Connection and performance of two-way CLT plates

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Prepared for

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ACCREDITED
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TL-333

April 6, 2018

EXECUTIVE SUMMARY

The two-way action of Cross Laminated Timber (CLT) is often ignored in the design of CLT due to its complexity. But in some cases, for example, large span timber floor/roof, the benefit of taking the two-way action into account may be considerable since it is often deflection controlled in the design. Furthermore CLT panels are typically limited to widths of less than 3 m. therefore, for practical applications, engaging CLT panels in two-way action as a plate in bending would require connecting two panels in the width/minor direction to take out-of-plane loading. To address this technically difficult situation, an innovative connection was developed to join the CLT panels in the minor direction to form a large continuous two-way plate. The two-way action of CLT was also quantified.

Static bending test was conducted on CLT panels in the major and minor directions to measure the Modulus of Elasticity (MOE). This provided a benchmark for the following connection test, and data for the future development of computer modeling. The average apparent MOE was 9.09 GPa in the major direction and 2.37 GPa in the minor direction.

Several connection techniques were considered and tested, including self-tapping wood screws, glued in steel rods, and steel connectors. One connecting system was found to be effective. For the panel configuration considered, the system was consisted of steel plates, self-tapping wood screws, and 45° screw washers. Two steel plates were placed on the tension side with sixteen screws, and one steel plates was placed on the compression side with four screws. When the screws were driven into the wood, the screws were tightly locked with the washers and steel plates, and at the same time, the wood members were pulled together by the screws. This eliminated any original gap within the connection.

The connector was installed to join two CLT members in the minor direction. They were tested under bending with the same setup as above. The connected panels had an average apparent MOE of 2.37 GPa, and an average shear-free MOE of 2.44 GPa, both of which were higher than the counterpart in the full panels. The moment capacity of the connected panels was also high. The minimum moment capacity was 3.2 times the design value.

Two large CLT panels were tested under concentrated loading with four corners simply supported. The deflection of nine locations within the panels was measured. This data will be used to validate the computer modeling for CLT two-way action.

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1 INTRODUCTION

Cross Laminated Timber (CLT) is an important structural element widely used as walls and floor/roof members in mass timber construction. Typically CLT floors are considered as one-way bending elements supported by walls or beams, although CLT has two way plate bending capacity as a result of the multiple alternating layers of wood elements. Since the governing factor for floor design is often deflection, CLT with two-way bending action may be a plausible solution for large span timber floor/roof. The minor direction may make considerable contribution to the stiffness of CLT, especially for thicker panels.

Commercially available CLT panels are typically limited to widths of less than 3 m. For practical applications, engaging CLT panels in two way action as a plate in bending would normally require connecting two panels in the width/minor direction. This connection system would need to allow the CLT panels to sustain out-of-plane loading. This project developed and tested connections used to join multiple CLT panels into a large continuous two-way plate, and the two-way action of CLT plate was quantified.

2 MATERIAL AND METHODS

The material used in the manufacturing and testing of specimens is shown in Table 1. The CLT was E1M5 175E 5 layer, manufactured by Structurlam Products Ltd. (Penticton, BC). The lumber in the major direction layers was MSR 2100 1.8E Spruce-Pine-Fir (SPF), and the lumber in the minor direction layers was SPF #2 & Better. The screws, washers, and pre-drilling jig were made by SWG Schraubenwerk Gaisbach GmbH (Waldenburg, Germany). The screws were fully threaded self-tapping wood screws with a diameter of 12 mm, and a length of 140 mm.

Table 1 Material list

Item	Description
CLT	E1M5 175 E 5 layer, 175 mm thick
Screws	ASSY Plus VG screws 12×140, CSK head, milling pocket
Washers	45° washers for 12 mm countersunk screw head
Steel plate	A36, 6.4 mm thick, 127 mm wide
Pre-drilling jig	For 12 mm screws at 45°

Table 2 Test configurations

Test	Replicates	Orientation	Specimen size
Bending test	10	Major	Width 305 mm, length 3.66 m
	10	Minor	Width 305 mm, length 3.66 m
Connection test	10	Minor	Width 305 mm, length 3.66 m
Two-way plate test	2	Both	Width 1.83 m , length 3.66 m

Three types of tests were conducted: the bending tests measured the Modulus of Elasticity (MOE) of intact CLT panels in its major and minor direction; the connection tests investigated the performance of two CLT panels joined together in the minor direction; the two-way plate tests evaluated the behavior of CLT in the two directions under a concentrated load in the center. The test configurations are shown in Table 2.

2.1 CLT bending test

The static bending test was conducted in accordance with the third-point load method in ASTM D198-15. The load was applied equally on two loading points located at one third of the span from the reactions. The test setup is shown in Figure 1. The span was 3150 mm and the span/depth ratio was 18:1. The loading rate was 5 mm/min. The deflection of the midspan relative to the supports on the neutral axis, and the deflection of the midspan relative to the two loading points on the neutral axis were measured by two LVDT transducers with yokes. The specimens with surface layers in the major direction was loaded to 20 kN, and the specimens with surface layers in the minor direction was loaded to 10 kN. The test was non-destructive since only MOE was to be measured. The moisture content of CLT was measured by Delmhorst RDM wood moisture meter.

