Development of Technology for Cross Laminated Timber Building Systems

Research Report
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EXECUTIVE SUMMARY

The interest in using CLT (Cross Laminated Timber) panel for building construction in North America is growing. However, as a practically newly innovated engineered wood product, it is short of engineering data regarding its behavior during the service. Therefore, it is necessary to generate such data, which are important for building design, supporting and enhancing further development and commercialization of this type of building material. The objectives of the research are investigating the rolling shear failure and the fatigue of CLT panels related to their application, manufacturing process variables and load duration response.

In this research, a Poly-Urethane adhesive, two types of wood (SPF and Hem-Fir) and two different pressures (0.1 and 0.4 MPa) were employed in manufacturing the CLT panels. 3-layer and 5-layer panels were made of SPF wood, whereas only 5-layer panels were made of Hem-Fir. The average apparent MOE (Modulus of Elasticity) of the panels was found to be 10.25 and 9.92 GPa for 3-layer SPF, 9.36 and 9.00 GPa for 5-layer SPF, and 10.33 and 9.72 GPa for 5-layer Hem-Fir, respectively for 0.1 and 0.4 MPa of pressures. Compared to MOE of the wood, the distribution of MOE values of 5-layer Hem-Fir CLT panels was found below the 11th percentile of MOE values of grade L_1 laminae. For SPF panels, it was found below the 31st percentile (for 5-layer panels) and below the 57th percentile (for 3-layer panels) of MOE values of SPF grade No.2^{+} used as the longitudinal layers. The maximum rolling shear capacity of all CLT panels made at 0.4 MPa of pressure was found to be higher than those made at 0.1 MPa of pressure. It was also higher for all panels made of SPF wood as compared to those made of Hem-Fir at the same pressure. Due to time constraint the cyclic bending test can only be completed for 5-layer Hem-Fir panels at this point in time. The test results showed that the number of cycles to failure varied greatly from test-specimen to test-specimen and from panel to panel regardless of pressures.

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1 INTRODUCTION

Cross Laminated Timber (CLT) has been commercially produced in Europe. In other part of the world, such as Japan and Taiwan, investigation on the possibility of adopting this product concept has started with their domestic species Sugi (*Cryptomeria japonica*). In Canada the interest is growing, particularly driven by the availability of huge amount of mountain pine beetle killed wood. An estimated volume of 620 million cubic meters of timber is available in British Columbia since the current infestation began. However, this type of wood contains blue stain in the sapwood and extensive checking that lower its commercial value for use as dimension lumber. For CLT panel the lower grade wood can be used as the core and/or cross layers. It is anticipated that this will not significantly affect the appearance or the strength properties of the panel.

Initially, the CLT building concept faced skepticism because the massive use of timber was considered wasteful and non-economical compared to North American light frame 2 x 4 construction method. However, CLT offers several advantages, such as high strength properties, high dimension stability and good fire resistance/confinement. In addition, it can be prefabricated, so it can shorten the construction time significantly. In Europe CLT has been used to build many low-rise and mid-rise buildings. Eventually, the CLT building concept is gradually getting acceptance in North America, as the University of British Columbia will build a CLT building from BC-made CLT. It is the first CLT building built with local component.

As CLT is practically a new building material in North America, it is short of engineering data and information regarding the behavior of the material during service. Therefore, the objective of the research is to develop the necessary engineering data to support the commercialization of BC-made CLT by studying in detail the rolling shear failure mode of the CLT in relation to its application, manufacturing process variables and load duration response. The research was conducted by Timber Engineering and Applied Mechanics (TEAM) Laboratory, Department of Wood Science, Faculty of Forestry, University of British Columbia, Vancouver, B.C. and funded by Forestry Innovation Investment (FII) Ltd. In this research TEAM Lab collaborates with CST Innovation Ltd. in New Westminster, B.C. to use their facility to manufacture the panels.

2 MATERIALS AND METHODS

2.1 Materials

Two types of wood, i.e., Hem-Fir (second growth BC coastal Hemlock) and SPF (including mountain pine beetle killed wood), were used in this study. Hemlock laminae were obtained from a previous TEAM (Timber Engineering and Applied Mechanic) research project (Yawalata *et al.*, 2010a). The actual dimension of the laminae had been measured. The average width was 117.6 mm (Stdev = 1.6 mm), the thickness was 30.2 mm (Stdev = 0.2 mm) and the length was 4000 mm. The moisture content and MOE (Modulus of Elasticity) of laminae were determined. The MOE values were determined by a vibration test method (Fig. 1). The laminae were graded by a certified lumber grader according to NLGA rule.

The SPF wood was bought from the industry in form of 2 x 6 (38 x 140 x 3658 mm) dimension lumber grade No. 2^+ and 2 x 6 (38 x 140 x 2743 mm) contractor stud. The wood was re-dried to an intended moisture content of about 12 %. The actual dimension and moisture content of the lumber was measured. The wood was also subjected to e-rating by a vibration test method before cutting and planning into desired dimensions required for manufacturing the CLT panels.

