Development of Hybrid Cross-laminated Timber Made of Lumber and OSB

By

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Abstract

Cross laminated timber (CLT) is a kind of prefabricated engineered wood product. However, it has been found that the relatively low rolling shear capacities of CLT could result in a noticeable amount of deflection in service and eventually failure. In the meantime, it has been discovered that the oriented strand board (OSB) shows good shear resistance. This study was aimed at developing a hybrid CLT made of spruce-pine-fir (SPF) lumber of a grade of #2 and OSB panel of a grade for wall sheathing to improve its out-of-plane bending properties. Two types of three-layer downsized CLT panels were designed and fabricated, namely hybrid CLT made of SPF lumbers as top and bottom layers in the major direction and OSB panel as transverse layer in the minor direction (the major direction of OSB panel was perpendicular to the major direction of CLT), and generic CLT made of all SPF lumbers that was used as control. The long-span bending, short-span bending, rolling shear and block shear tests were conducted to determine the flexural strength and stiffness, maximum shear strength, rolling shear strength and block shear strength of the specimens made in this study. It was found (1) The long-span bending test results showed that there was not a significant difference in the effective modulus of elasticity (MOE) between the hybrid and generic CLT in the both major direction and minor direction. What is more, hybrid CLT had an average effective MOR values of 26.85 MPa and 6.03 MPa in the major and minor directions, respectively, which were 42.4% and 38.0% lower than those of generic CLT. (2) The short-span bending test results showed that there was not a significant difference

between generic CLT and hybrid CLT (4.10 MPa for generic CLT and 3.83MPa for hybrid CLT). However, in the minor direction, the maximum shear strength of hybrid CLT was 0.87 MPa, 44.1% lower than that of generic CLT (1.56MPa) (3) The rolling shear test results showed that the rolling shear strength of lumber was 1.31 MPa, which was 14.5% higher than that of OSB. (4) The internal bonding strength of OSB was 1.64kPa, lower than bonding strength of lumber-to-lumber (approximately 2.68 kPa) and lumber-to-OSB (approximately 2.70 kPa). It could be concluded that the hybrid CLT, with OSB as the transverse layer material (the major direction of OSB panel was perpendicular to the major direction of CLT), developed in this study couldn't improve the overall properties of generic CLT noticeably. It could also be recommended that further research could focus on the orientation of OSB when used in the transverse layer in manufacturing of hybrid CLT by selecting OSB panels with higher grade.

Keywords: Hybrid cross-laminated timber, dimension lumber, oriented strand board, effective modulus of elasticity, effective modulus of rupture, rolling shear strength and modulus, block shear strength.

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1 Introduction

1.1 Project background

Nowadays modern engineered wood products (EWPs) have been widely developed and fabricated to provide more uniform structure than conventional lumber, and further better and more predictable physical and mechanical properties such as greater dimensional stability, greater strength and higher stiffness (Gong, 2019). Cross-laminated timber (CLT), one of the most popular EWPs, is made of an uneven number of layers of lumber (usually three, five and seven), orthogonally bonded side by side at an angle of 90 degrees with structural adhesive (Fig. 1). CLT, introduced in Austria and Germany in the mid-1990s, has recently gained popularity in residential and non-residential construction of roofs, floors, and walls around the world as an environmentally friendly building material whose strength and light weight help reduce the size and cost of foundations (Mohammad *et al.*, 2012). It was reported that the worldwide production volume of CLT panels from 2005 to 2015 (Fig. 2) indicated a dramatic increase in the global market (Brandner *et al.*, 2016). Now many high-rise timber buildings are made using CLT. The 85.4-metre-high Mjøstårnet in Brumunddal, Norway, has been deemed the world's tallest timber building by the Council on Tall Buildings and Urban Habitat (Block, 2019).

Park *et al.*(2006) investigated 30 types of 3-layer parallel- and cross-laminated panels made of five species, namely Sugi (*Cryptomeria japonica*), Hinoki (*Chamaecyparis obtusa*), Kiri (*Paulownia tomentosa*), Katsura (*Cercidiphyllum*), and Buna (*Fagus crenata*). They found that the bending creep performance perpendicular to the grain was improved by cross-lamination. Due to its cross lamination technology, as shown in Fig. 3, CLT

showed good dimensional stability since CLT was stable in its major direction because the wood itself has a relatively low shrinkage/swell along the longitudinal direction (approximately 0.1-0.2%) (Forest Products Laboratory, 2010), which could restrict the shrinkage/swell in its minor direction since the adjacent layers are bonded using adhesive and resistance from the upper layer which is perpendicularly placed can reduce the dimensional change (Brandner et al., 2016).

Apart from the surface bonding between adjacent layers and bonding in finger joints, edge bonding is a controversial reinforcement (Fig. 4), which can minimize the gaps between members in one layer and improve members' holistic four-dimensional stability since it connects them into a whole. In Europe, edge bonding is done in respect of building physical aspects, in particular regarding fire design, airborne sound and air tightness and offers good stiffness and strength for a CLT panel (Brandner, 2014). In North America, edge gluing is not a common practice due to the added manufacturing costs. Leaving gaps between lumber could provide some tolerances for wood movement due to the change in moisture in service. Anyhow, as a trade-off between manufacturing cost and improved panel performance, edge-gluing of selected layers could be adopted (Gong, 2019).

Fig. 1 Cross-Laminated Timber

(Source: https://technologyinarchitecture.com/cross-laminated-timber/)

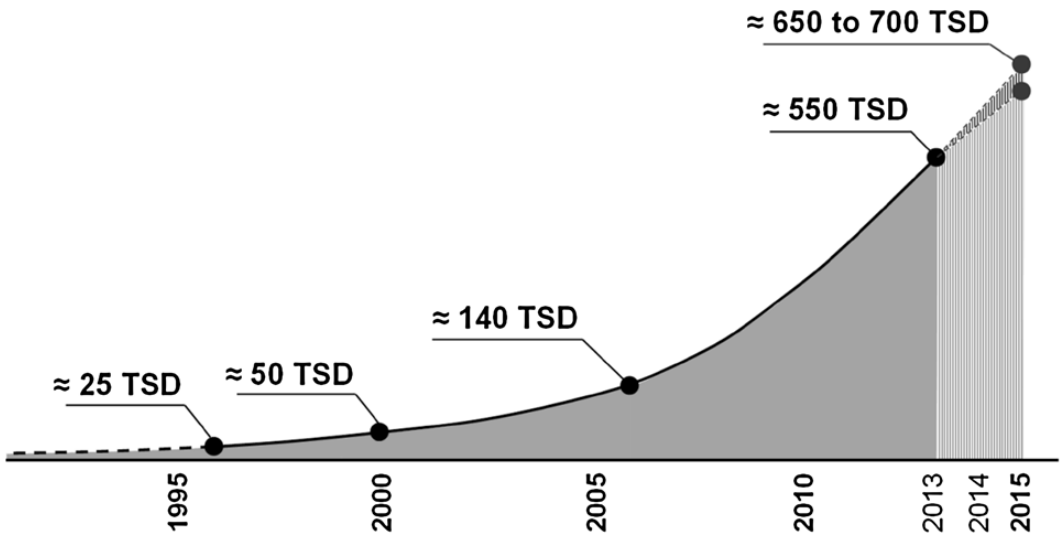

Fig. 2 Development of the worldwide production volume of CLT until 2013 and forecast until 2015 in (m3) (Brandner *et al.*, 2016)