Figure 1 CLT bending test setup

Two types of modulus of elasticity were defined and calculated in accordance with Section X.2 of ASTM D198-15. The apparent modulus of elasticity (MOE_{app}) was determined by the deflection of the midspan in relation to the two supports, thus MOE_{app} included the shear effect. The shear-free modulus of elasticity (MOE_{sf}) was determined by the deflection of the midspan in relation to the two loading points, which was in shear-free span. The equations to calculate MOE_{app}, and MOE_{sf} are as follows:

$$MOE_{app} = \frac{23Pl^3}{108bd^3\Delta} \tag{1}$$

$$MOE_{sf} = \frac{Pl\, l_{sf}^2}{4bd^3\Delta_{sf}} \tag{2}$$

where: MOE_{app}: apparent modulus of elasticity, calculated by the deflection within the full span (GPa)

MOE_{sf}: shear-free modulus of elasticity, calculated by the deflection within the shear free span (GPa)

P: increment of applied load below proportional limit (N)

l: span of beam (mm)

l_{sf}: shear-free span, the distance between the two loading points in this case (mm)

Δ: increment of deflection of the neutral axis measured at midspan over distance L (mm)

Δ_{sf}: increment of deflection of the neutral axis measured at midspan over distance l_{sf}, (mm)

b: width of beam (mm)

d: depth of beam (mm)

After measuring MOE, the ten specimens with surface layers in the minor direction were cut into halves for the following connection test. The two halves from the same specimen were joined together.

2.2 CLT connection test

The connection of two CLT panels in the minor direction is critical to the application of continuous two-way CLT plate. Since the design of large span CLT floor is governed by deflection, the aim is to achieve a joined panel having equivalent stiffness compared to the intact panel. Several connection techniques were considered and tested, including self-tapping wood screws, glued in steel rods, and steel connectors. Only the optimal solution is presented here.

The connector was consisted of steel plates, self-tapping wood screws, and 45° screw washers. Elliptic washer slots were machined on the steel plates to fit the washers. The size and slot locations are shown in Appendix A. The tolerance for the length and width of the slots was ±1 mm. The minimum edge spacing for the screws was 36 mm. Two long plates were manufactured for the tension side, and one short plate for the compression side.

The center of the steel plates was aligned with the connecting interface between the two CLT. Pilot holes were drilled by using the pre-drilling jig and the diameter of the pre-drilling bit was 6.35 mm (¼").The depth of the pilot holes was less than 50 mm. The connection configuration is shown in Figures 2-3. The connection after installation is shown in Figure 4. The connected CLT panels were tested under third-pint bending with the same setup shown in Section 2.1.