2.2 Methods

2.2.1 Manufacturing of CLT panels

Hem-Fir CLT panels were composed of 5 layers. L_1 grade laminae were used for the surface (top and bottom) layers, whereas L_2 grade laminae were used for the cross and core layers. The size of the panels was 1219.2 mm (4 ft) x 4000 mm. The cross layers were laid perpendicular (90 degrees) to the surface layers. All laminae were planed into 114 mm wide and 27.5 mm thick. The panels were glued with PURBOND HB E202, a fast-cure Poly-Urethane adhesive with 20 min open time, at two different pressures, i.e., 0.1 MPa (14.5 psi) and 0.4 MPa (58.02 psi). The spread rate of adhesive was 160 g/m^2. The cure (press) time was 60 min. The number of replicates was 3, so the total number of panels made was 6.

SPF CLT panels were made in 3 and 5 layers with 0.1 and 0.4 MPa of pressure. Dimension lumber 2 x 6 grade No. 2^+ was used for the top, core (especially for 5-layer) and bottom layers, whereas 2 x 6 contractor stud was used for the cross layers. After e-rating (Fig. 1), dimension and moisture content measurements, the wood was cut and/or planed into the sizes of 34 x 138 mm and 19 x 138 mm (for cross layers of 5-layer panels). For 3-layer panels, the thickness configuration was 34 + 34 + 34 mm (= 102 mm). For 5-layer panels, it was 34 + 19 + 34 + 19 + 34 mm (= 140 mm). The actual dimension of the panels was measured at the time the MOE (Modulus of Elasticity) bending test conducted. The adhesive used to make SPF panels was also PURBOND HB E202. The spread rate of adhesive was 160 g/m^2. The cure (press) time was 75 min. The number of replicates was 3, so the total number of panels made was 12. All CLT panels were subjected to mechanical properties test.

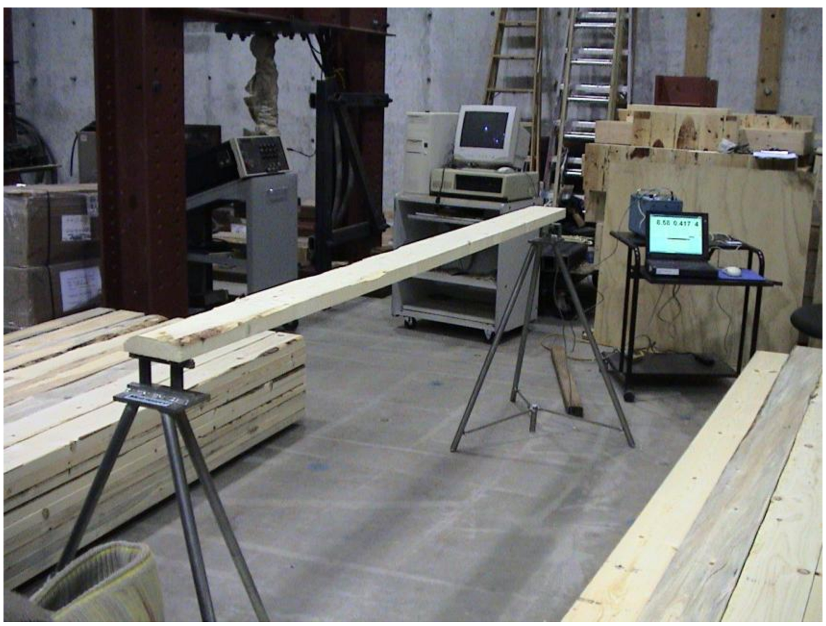

Figure 1 Setup of MOE vibration test.

Figure 2 Manufacturing of 3-layer and 5-layer CLT panels.

2.2.2 Mechanical properties test of CLT panels

The CLT panels were subjected to a bending test to determine the MOE values. After e-rating, the panels were cut into smaller specimens for rolling shear and cyclic bending tests.

2.2.2.1 MOE bending test

The MOE bending test was carried out on the CLT panels. The actual size of the panels was recorded. The test span was 3658 mm (144 in.) for Hem-Fir CLT panels and 3353 mm (132 in.) for SPF panels. The loading method was Third-Point Loading. The speed of testing was 3 mm/min. Deflection was measured by using 10 transducers (pots), located at the ends of the span (the reaction point), mid-span and third-spans on both sides of the panel (see Fig. 3). The deflection was measured up to 20 mm based on the transducers placed in the mid-span.

Figure 3 Setup of MOE bending test of CLT panel.

2.2.2.2 Rolling shear test

Ten test specimens were cut from each CLT panel. The width was 50.8 mm (2 in.), whereas the length was 914.4 mm (36 in.) for 5-layer and 685.8 mm (27 in.) for 3-layer panels. The exact size of each test specimen was measured and recorded during the test. The test was conducted at a span-depth ratio of 6. Thereby, the test span was 838.2 mm (33 in.) for 5-layer and 609.6 mm (24 in.) for 3-layer panels. The speed of testing was 2 mm/min (0.08 in./min) for 5-layer panels and 1.5 mm/min (0.06 in./min) for 3-layer panels, in which speed the time to failure was about 10 min. The loading method was Center-Point Loading. A high speed video camera was also employed to observe the course of failure. The test setup is shown in Fig. 4.