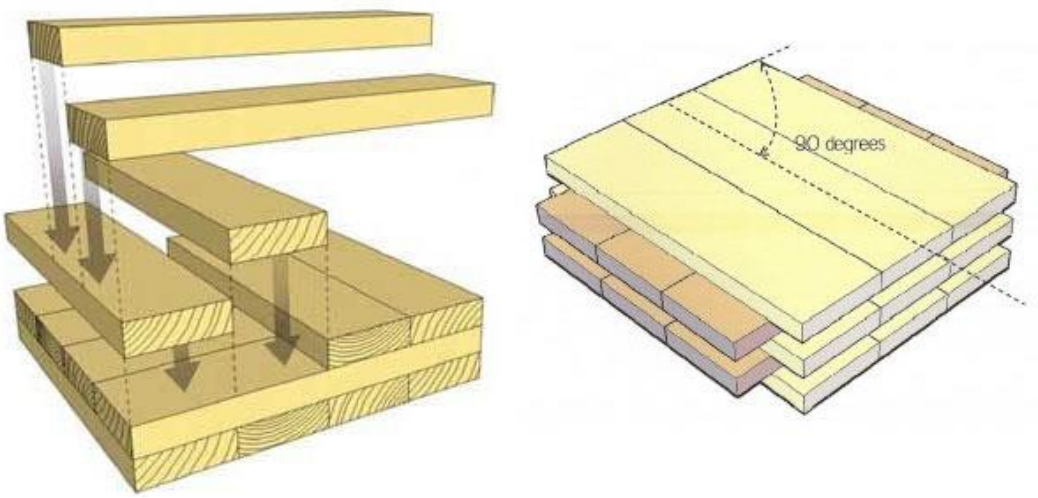

Fig. 3 Cross-laminated surface bonding during manufacturing of CLT

(Source: https://evohouse.eu/arhitectura-viitorului/principii-ecologice/)

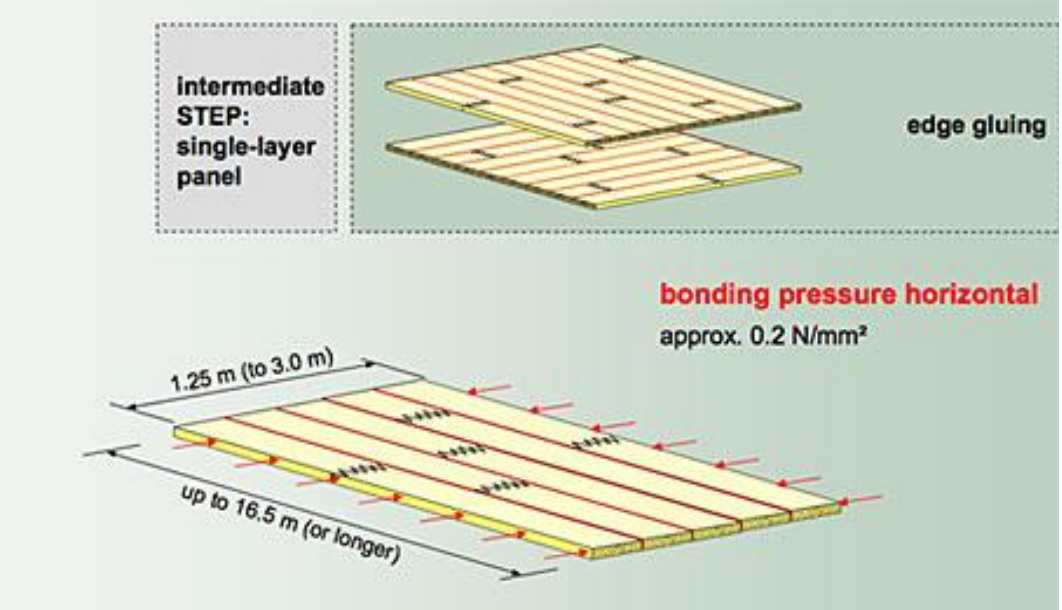

Fig. 4 Edge bonding during manufacturing of CLT

(Sourse:http://www.fourthdoor.co.uk/unstructured/unstructured_09/extra/gerhard_schickhofer.php)

1.2 Rolling shear failure

The main problem limiting the mechanical capacities of CLT is due to the shear failure in the cross section of wood when CLT is subjected to out-of-plane loading. It is commonly called rolling /planar shear failure (Figs. 5- 6), which results in excessive deflection when subjected to out-of-plane loading. Scientists have identified the rolling shear modulus and strength in CLT as key issues that may control the design and performance of CLT floor or roof systems (Davids *et al.*, 2017; Gong, 2015). In CLT Handbook, Gagnon and Pirvu (2019) explained that when a CLT panel is subjected to out-of-plane loading, rolling stress occurs and causes rolling shear stress, as illustrated in Fig. 5.

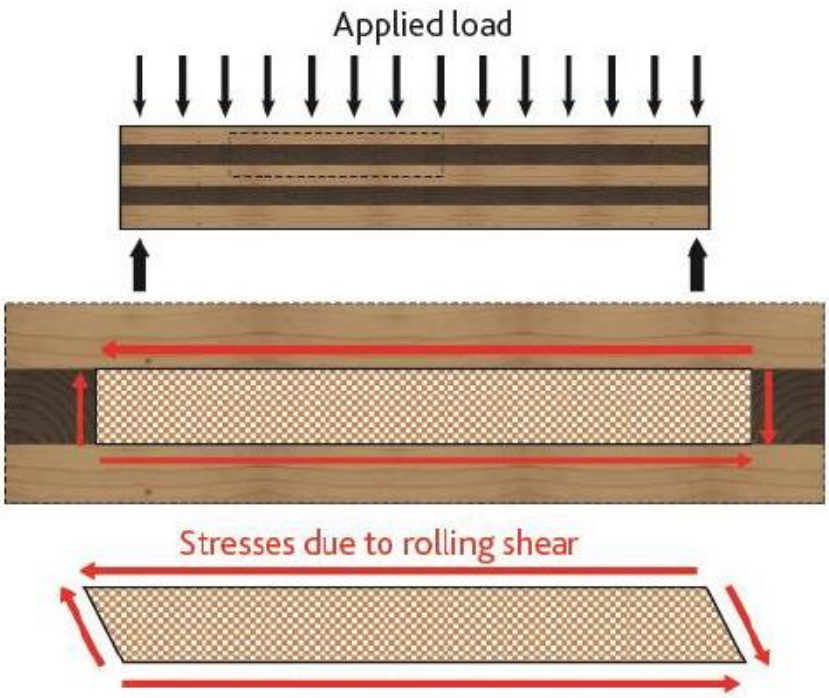

Fig. 5 Rolling shear in CLT (Gagnon and Pirvu, 2019)

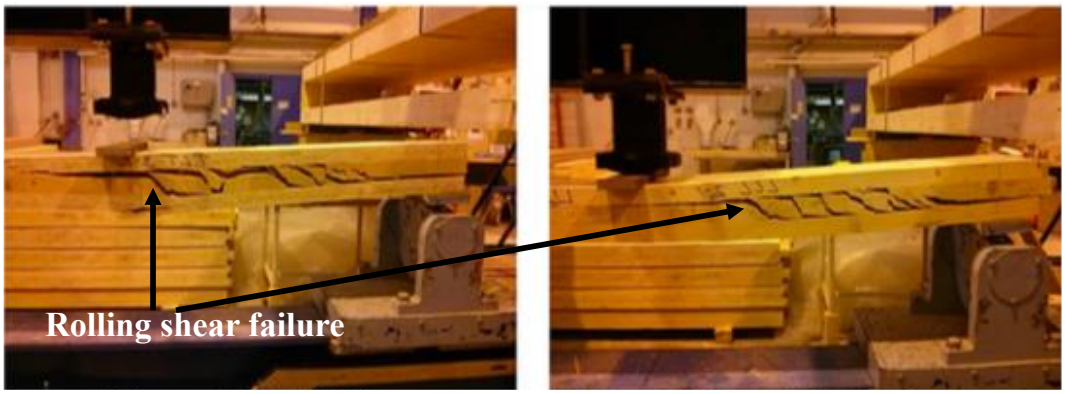

Fig. 6 Rolling shear failure in flexure test (Wang et al., 2015)

Fig. 7 demonstrates the typical failure modes under rolling shear stresses: The top two pictures of Fig. 7 shows that the failure occurred along with the annual rings, followed by the delamination along the bond line. The bottom two pictures of Fig. 7 shows that the failure only occurred in the annual rings, suggesting a very good bond strength between two laminations.