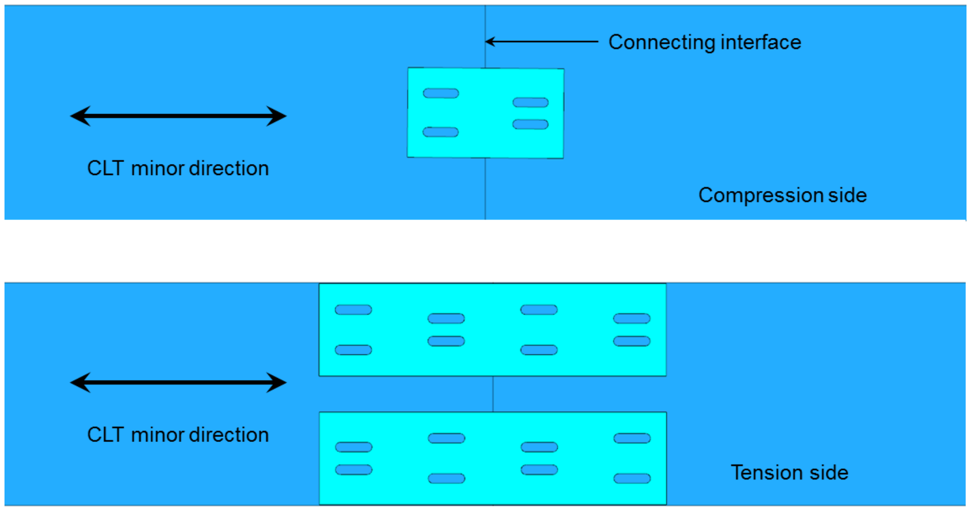

Figure 2 Connection configuration: steel plate locations

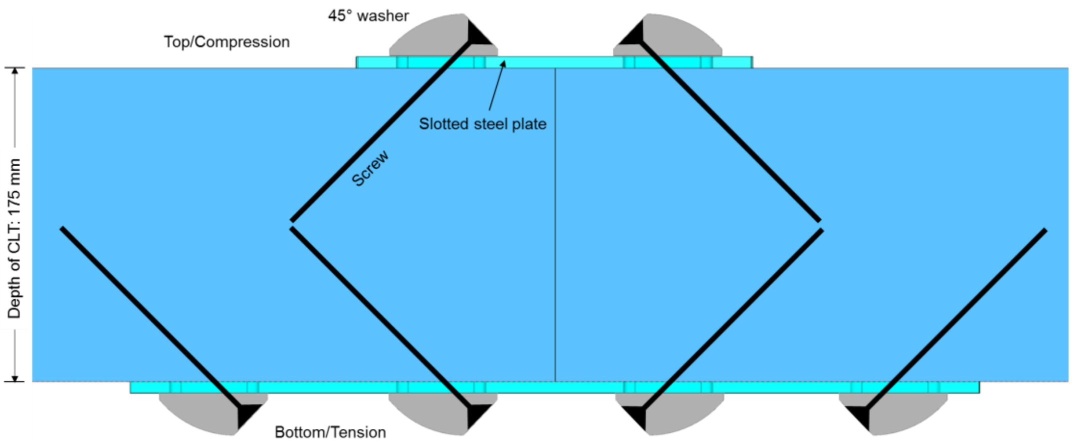

Figure 3 Connection configuration: screws and washers

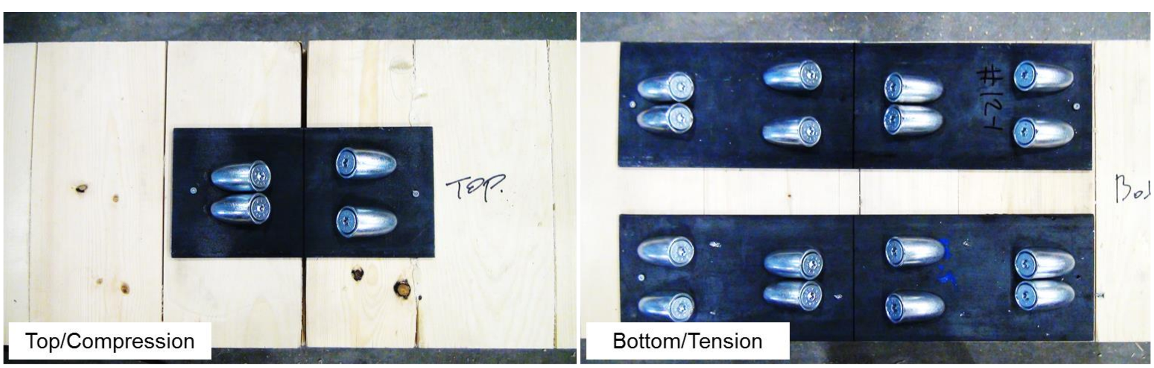

Figure 4 Connection installation

2.3 Two-way CLT plate test

This test was designed to investigate the two-way behavior of CLT plate, and obtain data for the future development of computer modeling. The test was conducted under concentrated loading and the panel was simply supported at the four corners, as shown in Figure 5. Nine transducers were installed to measure the deflection of the floor at different locations. The load was applied on an area of 240 mm by 400 mm at the center. Five steel plates were added one by one at an interval of 5 min. Each steel plate had a weight of 791.5 kg, equivalent to 7.76 kN. The test setup is shown in Figure 6. The specimens were not loaded to failure.