Figure 4 Setup of rolling shear and cyclic bending tests.

2.2.2.3 Cyclic bending test

Ten test specimens were cut from each CLT panel. The size of test specimen and the test setup were set to be the same as those of rolling shear test (Fig. 4). The load applied was of the 25th percentile of MOR (Modulus of Rupture) values obtained from rolling shear test. The loading rate was 37.5 kN/min. The load was cyclically applied until the test specimen totally failed. The number of cycles was recorded.

3 RESULTS AND DISCUSSION

3.1 Moisture Content of the wood

Moisture content of the wood used to manufacture the CLT panels can be seen in the following table and figures. In general, the average moisture content was about 13 %. For more detail regarding the moisture content distribution of each type of wood and grade, it can be seen in Figures 5 – 8. As it is shown in the figures, there were few pieces of wood having moisture content of 20 % or greater. It should be noted that these pieces were discarded. Particularly for Hem-Fir laminae, the moisture content presented was previously determined.

However, after randomly checking few pieces, the moisture content was found to be within the range of previous measurement.

Table 1 Moisture content of the wood (%).

Type of wood	Hem-Fir laminae		SPF 2x6	
Grade	L_1	L_2	Stud	No.2$^+$
Average	12.7	13.0	12.9	13.2
Stdev	2.2	2.4	3.2	1.6
Cov (%)	16.9	18.6	24.7	12.1
Minimum	8.5	8.6	7.8	10.2
Maximum	22.6	27.4	49	26.2
Count (N)	330	276	256	280

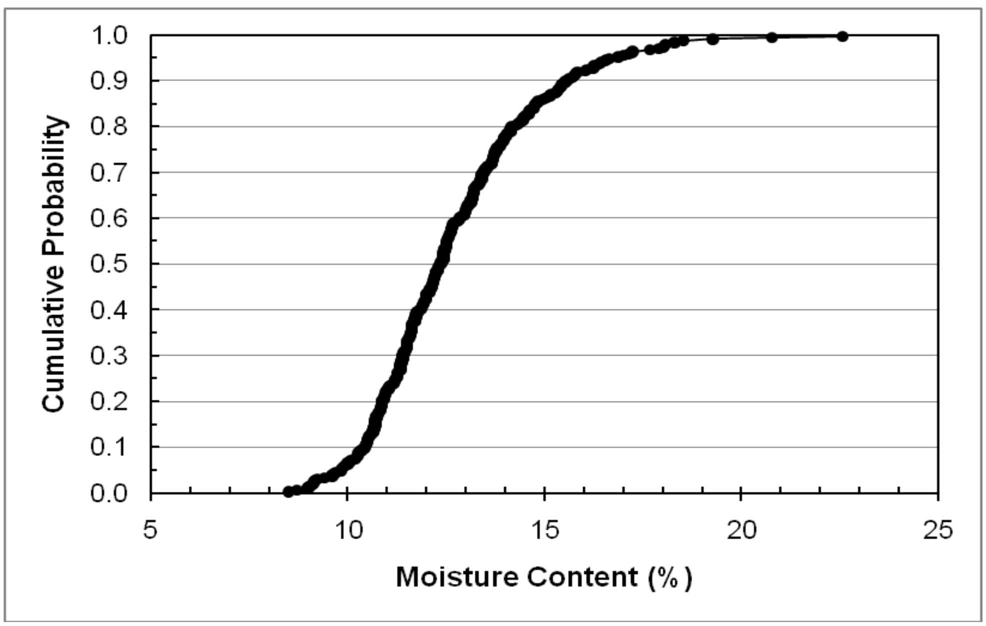

Figure 5 Distribution of moisture content of Hem-Fir laminae grade L_1.