In conclusion, it is critical to understand and control the rolling shear failure and large deflection of a CLT beam under bending.

Fig. 7 Typical failures of specimens: spruce, pine, beech and ash (from top left to bottom right) (Ehrhart, 2015)

1.3 Methods for improving rolling shear capacities

Substituting transverse layers of CLT with engineered timber products, such as solid hardwood lumber, laminated strand lumber (LSL), lamination veneer lumber (LVL) and plywood, is a common way to reduce the potential rolling shear failure (Brandner *et al.*, 2016; Gong, 2015), the original and hybrid CLT models are shown in Fig. 8.

The suitability of the substitute has been verified in several investigations which were designed to compare the rolling shear properties and failure modes. The replacement can be roughly divided into two kinds. In the first method, they use different species, such as hardwoods with high shear-resistance in the transverse layers. Gong et al. (2014) assessed the rolling shear modulus and strength of three-layer CLT whose transverse layers were made of aspen (*Populus tremuloides*), yellow birch (*Betula alleghaniensis*) and white birch (*Betula pubescens*), respectively, compared them with traditional CLT made of eastern SPF and concluded that aspen and birch exhibited a larger resistance to rolling shear stresses than softwood, reaching 180 MPa in rolling shear modulus and 3.00 MPa in strength. Wang et al. reached a similar conclusion that use of Douglas fir (*seudotsuga menziesii*) in the transverse layer increased the effective modulus of elasticity by 35% compared with original CLT (Wang *et al.*, 2014). In China, bamboo (*Bambusoideae*) attracts much attention due to both its high structural properties and its large standing volume. Li et al. (2019) did research on bamboo wood composite cross-laminated timber, discovering that bamboo had the potential to resist rolling shear failure but more data were required to verify using experiment. In the other method, they used the engineeredwood products (EWP) in transverse layers. Davids et al. (2017)

experimentally assessed the use of LSL in transverse layers (as shown in Fig. 9) of three-layer hybrid CLT panels, LSL in face layers of three-layer hybrid CLT panels and three-layer CLT 100% made of LSL, demonstrating that the hybrid CLT with LSL in transverse layers had a mean bending stress at failure 23% greater than the all-SPFs panels and about 46% greater shear stress. Wang et al. (2015) performed a similar experiment and concluded that the average MOE and MOR of hybrid three-layer CLT with LSL in transverse layer were 13% and 24% higher than those of generic CLT, respectively. Additionally, Wang et al. (2017) did a study of assessing the use of LVL as the transverse layer (as shown in Fig.10) and found that the bending properties of generic CLT had been reduced by using LVL as transverse layer, suggesting the utilization of LVL in transverse layers of CLT could not improve the rolling-shear properties a lot. In this experiment, they examined the failure morphology of CLT from the wood anatomy point of view under with the microscope, finding that the typical crack(s) was initiated and propagated along the wood ray direction.

Choi et al. (2018) used plywood as transverse layer(s) to make three-layer and five-layer thin hybrid CLT and discovered that the plywood-CLT had an effective MOR of 25.5 MPa or more that met F255 grade stipulated in the Japanese Agricultural Standard. What is more, they determined that it was possible to maintain the strength of plywood-CLT to increase the in-plate shear resistance by increasing the thickness of the veneer rather than increasing the number of layers of the plywood.

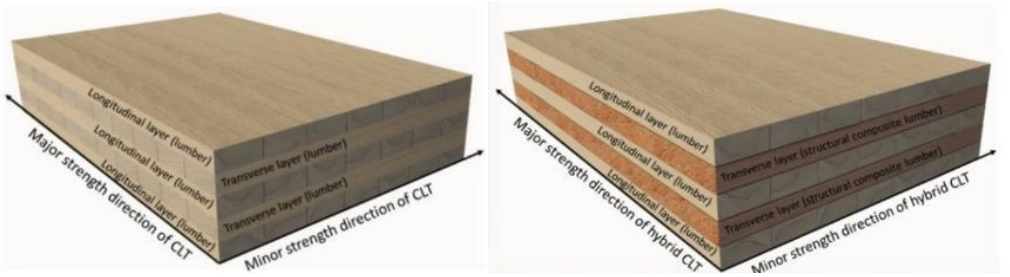

Fig. 8 CLT products (Upper: a generic CLT made of lumber only; lower: a hybrid CLT made of dimension lumber in the major strength direction and structural composite lumber in the minor strength direction) (Gong, 2019)

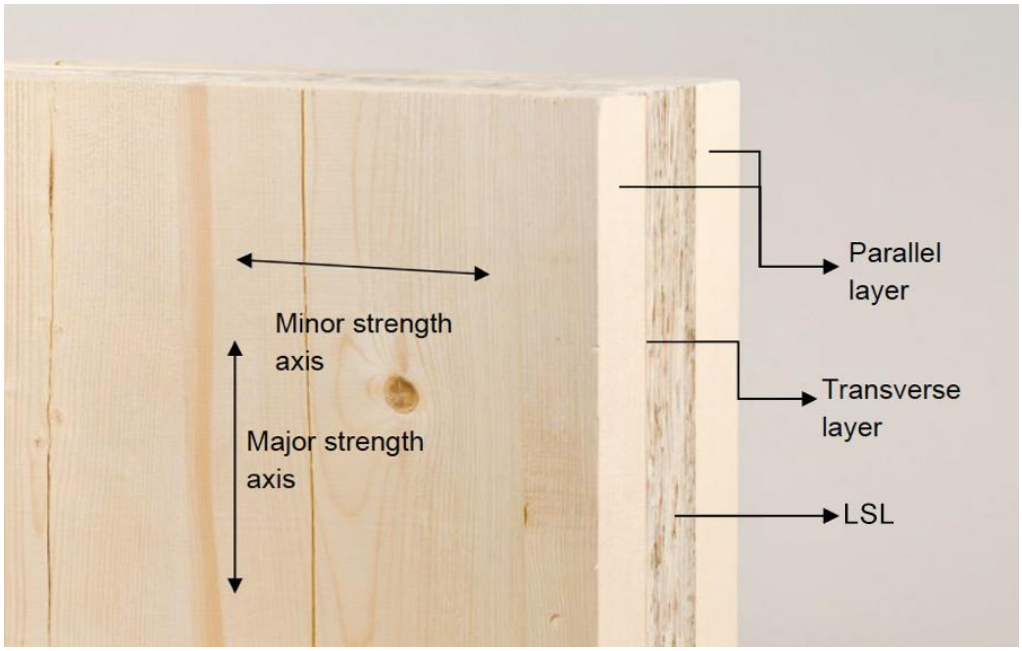

Fig. 9 A three-layer CLT panel made with a combination of sawn lumber (outer layer) and LSL (transverse inner layers)

