3	3	79	0	0	0	0	0	0	0	19.8	0.0
9_1	1	0	0	0	0	0	0	0	0	0.0	0.0
9_1	2	0	0	21	0	100	0	23	0	36.0	0.0
9_1	3	0	0	33	0	0	0	0	0	8.3	0.0
9_1	4	0	0	0	0	0	0	0	21	0.0	5.3
9_1	5	0	0	0	0	0	0	0	0	0.0	0.0
10_3	2	0	0	0	0	0	0	0	0	0.0	0.0
10_3	3	37	0	0	0	0	14	0	14	9.3	7.0
10_3	4	0	0	0	0	0	0	0	0	0.0	0.0
10_3	5	43	0	0	0	0	0	0	0	10.8	0.0
12_5	1	0	0	0	0	0	0	0	0	0.0	0.0
12_5	2	85	10	50	27	48	29	0	100	45.8	41.5
12_5	3	37	0	0	0	0	0	0	0	9.3	0.0
12_5	4	0	0	0	0	0	0	0	0	0.0	0.0
12_5	5	29	16	0	0	0	41	0	0	7.3	14.3

Appendix C: Long-Span Flexure Test Results

Specimen	Panel	Loc.	Grade	Max Load (lbf)	MOR (PSI)	MOE (PSI)
1_A	1	A	2	6022	3362	1294648
1_B	1	B	2	5178	2891	2647261
1_D	1	D	2	7191	4015	1172119
1_F	1	F	2	7917	4420	1391475
1_G	1	G	2	8404	4692	1731027
2_A	2	A	2	9451	5277	1466078
2_B	2	B	2	9636	5380	1466800
2_D	2	D	2	8706	4861	1274327
2_F	2	F	2	7534	4207	1251483
2_G	2	G	2	8206	4581	1287770
4_A	4	A	2	6793	3793	1295390
4_B	4	B	2	5729	3198	1328370
4_D	4	D	2	8435	4709	1469006
4_F	4	F	2	7598	4242	1373095
4_G	4	G	2	10371	5790	1255669
5_A	5	A	2	11732	6550	1572422
5_B	5	B	2	8247	4605	1281215
5_D	5	D	2	8872	4954	1353063
5_F	5	F	2	8174	4563	1282541
5_G	5	G	2	8698	4856	1270360
6_A	6	A	3	9461	5282	1425766
6_B	6	B	3	7297	4074	1228487
6_D	6	D	3	6500	3629	1206859
6_F	6	F	3	9563	5339	1238041
6_G	6	G	3	7244	4044	1090954
7_A	7	A	3	7089	3958	1287038
7_B	7	B	3	10770	6013	1461845
7_D	7	D	3	5919	3304	1219393
7_F	7	F	3	11844	6613	1509095
7_G	7	G	3	8339	4656	1437194
8_A	8	A	3	11430	6381	1506627
8_B	8	B	3	8041	4489	1481021
8_D	8	D	3	9713	5423	1377698
8_F	8	F	3	10048	5610	1408895
8_G	8	G	3	7218	4030	1461687
9_A	9	A	3	11151	6226	1528773

9_B	9	B	3	11139	6219	1497074
9_D	9	D	3	8612	4808	1427377
9_F	9	F	3	8097	4521	1298713
9_G	9	G	3	8914	4977	1380301
10_A	10	A	3	7981	4456	1333158
10_B	10	B	3	12383	6914	1517730
10_D	10	D	3	7802	4356	1324271
10_F	10	F	3	8051	4495	1252260
10_G	10	G	3	11970	6683	1333599
11_A	11	A	2	9667	5397	1544640
11_B	11	B	2	11454	6395	1499154
11_D	11	D	2	9690	5410	1408530
11_F	11	F	2	8183	4569	1300780
11_G	11	G	2	9118	5091	1277509
12_A	12	A	3	9751	5444	1379924
12_B	12	B	3	10229	5711	1299201
12_D	12	D	3	7285	4067	1145485
12_F	12	F	3	6633	3703	1322799
12_G	12	G	3	9328	5208	1420838
13_A	13	A	2	8872	4954	1196926
13_B	13	B	2	5926	3309	1037348
13_D	13	D	2	8734	4876	1251904
13_F	13	F	2	7771	4338	1142557
13_G	13	G	2	9128	5096	1255591

Appendix D: Short-Span Flexure Test Results

Specimen	Panel	Loc.	Grade	Max Load (lbf)	Fv (PSI)
1_2	1	2	2	20273	307
1_4	1	4	2	20883	316
1_8	1	8	2	18702	283
2_2	2	2	2	19331	293
2_4	2	4	2	23036	349
2_6	2	6	2	22271	337
2_8	2	8	2	17794	270
3_2	3	2	3	17465	265
3_4	3	4	3	14828	225
3_6	3	6	3	18127	275
3_8	3	8	3	16384	248
4_2	4	2	2	25497	386
4_4	4	4	2	10983	166
4_6	4	6	2	22360	339
4_8	4	8	2	22565	342
5_2	5	2	2	24292	368
5_6	5	6	2	21851	331
5_8	5	8	2	17643	267
6_2	6	2	3	20228	306
6_4	6	4	3	21213	321
6_6	6	6	3	19559	296
6_8	6	8	3	21166	321
7_2	7	2	3	18644	282
7_4	7	4	3	19833	300
7_6	7	6	3	19078	289
7_8	7	8	3	19037	288
10_2	10	2	3	21383	324
10_4	10	4	3	23993	364
10_8	10	8	3	23182	351
11_2	11	2	2	21515	326
11_4	11	4	2	24197	367
11_6	11	6	2	21766	330
11_8	11	8	2	22697	344
12_2	12	2	3	20084	304
12_4	12	4	3	22424	340

12_6	12	6	3	15769	239
12_8	12	8	3	19033	288
13_2	13	2	2	22323	338
13_4	13	4	2	20507	311
13_6	13	6	2	21456	325
13_8	13	8	2	21112	320

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Appendix E: Moisture Content and Specific Gravity

Sample ID	MC%	SG
2-1	10.6%	0.405
2-2	12.5%	0.379
2-3	10.5%	0.381
2-4	10.5%	0.413
2-5	11.1%	0.380
4-1	8.7%	0.407
4-2	11.2%	0.397
4-3	10.2%	0.428
4-4	10.1%	0.432
4-5	10.9%	0.409
5-1	10.2%	0.396
5-2	10.4%	0.392
5-3	8.5%	0.427
5-4	8.8%	0.406
5-5	10.3%	0.406
9-1	9.6%	0.407
9-2	9.4%	0.401
9-3	12.1%	0.406
9-4	7.7%	0.396
9-5	8.6%	0.406
12-1	22.2%	0.381
12-2	14.1%	0.366
12-3	11.7%	0.391
12-4	8.8%	0.365
12-5	10.6%	0.367
Mean	10.8%	0.398
SD	2.78%	0.018
COV	25.77%	4.64%

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