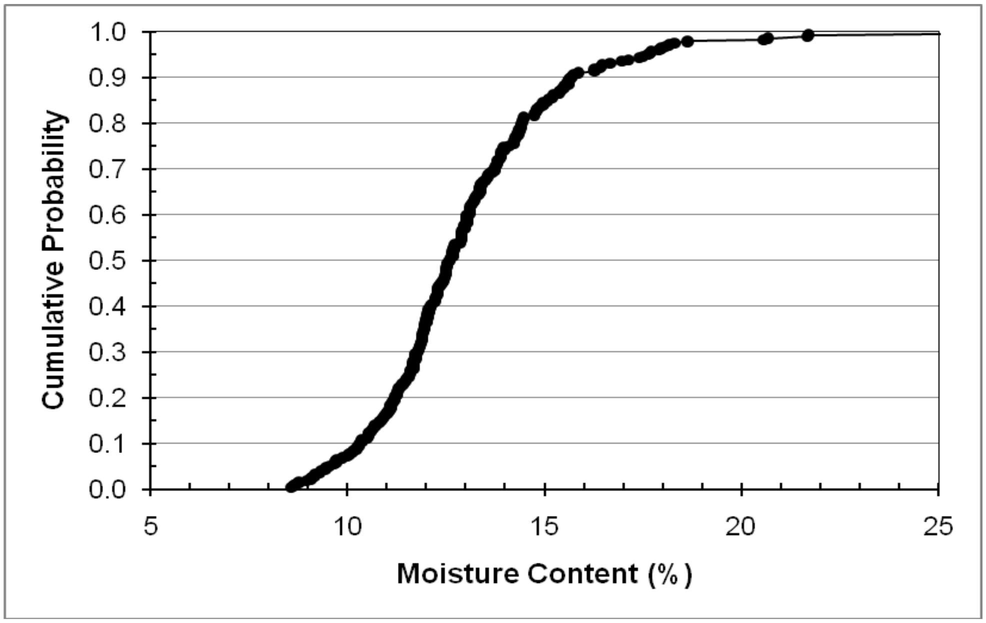

Figure 6 Distribution of moisture content of Hem-Fir laminae grade L_2.

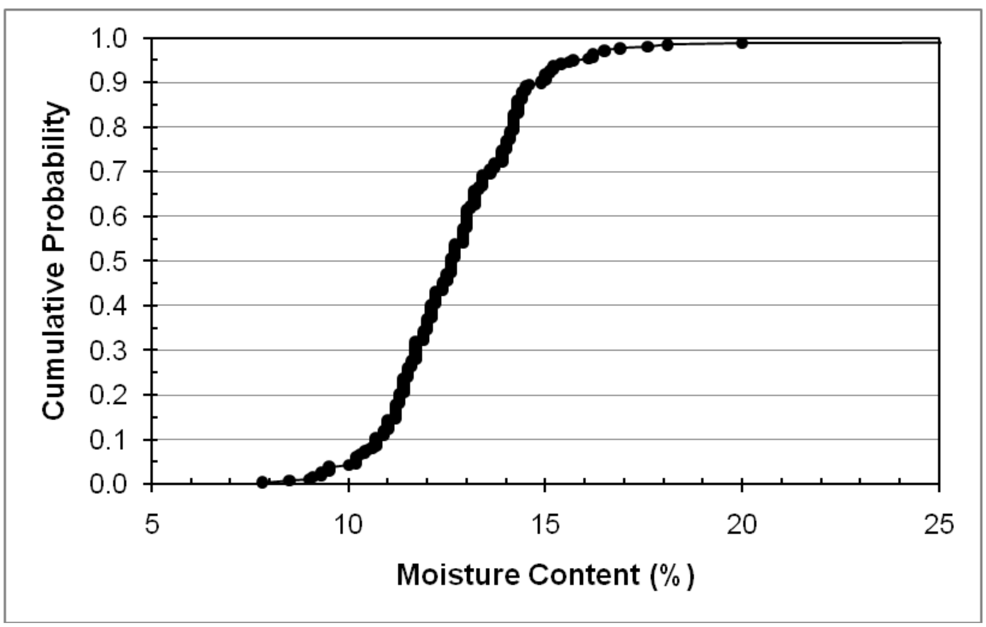

Figure 7 Distribution of moisture content of SPF 2x 6 contractors Stud.

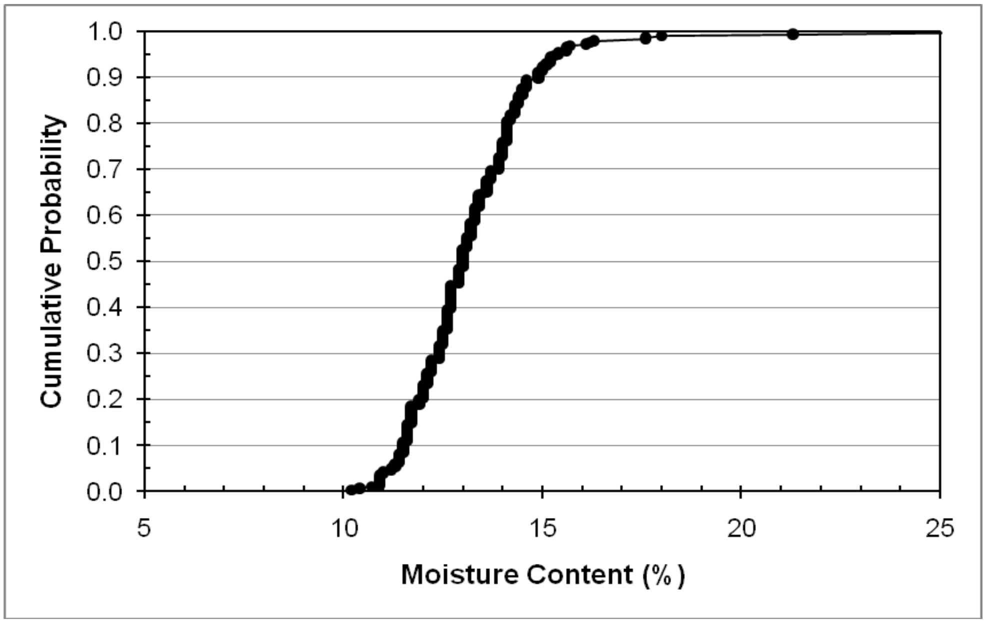

Figure 8 Distribution of moisture content of SPF 2x6 No.2$^+$.