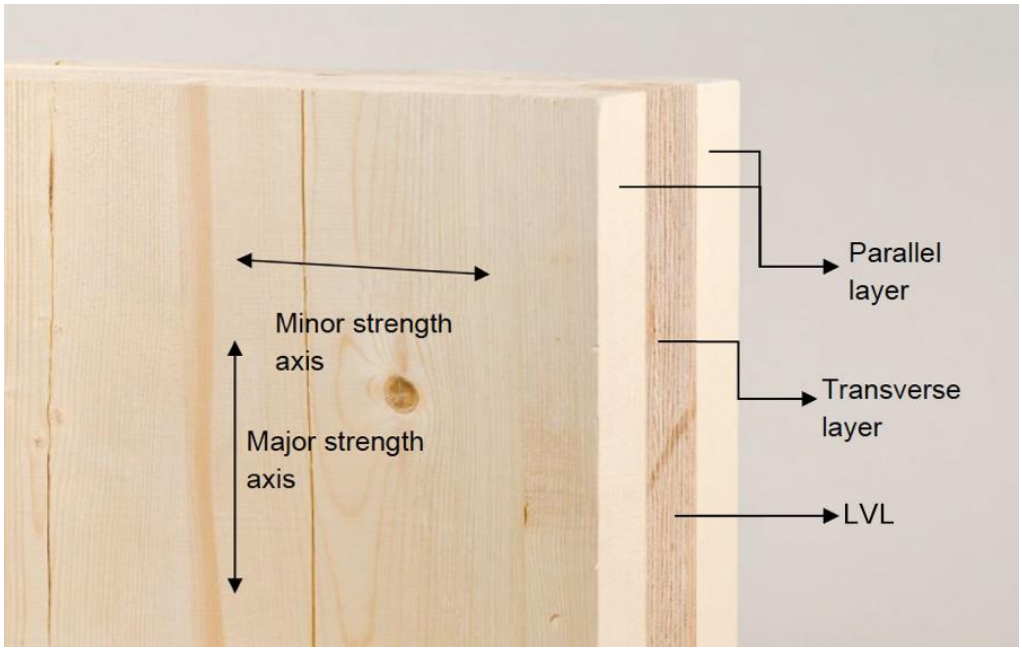

Fig. 10 A three-layer CLT panel made with a combination of sawn lumber (outer layer) and LVL (transverse inner layers)

1.4 Oriented strand board

Fig. 11 shows oriented strand board (OSB), a type of engineered wood product which is similar to plywood, which is manufactured in a cross-oriented pattern. It is composed of thin rectangular-shaped wood strands arranged in layers at right angles to one another, which are laid up into mats that form a panel (APA, 2020).

OSB was invented by Armin Elmendorf in California in 1963 (Deutsches Patentund Markenamt, 1965). OSB typically possesses better dimensional stability than dimensional lumber, superior predictable strength and stiffness, and relatively high shear resistance compared to other panel wood products. Table 1 gives the major design strength values of OSB and plywood in a thickness of 9.5 mm, which is closest to the thickness of the OSB was used in this project because the shear strength of plywood in a thickness of 11 mm is not recorded. In terms of the shear-through-thickness, the value of OSB is approximately twice that of plywood. In terms of rolling shear under bending and rolling shear under in-plane shear, at an angle of 0° the values of both products are similar, but at an angle of 90° OSB has a higher planar shear under bending and a lower planar shear in plane than plywood. In conclusion, OSB has a better performance in shear resistance which is approximately twice that of larger than that of plywood (Canadian Standards Association, 2019).

Besides as shown in Fig. 12, OSB has a very high yield of raw materials, which can reach as much as 90%, and costs less in manufacturing compared with others because

the wood flakes can be made from the small-diameter and fast-growing trees (Chapman, 2006).

Fig. 11 OSB panels (Source: https://adlroofing.co.uk/products/osb-board/)

Table. 1 Comparation of shear strength between OSB and plywood (Canadian Standards Association, 2019)

	Minimum nominal thickness (mm)	Shear-through-thickness, v_p (N/mm)	Planar shear: bending, v_{psb} (N/mm)		Planar shear: shear in-plane, v_{pf} (Mpa)	
		0° and 90°	0°	90°	0°	90°
Construction sheathing OSB	9.5	42	3.8	2.4	0.60	0.38
Canadian regular plywood	9.5	23	3.9	1.3	0.55	0.72

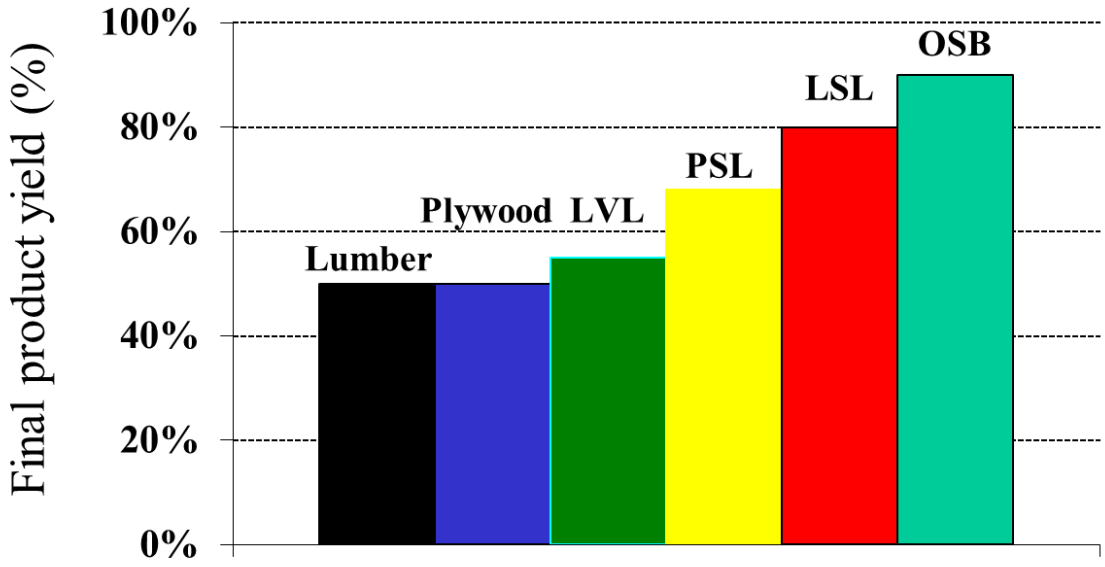

Fig. 12 Final product yield of logs (Gong, 2019)

1.5 Surface activation of OSB

Surface activation of a material is a critical factor governing adhesion properties and furthermore bond quality (Ma 2018). If a surface with poor wettability and penetrability, it can be defined as surface inactivation, eventually causing the bonding problems (Forest Products Laboratory, 2010). During the manufacturing of OSB, the high temperature of hot pressing, use of adhesive and densified surface layers result in a low surface activation, which will cause a low-quality bond line between OSB and dimensional lumber or other SCL. This will result in the low-strength connection or non-connection between layer to layer, significantly increasing the potential of failure of CLT.

To improve the surface activation of OSB, proper surface treatments should be applied. Ma (2018) used sanding and metal tooth-plate indenting to treat the surfaces(Fig. 13) and then made two-layer adhesively laminated OSB specimens. He found that using sanding and metal tooth-plate indenting were efficient surface treatment methods to improve the bond quality of laminated-OSB; values are shown in Table 2.

Fig. 13 Metal tooth-plate indenting and sanding with mesh paper (Ma, 2018)

Table. 2 Horizontal shear strength in two different panel positions (Ma, 2018)

Position	Surface treatment	horizontal shear strength (MPa)
Center	None	2.03
	100 Sanding	2.11
	600 Sanding	2.48
	Tooth-plate	3.02
	100 Sanding & tooth-plate	3.42
	600 Sanding & tooth-plate	3.44
Edge	None	1.99
	100 Sanding	1.99
	600 Sanding	2.06
	Tooth-plate	2.56
	100 Sanding & tooth-plate	2.88
	600 Sanding & tooth-plate	3.31

Patloka et al. (2019) designed five different bonding primers and penetrative coatings, which were applied on the surfaces of OSB before bonding: modified dispersion with quartz sand; one-component solvent-free coating mixture of fillers and aggregates in a water styrene-acrylate dispersion with additional additives; solvent-free water-soluble primer based on a synthetic resin dispersion and mineral additives; a mixture of water and a nano-dispersion of styrene-acrylate copolymer and additives and acrylic copolymer water emulsion penetration primer. They discovered their treatment of an OSB substrate had effects when using adhesion of cement adhesive. These five kinds of treatment are shown in Fig. 14.