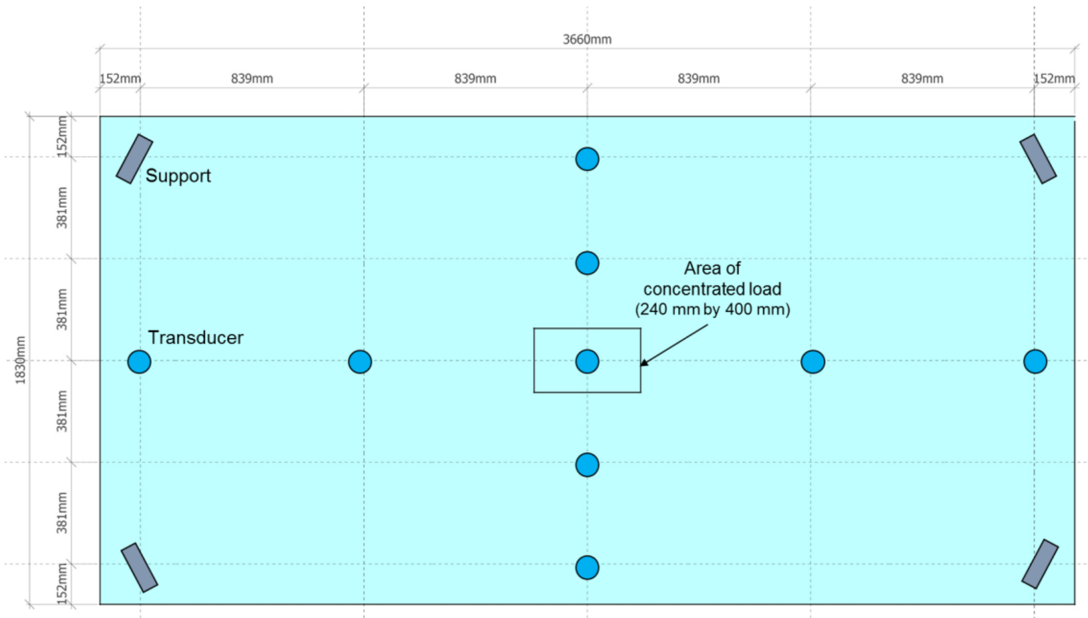

Figure 5 Support and transducer locations in two-way CLT plate test

Figure 6 Test setup of two-way CLT plate test

3 RESULTS AND DISCUSSIONS

The average moisture content of the CLT tested was 14.6%. The results of the CLT bending test are shown in Table 3. The average MOE_{app} in the major direction was 9.09 GPa, with a CV of 4%. The average MOE_{app} in the minor direction was 2.37 GPa, about 26% of the MOE_{app} in the major direction. The MOE_{sf} was higher than MOE_{app} in both groups, and the difference was higher in the major direction.

Table 3 MOE of full CLT panels in the major and minor directions

Full panels	Major direction			Minor direction		
	MOE_{app} (GPa)	MOE_{sf} (GPa)	MOE_{sf}/ MOE_{app}	MOE_{app} (GPa)	MOE_{sf} (GPa)	MOE_{sf}/ MOE_{app}
Max	9.65	10.73	118%	2.65	2.80	107%
Min	8.57	9.29	105%	2.01	2.03	100%
Average	9.09	10.04	111%	**2.37**	**2.45**	103%
Stdev	0.39	0.49	4%	0.19	0.20	2%
CV	4%	5%	4%	8%	8%	2%
Replicates	10	10	10	10	10	10

The properties of the connected CLT panels are shown in Table 4. The connected panels had higher MOE_{app} and MOE_{sf} than the full panels in the minor direction. On average the increase was 9% for MOE_{sf} and 4% for MOE_{app}. The average MOR was 11.5 MPa with a coefficient of variation of 7%. The minimum moment capacity was 51.9 kN m/m, 3.2 times the design moment capacity of 16.0 kN m/m.

The failure mode of the connected panels is shown in Figure 7. The failure occurred at the interface between the bottom layer and the adjacent longitudinal layer, in the form of tension-shear. No visible damage to the screw or steel plate was observed. Examples of load-displacement relationship are shown in Figure 8. The failure was brittle in most specimens.

Table 4 Properties of connected CLT panels in the minor direction

Connected panels	MOE_{app} (GPa)	MOE_{sf} (GPa)	MOE_{sf}/ MOE_{app}	Peak load (kN)	MOR (MPa)	M (kN m/m)
Max	2.69	3.12	120%	36.24	12.17	63.4
Min	2.27	2.22	92%	29.72	9.97	51.9
Average	**2.46**	**2.67**	109%	34.36	11.50	59.9
Stdev	0.13	0.34	11%	2.34	0.77	4.0
CV	5%	13%	10%	7%	7%	7%
Replicates	10	10	10	10	10	10