3.2 MOE of the wood

The results of vibration test to determine MOE values of the wood are summarized in Table 2, whereas the distributions of the MOE values are shown in Figures 9-12. Generally, the MOE values of Hem-Fir were higher than those of SPF wood. As can be seen in Table 2, the average MOE values of Hem-Fir were 13.83 GPa (grade L_1) and 12.01 GPa (Grade L_2), while the average MOE values of SPF were 11.43 GPa (9-ft contractor stud) and 10.66 GPa (12-ft No.2$^+$). As shown in Figures 9 and 10, only 4 % of grade L_1 and 22 % of grade L_2 Hem-Fir were found to have MOE values of 10.0 GPa or lower, whereas for SPF the proportion was higher, 24 % for contractor stud and 36 % for grade No. 2$^+$ (Figs. 11 and 12).

Table 2 MOE of the wood (GPa).

Type of wood	Hem-Fir laminae		SPF 2x6	
Grade	L_1	L_2	Stud	No.2$^+$
Average	13.83	12.01	11.43	10.66
Stdev	2.34	2.43	1.88	1.97
Cov (%)	16.9	20.3	16.4	18.5
Minimum	7.14	5.83	5.36	4.23
Maximum	20.55	18.75	16.13	16.32
Count (N)	329	276	256	280

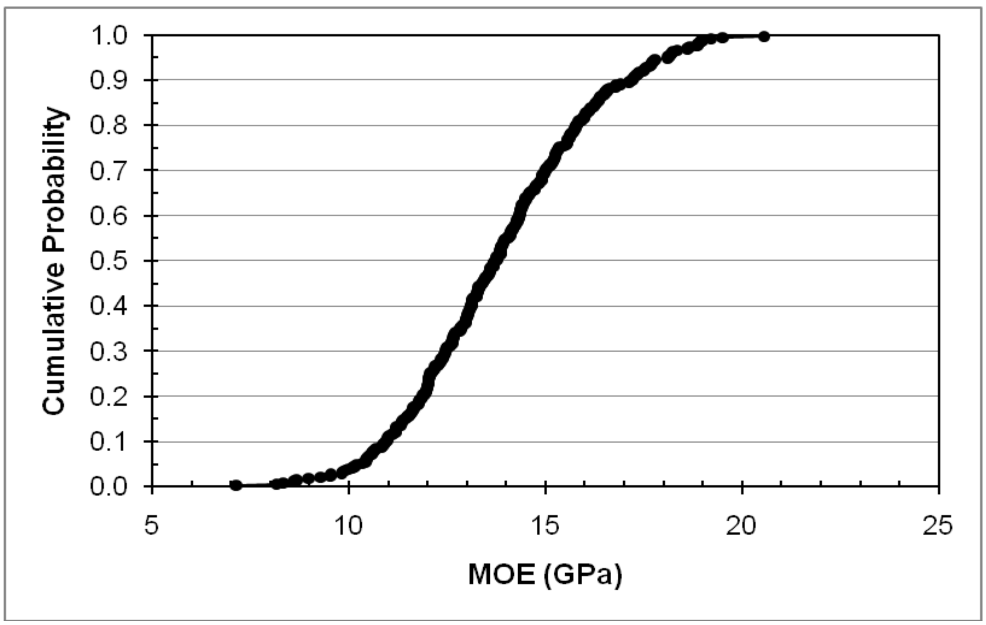

Figure 9 Distribution of MOE values of Hem-Fir laminae grade L_1.