Treatment number	Product description	Product type	Pictures
1	Modified dispersion with quartz sand	Bonding primer	
2	One-component solvent-free coating, mixture of fillers and aggregates in a water styrene-acrylate dispersion with additional additives	Bonding primer	
3	Solvent-free water-soluble primer based on a synthetic resin dispersion and mineral additives	Bonding primer	
4	Mixture of water and a nanodispersion of styrene-acrylate copolymer and additives	Penetrative coating	
5	Acrylic copolymer water emulsion penetration primer	Penetrative emulsion	

Fig. 14 Specifications for penetrative coating and bonding premier (Patloka, 2019)

1.6 Summary

Generic CLT shows low resistance to rolling shear stresses, resulting in failure in shear in transverse layer and large deflection when subjected to out-of-plane loading. OSB has a good shear resistance compared to solid wood and other wood-based panel products. But low surface activation of OSB which is caused during its manufacture will lead to poor bonding quality between OSB and other members. It is necessary to conduct suitable surface treatments, such as sanding, tooth-plate roughening or primer application before bonding. In conclusion, OSB has great potential to be used as transverse layers in manufacturing CLT to reduce the risk of rolling shear failure.

1.7 Objectives and Scope of Work

This thesis project was aimed to develop OSB-lumber CLT. To achieve this, two kinds of 3-layer CLT panels were made, namely hybrid CLT with SPF lumber in two surface layers and OSB in the transverse layer, and generic CLT made of SPF lumber used for comparison. Mechanical tests were conducted on CLT specimens cut from the 3-layer panels, including bending, rolling shear, block shear tests to assess both bending, shear strength of both hybrid and generic CLT. The values were compared.

2 Materials and Methods

Details of the fabrication of test specimens are given in Figs. 15-16 and are discussed in the following sections.

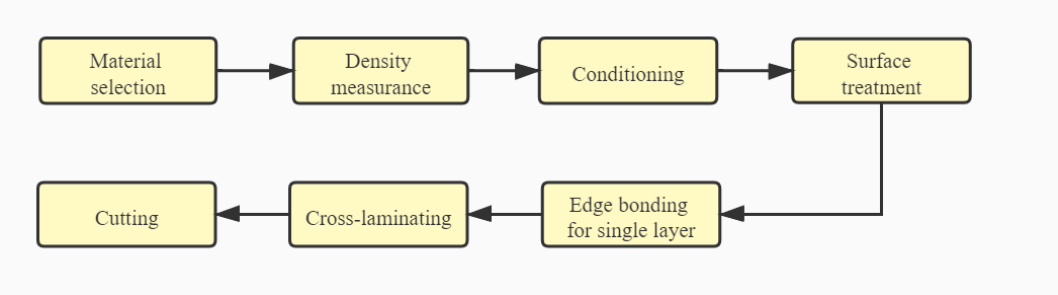

Fig. 15 Flowchart showing the fabrication of test specimens used in generic CLT

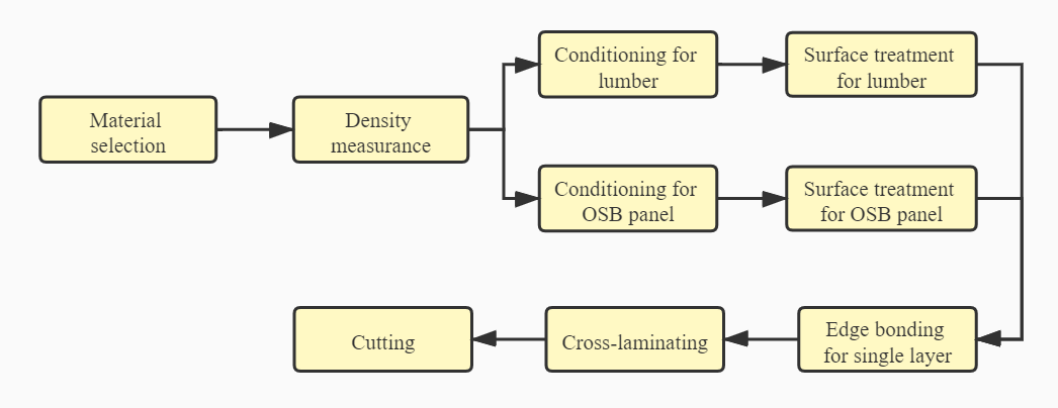

Fig. 16 Flowchart showing the fabrication of test specimens used in hybrid CLT

2.1 Materials

The wood materials used were 2x6” kiln-dried SPF lumber of a grade of No. 2 and Better (Fig. 17), which was purchased from Home Depot, Fredericton, New Brunswick, Canada. The No. 2 grade of SPFs meets the minimum grade of lumber stipulated in the CLT Handbook (Gagnon and Pirvu 2019) and American standard PRG320 “Standard for Performance-Rated Cross-Laminated Timber” (APA, 2019).

The 4’x8’ OSB sheets were provided by UNB Wood Science and Technology Centre, which had a stamp (Fig. 18) indicating the OSB panels used had a grade of “rated sheathing for wall” and a thickness of 7/16” (11mm).

According to the thickness of OSB, dimension lumber was cut into strips of the same thickness of OSB, i.e., 11 mm.

Single-component polyurethane (PUR) adhesive (Akfix AK-PA360 PUR Wood Glue) was purchased from Home Depot as well.

In this thesis report, two kinds of 3-layer downscaled CLT panels were designed and illustrated in Fig. 19 and Fig. 20.