Figure 7 Failure mode of connected CLT panels under bending

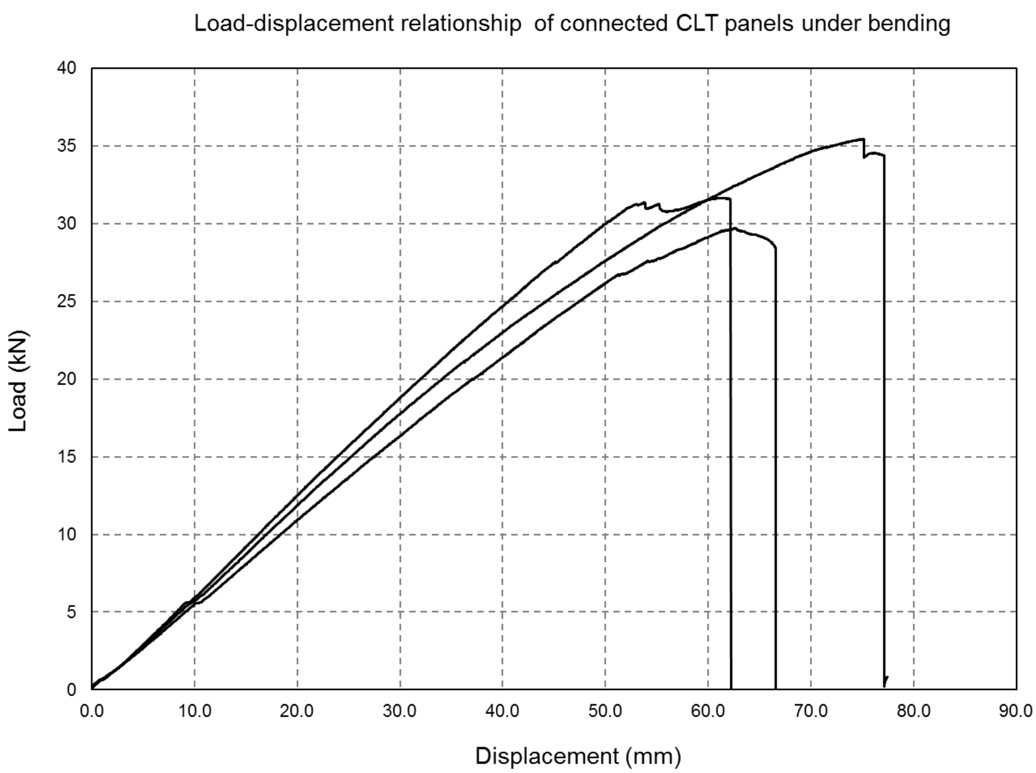

Figure 8 Load-displacement relationship of connected CLT panels under bending

Based on the connection method proposed, the stiffness and strength of the connected CLT specimens exceeded the values of the intact panels. The screws were tightly locked with the washers and steel plates when they were driven into the wood. The torsion/tension created between the wood and screws also pulled the CLT members together. In the end, this technique eliminated the original gap within the connection, which had been a persistent problem during the testing of other connecting methods. Due to the high stiffness of steel, the main displacement occurred between the screw and wood on the tension side. Therefore, the critical factor was the lateral stiffness of the screw in wood. In the current configuration, the screws were pressing against the wood perpendicular to grain, on the first layer of the tension side. This was one reason why large number of screws had to be installed. The number of screws required to reach certain stiffness may be calculated from the lateral stiffness of a single screw. The effects of screw length, screw diameter, screw pattern, steel plate thickness, and steel plate shape on the performance and cost of the connection are yet to be investigated. The number of screws and the amount of steel plates used are expected to be reduced after further optimization.

The deflection of the two-way CLT plate under concentrated loading is shown in Figures 8-11.The center deflection relative to the panel edges was greater along the major direction than the minor direction. The maximum deflection of Panel #2 was 5.67 mm, about 10% lower than that of Panel #1. And this trend was observed at every point of measurement. The deflection along the major direction was much higher than that along the minor direction. The relative center displacement relative to the edge was 4.11-4.38 mm in the major direction, and 0.79-0.82 mm in the minor direction. After the load was released, some residual deflection remained, as shown in Figure 13. The amount of residual deflection was less than <0.3 mm.