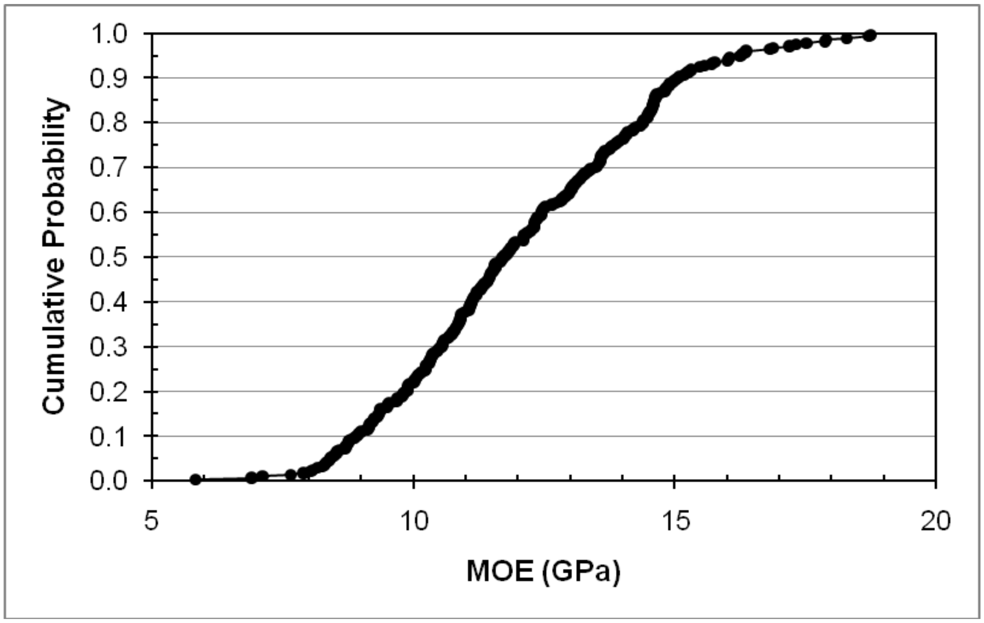

Figure 10 Distribution of MOE values of Hem-Fir laminae grade L_2.

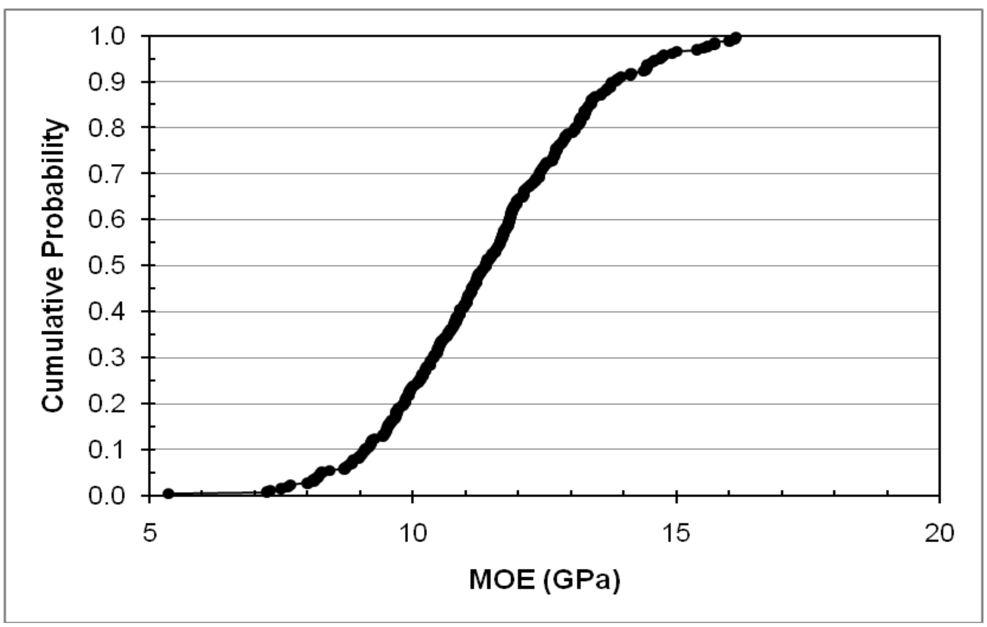

Figure 11 Distribution of MOE values of SPF 2x6 contractor Stud.

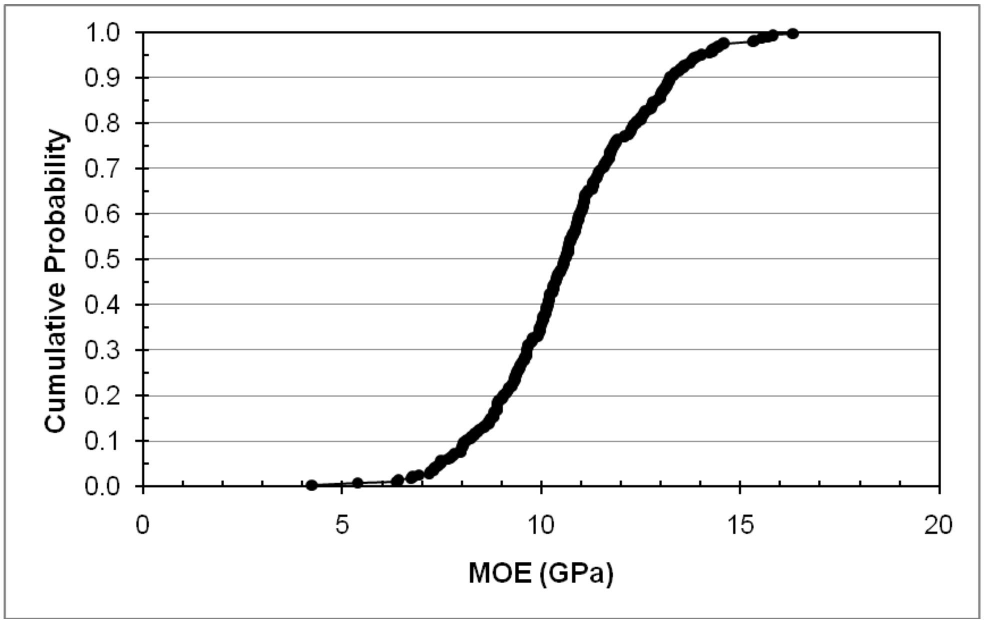

Figure 12 Distribution of MOE values of SPF 2x6 No.2^+.