Fig. 17 Dimension lumber materials

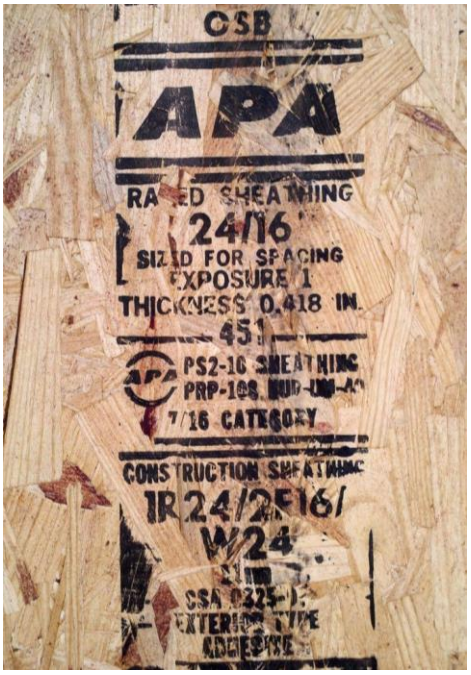

Fig. 18 OSB panel

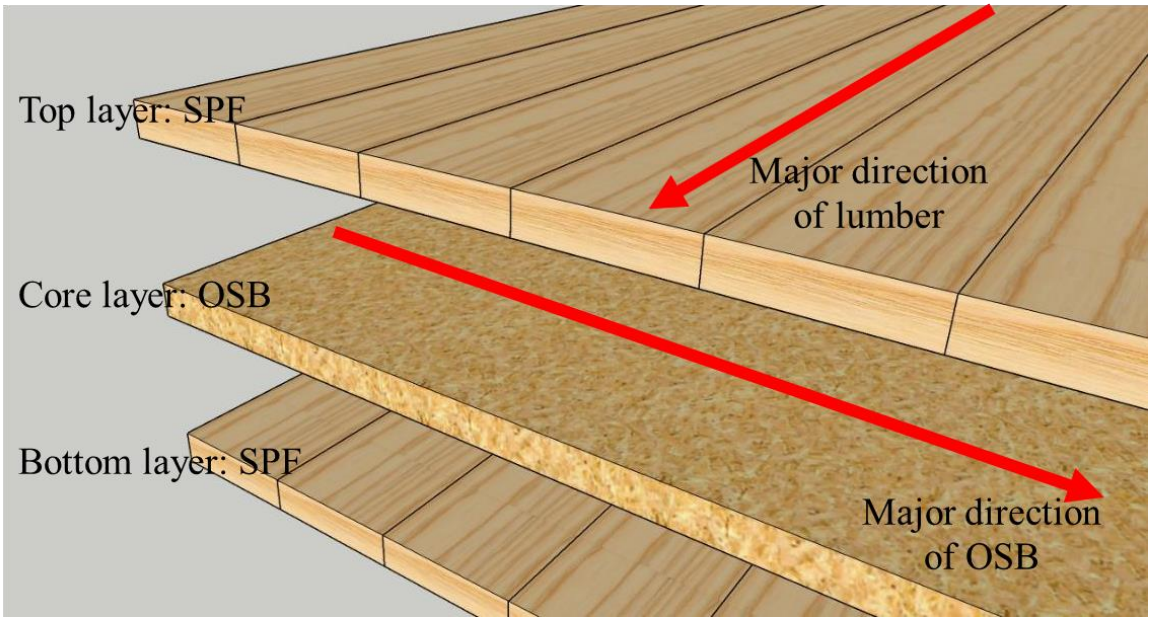

Fig. 19 Model of hybrid CLT with lumber and OSB

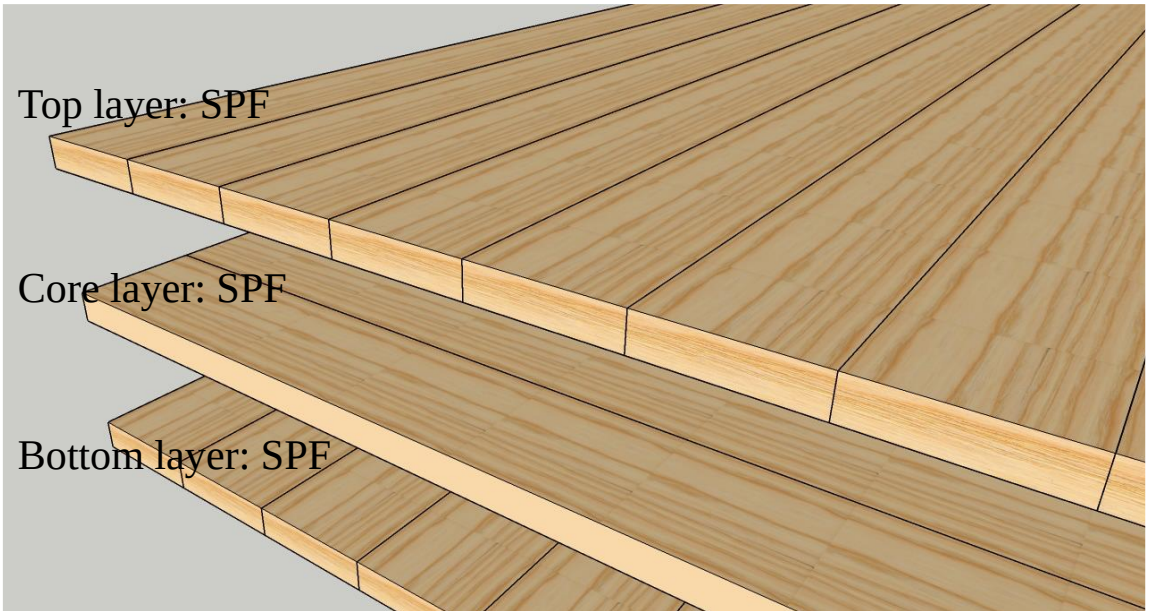

Fig. 20 Model of generic CLT with lumber

2.2 Design of experiment

2.2.1 Flexural test specimens

The sizes of downscaled CLT panels were designed based on the thickness of OSB (11mm). First, Fig. 21 shows letter represent each size in PREN 16351, according to PREN 16351 (BSI, 2011), the compliance of the ratio $w/t \geq 4$ shall be kept or the stiffness against bending and torsion deformations would be increased and the rolling shear strength of CLT would be decreased. Second, as shown in Fig. 22, according to ASTM-D198-15-X5.3, the length of flexure specimens intended primarily for evaluation of shear strength shall be such that the shear span was relatively short; it was assumed that a specimen with a/d near 2.5 would produce a high percentage of shear failure, in which *d* represents the depth (mm) of rectangular flexure and *a* represents the distance (mm) from reaction to nearest load point (i.e. ½ shear span). In order to evaluate flexural properties (such as modulus of elasticity and modulus of rupture), the span length of the specimen shall be relatively long. Thus, the recommended specimen would have a/d ratios ranging from 4 to 6 (ASTM International, 2015).

In the condition that the thickness of one single wood member was $t = 11mm$ $(7/16")$, the width (*w*) of a single strip was $50.8mm$ $(2")$ $(i.e. 4.6\ t)$. So, the depth (*d*) of a rectangular flexure was approximately 33 mm ($1\frac{1}{3}$") (i.e. 3*t*). Fig. 23 shows the size in SketchUp model of hybrid CLT.