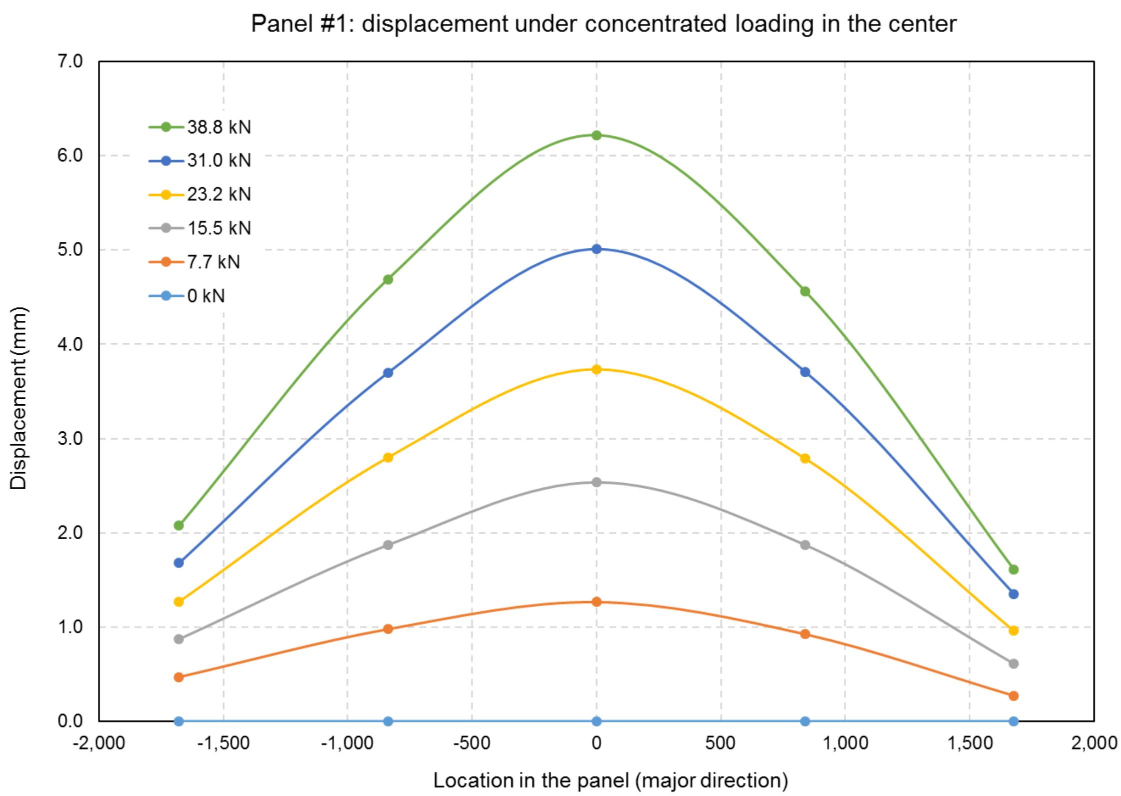

Figure 9 Displacement of Panel #1 along the major direction

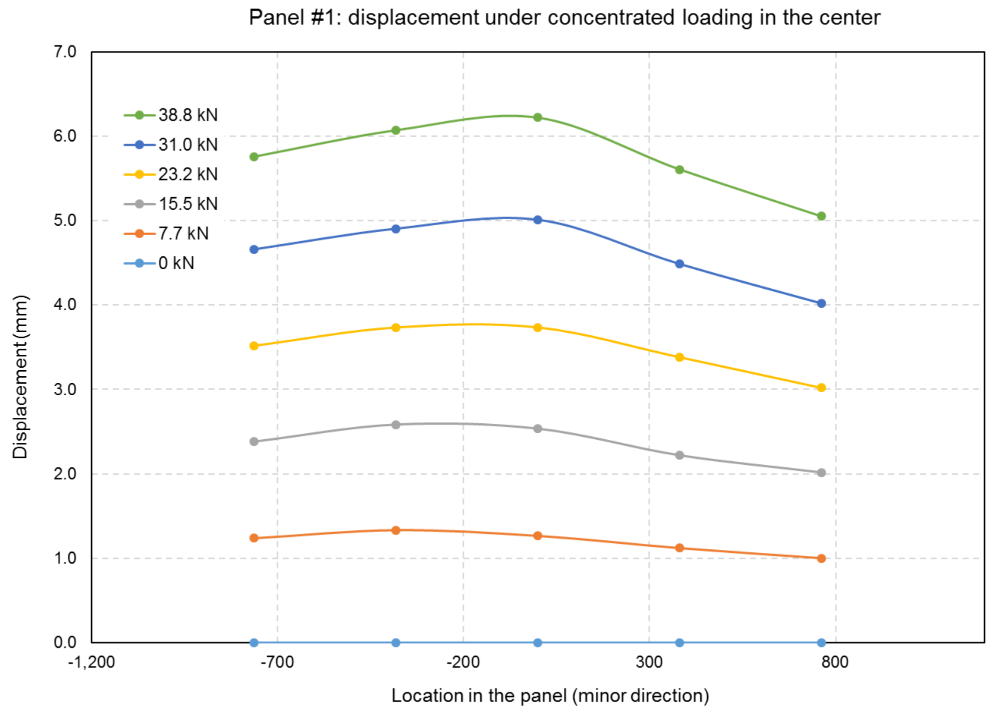

Figure 10 Displacement of Panel #1 along the minor direction

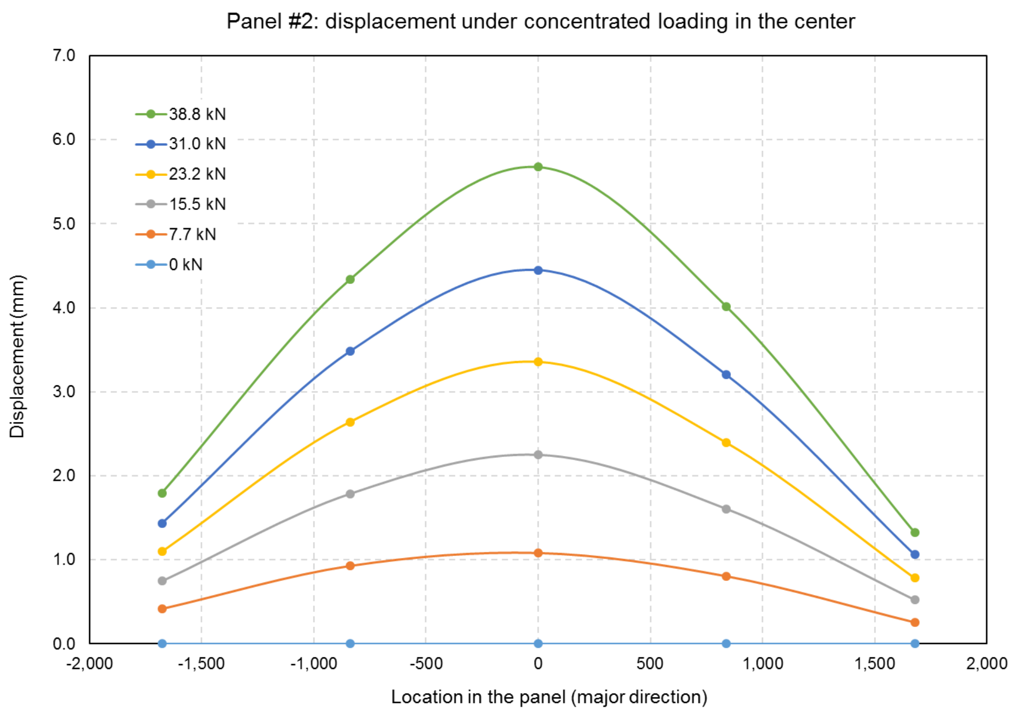

Figure 11 Displacement of Panel #2 along the major direction

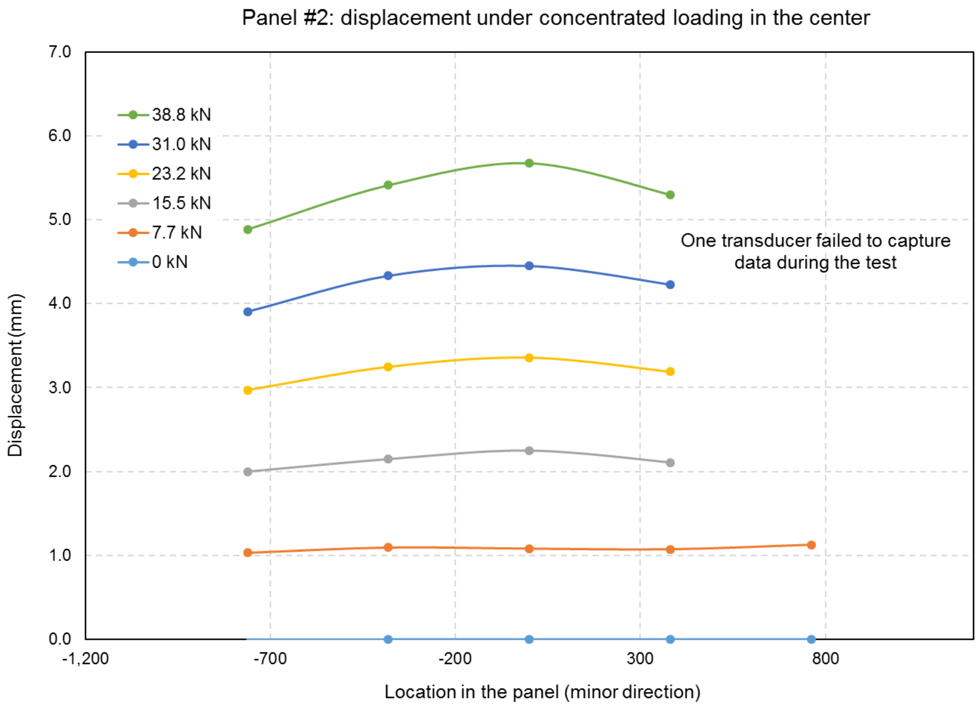

Figure 12 Displacement of Panel #2 along the minor direction

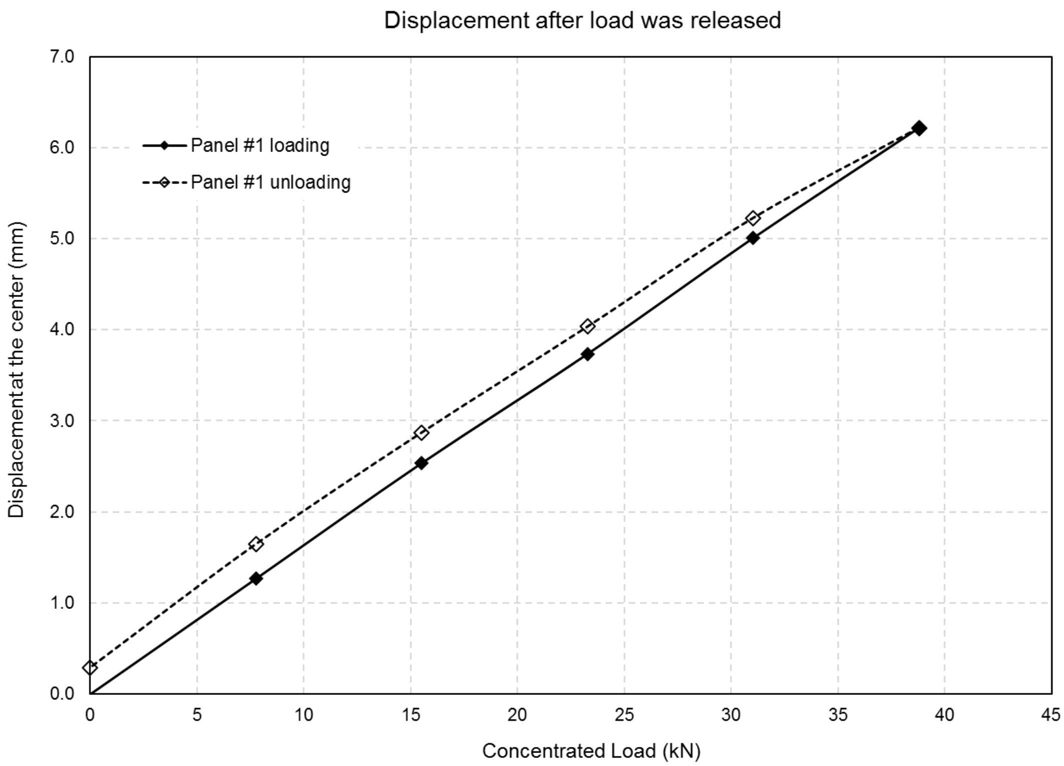

Figure 13 Displacement after the load was released

4 CONCLUSIONS

An innovative connection for joining the minor direction of CLT panels was developed and tested. The connector is based on self-tapping wood screws, steel plates, and 45° cast iron screw washers. It is easy to work with and fast to install. When the screws are driven in, the system has a locking mechanism to close any initial gap between CLT members, as well as between washers and steel plates. Therefore, the stiffness of the connected specimens exceeded that of the full panels. The minimum moment capacity of the cross section was 3.2 times the design value.