3.3 MOE of CLT Panels

The results of bending test to determine MOE values of CLT panels are presented in Tables 3-5. As described in Section 2.2.1., the CLT panels were made at two different pressure levels however the effect of pressure will not materialize below the proportional limit where the MOE value is determined. Therefore, the effect of pressure cannot be evaluated at this point. In term of species effect, the MOE values of 5-layer Hem-Fir were slightly higher than those of 5-layer SPF panels (see Tables 3 and 4). This phenomenon appears to be consistent with MOE of the wood.

If compared to the distribution of MOE values of the wood, the distribution of MOE values of 5-layer Hem-Fir panels was found below the 11th percentile of MOE values of grade L_1 laminae. For SPF panels, it was found below the 31st percentile (for 5-layer) and below the 57th percentile (for 3-layer) of MOE values of SPF grade No. 2^+ used as the longitudinal layers.

In current study the CLT panel was made of the same wood species. However, in a previous TEAM research project (Yawalata *et al*., 2010b) with a Poly-Urethane adhesive, 5-

layer mixed species panels have been made and studied. The panel was composed of SPF wood as the longitudinal layers and Hem-Fir for the cross layers. The MOE values were 9.39 – 9.73 GPa (apparent MOE) and 9.09 – 10.10 GPa (true MOE). These values are comparable to those currently obtained (Table 4).

Table 3 MOE of 5-layer Hem-Fir CLT panels.

Specimen No.	Apparent MOE (GPa)		True MOE (GPa)	
	0.1 MPa	0.4 MPa	0.1 MPa	0.4 MPa
01	9.85	9.50	9.58	9.11
02	10.15	9.91	9.68	9.45
03	10.98	9.77	10.62	9.20
Average	10.33	9.72	9.96	9.26

Table 4 MOE of 5-layer SPF CLT panels.

Specimen No.	Apparent MOE (GPa)		True MOE (GPa)	
	0.1 MPa	0.4 MPa	0.1 MPa	0.4 MPa
01	9.49	9.36	9.65	9.30
02	9.38	8.94	9.40	9.26
03	9.21	8.70	9.24	8.58
Average	9.36	9.00	9.43	9.05

Table 5 MOE of 3-layer SPF CLT panels.

Specimen No.	Apparent MOE (GPa)		True MOE (GPa)	
	0.1 MPa	0.4 MPa	0.1 MPa	0.4 MPa
01	10.71	9.66	10.85	9.73
02	10.13	10.23	9.98	10.19
03	9.92	9.87	9.91	9.81
Average	10.25	9.92	10.25	9.91

3.4 Rolling Shear Strength of CLT Panels

Rolling shear is a typical phenomenon occurred when the wood is glued with grain direction of adjacent layer in perpendicular to one another, such as CLT panel. In this research a short span static bending test with span-depth ratio of 6 was set to evaluate the rolling shear strength (nominal) of the CLT panel. The test results showed that majority type of failure taking place was rolling shear and/or shear (Fig. 13). However, occasionally tension type of failure also occurred as can be seen in Figure 13 bottom right.

The results of rolling shear test are summarized in Table 6. As shown in the table, the maximum rolling shear strength (nominal) of all CLT panels made at 0.4 MPa of pressure was found to be higher than those made at 0.1 MPa of pressure. This finding indicates that the vacuum pressure, which is lower than 0.1 MPa, may not be sufficient to provide a good and strong bonding in CLT panel. On the other hand, it seems to suggest that probably applying a pressure higher than 0.4 MPa may result in better and stronger bonding, which is subsequently producing stronger panels.

Regarding wood species, the 5-layer panels made of SPF wood was also found to be higher in maximum rolling shear strength (nominal) as compared to Hem-Fir panels although the Hem-Fir laminae have higher MOE values than the SPF wood. The difference seems to be contributed by thicker longitudinal layers and thinner cross layers of SPF panels, as described in Section 2.2.1.

Table 6 Rolling shear strength of CLT panels.

Test group	Peak Load mean	MOR	Max. Rolling Shear Strength (nominal)	COV	Number of specimens
	KN	MPa	MPa	%	
HemFir5-0.1MPa	19.06	24.27	1.62	11.7	30
HemFir5-0.4MPa	19.70	25.29	1.68	12.1	30
SPF5-0.1MPa	20.98	25.62	1.85	16.2	30
SPF5-0.4MPa	21.78	26.78	1.93	7.1	30
SPF3-0.1MPa	15.13	25.73	2.04	10.8	30
SPF3-0.4MPa	16.51	28.27	2.22	19.0	30