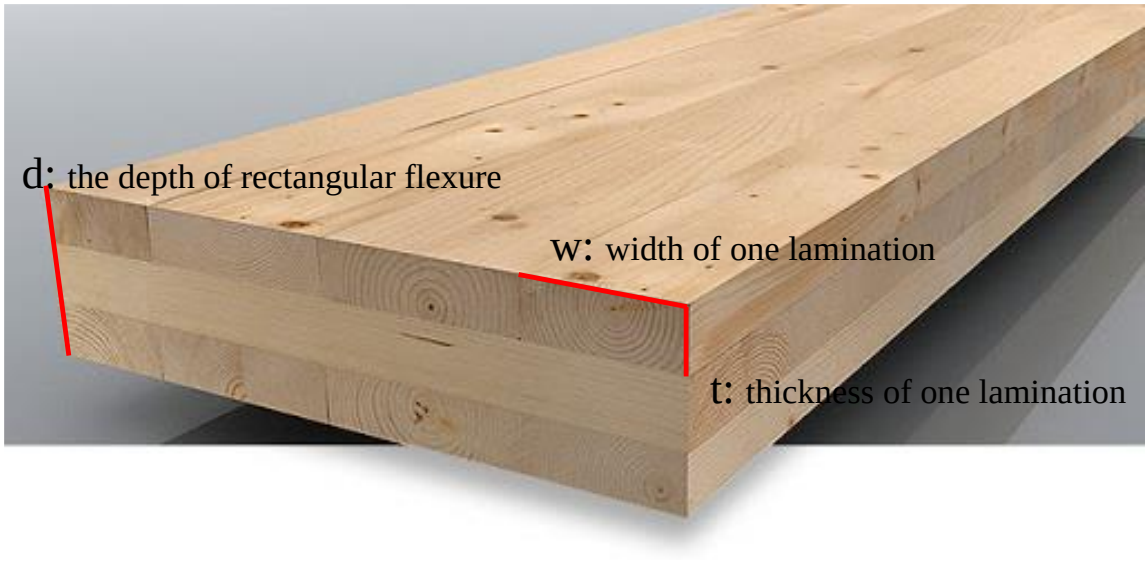

Fig. 21 Letter represent each size in PREN 16351

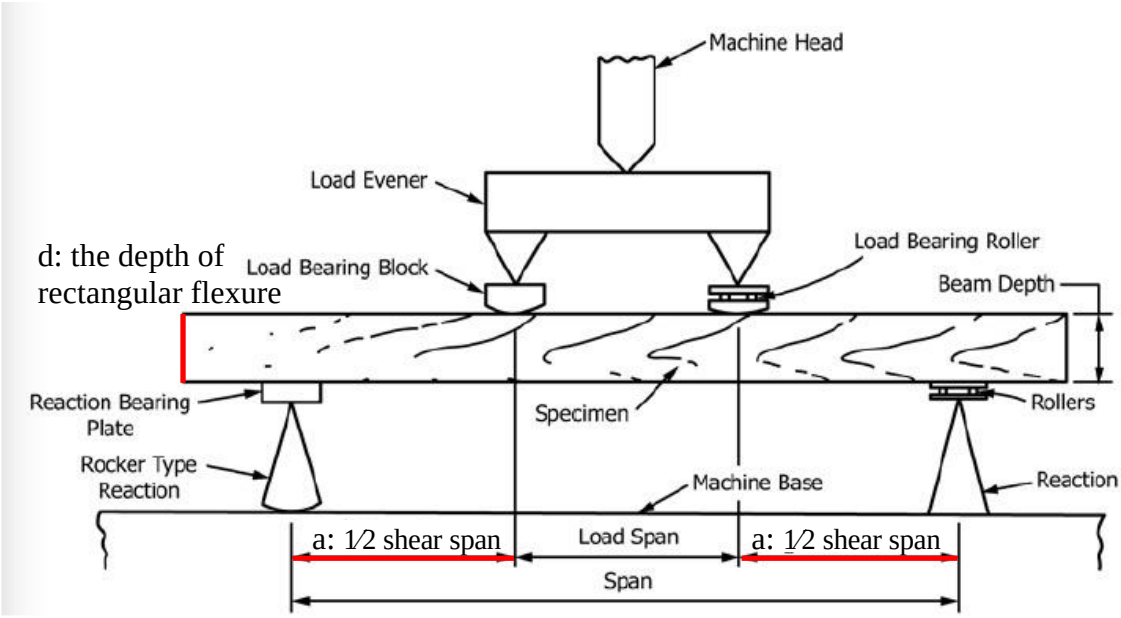

Fig. 22 Letters represent each size in ASTM D198

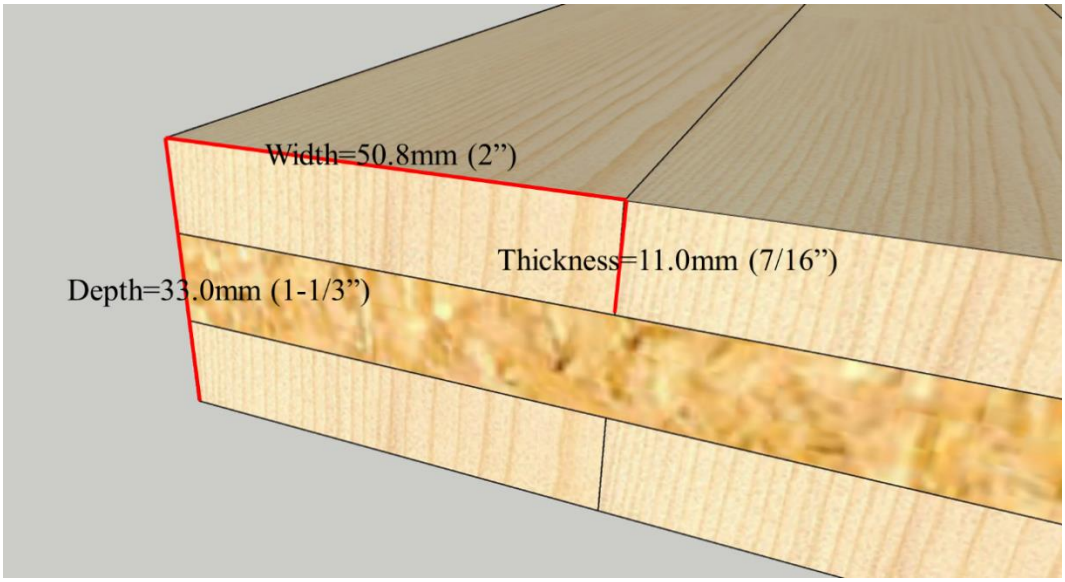

Fig. 23 Dimensions of downscaled CLT panels

Fig. 24 shows the short-span three-point bending test, where $a = 2.5d = 84.7mm$ ($3\frac{1}{3}$"), so the designed length (l) of the shear specimens is 216.0mm ($8\frac{1}{2}$") [50.8mm for overhand (h) and 165.0 mm (about $6\frac{1}{2}$") for shear span].

Fig. 25 shows the long-span four-point flexure test a/d within 4-6 radio so the designed length of the shear specimens is 584.2mm (23") [50.8mm for support, 177.8(7")mm for load span and 406.4mm(14") for shear span].

Note: For checking, the short-span specimens, $a = \frac{165}{2} = 82.5mm = 2.5d$; the long-span specimen, $a = \frac{533.4}{3} = 200mm = 5.4d$; the whole length of short-span (expect supporting length) is $165 = 5d$; the whole length of long-span (expect supporting length) is $533.4 = 21d$.

In summary, considering the trimming of four edges of each downscaled CLT panel, the dimensions are designed as 584.2 mm (23") in length, 50.8 mm (2") in width, and 33mm ($1\frac{1}{3}$") in thickness. From each CLT panel, the following specimens were made: six specimens were for long-span bending tests, six specimens were made for short-span bending tests, six specimens were made for rolling shear tests. In addition, block shear specimens were made from the same CLT panel.