The connection was found to be effective in joining two CLT panels in the minor direction. The large span two-way CLT floor/roof created by this system can be conservatively considered as a one continuous CLT plate without connections in the design. The two-way action of CLT plates was quantified in the test. This data will be used to calibrate the computer modeling of two-way CLT.

5 ACKNOWLEDGEMENTS

This project was financially supported by Forestry Innovation Investment. The material support from Structurlam Products Ltd. is gratefully acknowledged.

6 REFERENCES

ASTM D198-15, Standard Test Methods of Static Tests of Lumber in Structural Sizes, ASTM International, West Conshohocken, PA, 2015, www.astm.org

Appendix A Specifications of steel plates

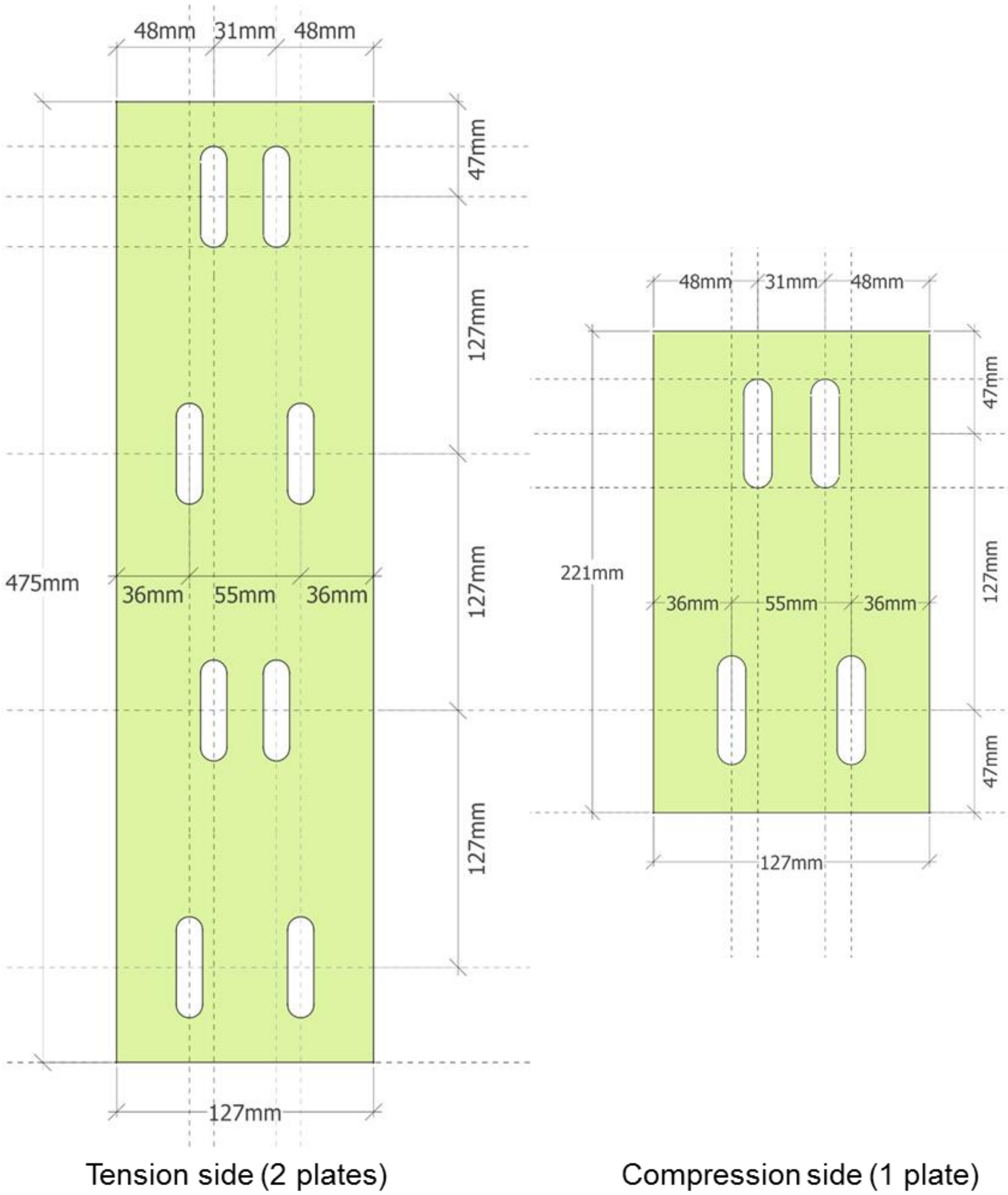

Figure A- 1 Steel plate size and slot locations

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