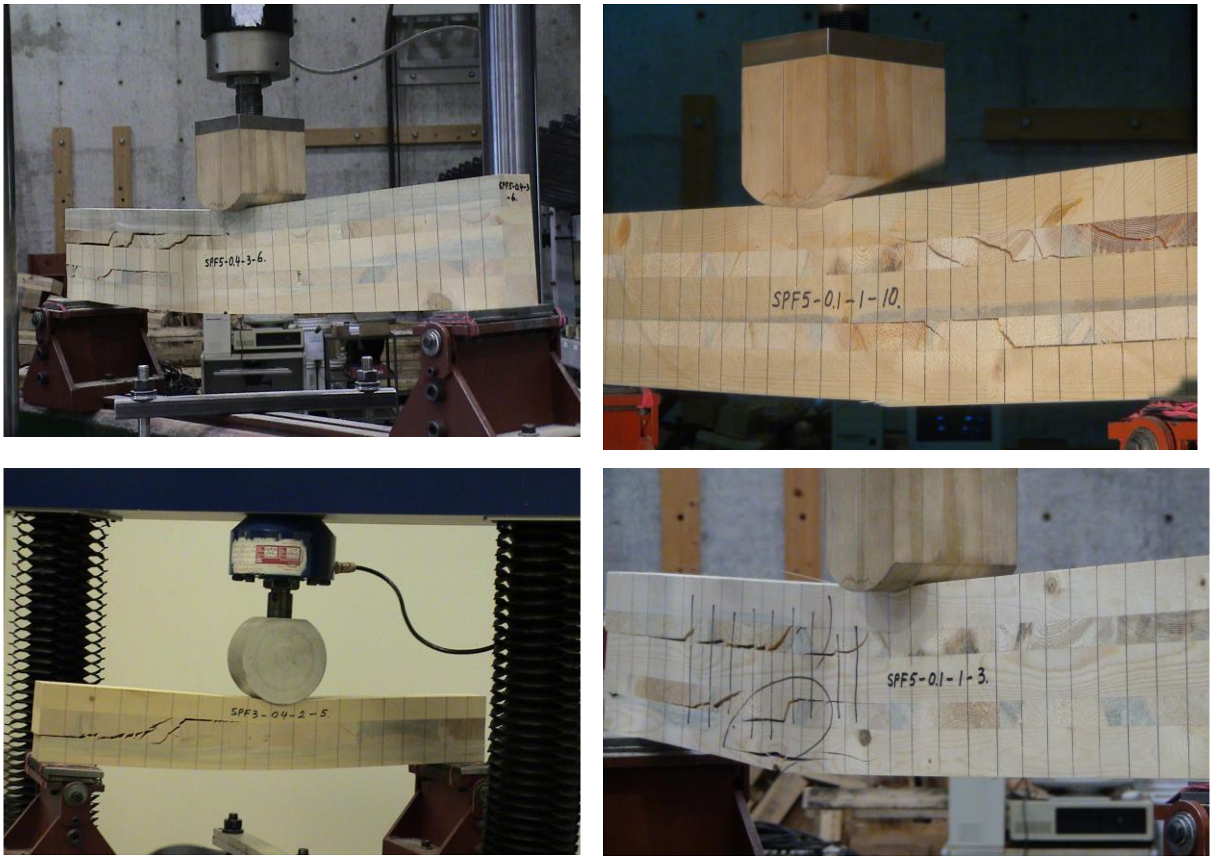

Figure 13 Type of failure occurred in the short span static bending test of CLT panels.

3.5 Cyclic Bending Test of CLT Panels.

At this point in time, the test can only be completed for 5-layer Hem-Fir panels because of time constraint and time consuming nature of the test. The test results as presented in Table 7 showed that the number of cycles to failure varied greatly from test-specimen to test-specimen and from panel to panel regardless of pressures. The number of cycles could be as few as 1 up to more than 300.

Table 7 Results of cyclic bending test for 5-layer Hem-Fir CLT panels.

Panel No.	Specimens / panel	Load for low cycle fatigue tests		Number of cycles to failure		
		25th% Strength Load (N)	Load Ratio of 25th%/Mean	Mean	STDEV	Not fail (>300)
HemFir5-0.1-01	10	17383.6	0.948	6	6.68	0
HemFir5-0.1-02	10	20353.8	0.965	89	85	0
HemFir5-0.1-03	10	15658.4	0.882	103	110.76	2
HemFir5-0.4-01	10	19000.9	0.938	22	25.38	0
HemFir5-0.4-02	10	17407.5	0.876	36	39.54	0
HemFir5-0.4-03	10	17932.1	0.946	23	35.26	0

4 CONCLUSIONS

Investigation of manufacturing variables related to mechanical properties of CLT panels has been conducted. The distribution of MOE values of 5-layer Hem-Fir panels was found to be below the 11^{th} percentile of MOE values of grade L_1 laminae. For SPF panels, the MOE values distributed below 31^{st} percentile (for 5-layer panels) and below the 57^{th} percentile (for 3-layer panels) of MOE values of SPF grade No. 2^{+} used as the longitudinal layers. The maximum rolling shear strength (nominal) was found to be higher for all panels made at 0.4 MPa of pressure. It was also higher for all panels made of SPF wood as compared to those made of Hem-Fir at the same pressure. The cyclic bending test results of 5-layer Hem-Fir panels found that the number of cycles to failure varied greatly from test-specimen to test-specimen and from panel to panel regardless of pressures.

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