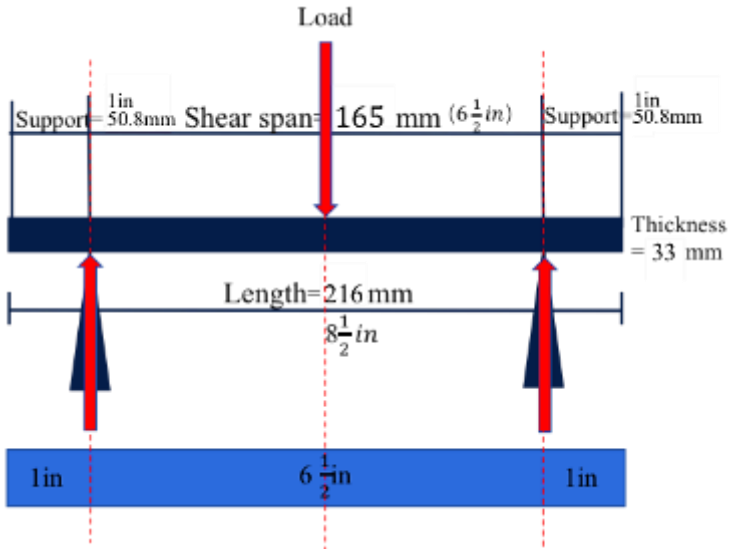

Fig. 24 Dimensions of specimens for short-span three-point bending test

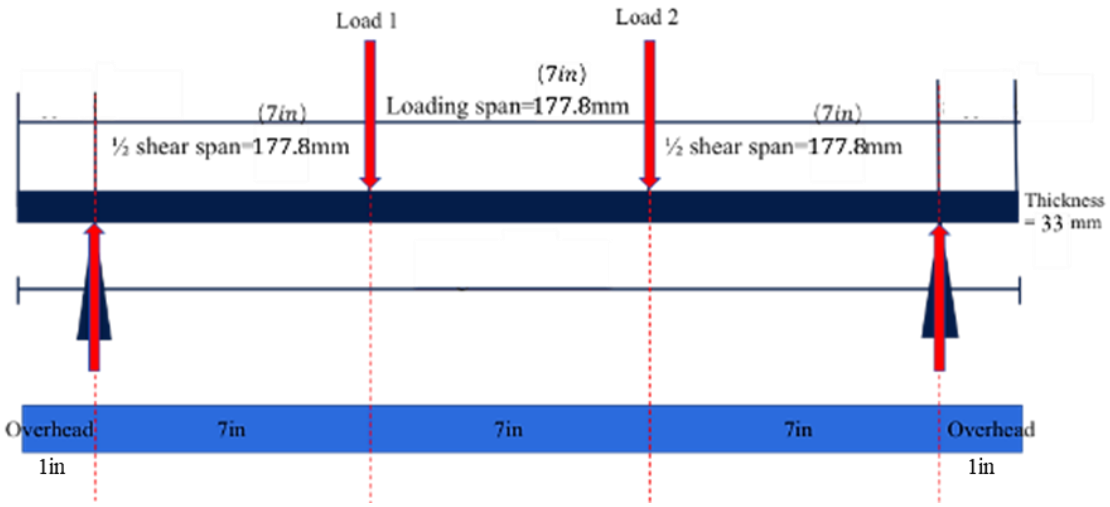

Fig. 25 Specific size of long-span four-point shear test in this design

Two types of CLT were designed, hybrid CLT made of SPF lumber and OSB and generic CLT made of SPF lumber only. Also, each type had two panels for both major and minor directions for long-span test and short-span tests. The effective MOE and MOR values (Note: To facilitate writing, MOE and MOR were used in this report.) were calculated according to Equations (1) and (2) for the four-point long-span bending tests.

$$MOE_4 = \left(\frac{\Delta P}{\Delta d}\right)\frac{23L^3}{108bh^3} \quad (1)$$

$$MOR_4 = \frac{P_{max}L}{bh^2} \quad (2)$$

The effective MOE and MOR values, and maximum shear strength were calculated using Equations (3), (4) and (5) for the three-point short-span bending tests:

$$MOE_3 = \left(\frac{\Delta P}{\Delta d}\right)\frac{L^3}{4bh^3} \quad (3)$$

$$MOR_3 = \frac{3P_{max}L}{2bh^2} \quad (4)$$

$$\tau_{max} = \frac{3P_{max}}{4bh} \quad (5)$$

Where, $\frac{\Delta P}{\Delta d}$ represents the slope of load-deflection curve in the linear region,

L represents the span of a specimen,

b represents the width of the specimen,

h represents the height of the specimen,

P_{max} represents the load at failure,

τ_{max} represents the maximum shear strength.

2.2.2 Rolling shear test specimen

Gong et al. (2015) studied the rolling shear properties about hardwood CLT and described the design of sandwich panels in detail (Fig. 26). The length-to-width ratio was around 2.5 (Gong et al, 2015); the depth did not have a statistically significant impact on the rolling shear modulus and strength of sandwich wood specimens (Gong and Chui, 2015). So, in this project the length-to-width ratio was 2.5, the angle was 15.5 degree to make sure the load applied on a horizontal line across the specimen. The detailed sizes of rolling shear specimens are shown in Table. 3 and Fig. 27.

Rolling shear modulus and strength were used to evaluate the internal shear force according to Equations (6) and (7). (Gong and Chui, 2015)

$$G = \frac{t_{cross}}{L \cdot w} \cdot \frac{P}{\Delta} \cdot \cos\alpha \qquad (6)$$

$$\tau = \frac{P_{max} \cdot \cos\alpha}{L \cdot w} \qquad (7)$$

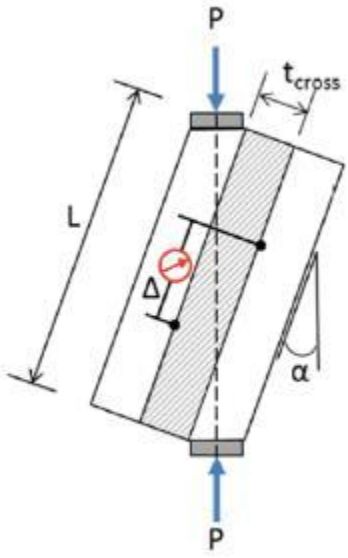

Fig. 26 Sandwich panel specimen (Gong and Chui, 2015)

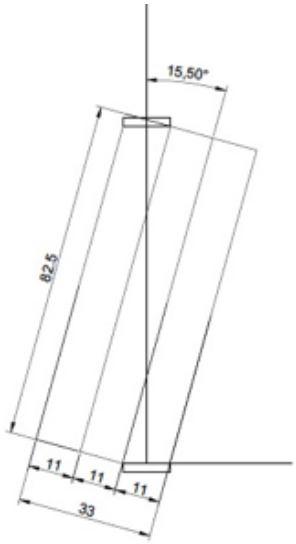

Fig. 27 Design of the rolling shear specimen

Table 3. Sizes of the rolling shear specimen

	Length		**Width**		**Depth**		**Core layer thickness**	
	inch	mm	inch	mm	inch	mm	inch	mm
Generic CLT	3.5	88.9	4/3	33	5/4	31.8	7/16	11.0
Hybrid CLT	3.5	88.9	4/3	33	5/4	31.8	7/16	11.0

2.2.3 Block shear test specimen

According to the standard ASTM D905 “Standard Test Method for Strength Properties of Adhesive Bonds in Shear by Compression Loading” (ASTM International, 2013), the design and the size of block shear test specimens are shown in Fig. 28.

The CLT panels in this project were 3-layer design so there were two bonding lines in each CLT panels. The OSB panels had a rough surface and a smooth surface which could make differences on bonding quality. So there were 9 different designs of block shear test specimens and the detailed cutting patterns were decided by the material left and shown in Fig. 29-30. And Figs. 31-32 were the real specimens:

A. Block shear specimens of generic CLT

   a) W1A boning line,

   b) W1B bonding line,

   c) W2A boning line,

   d) W2B bonding line,

B. Block shear specimens of hybrid CLT

   e) bonding line on OSB’ rough surface with load perpendicular to grain applied,

   f) bonding line on OSB’ rough surface with load parallel to grain applied,

   g) bonding line on OSB’ smooth surface with load perpendicular to grain applied,

   h) bonding line on OSB’ smooth surface with load parallel to grain applied,

   i) internal bonding quality of OSB panel.

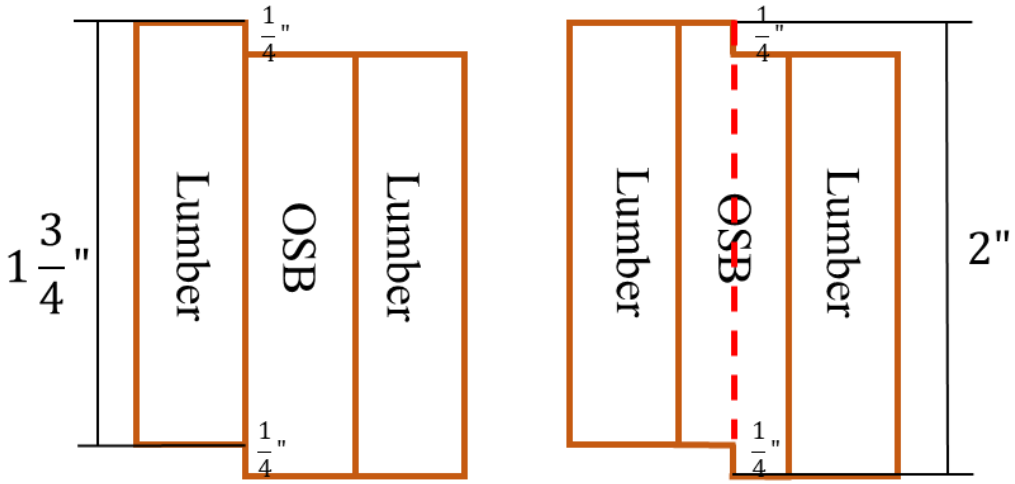

Fig. 28 block shear specimen design

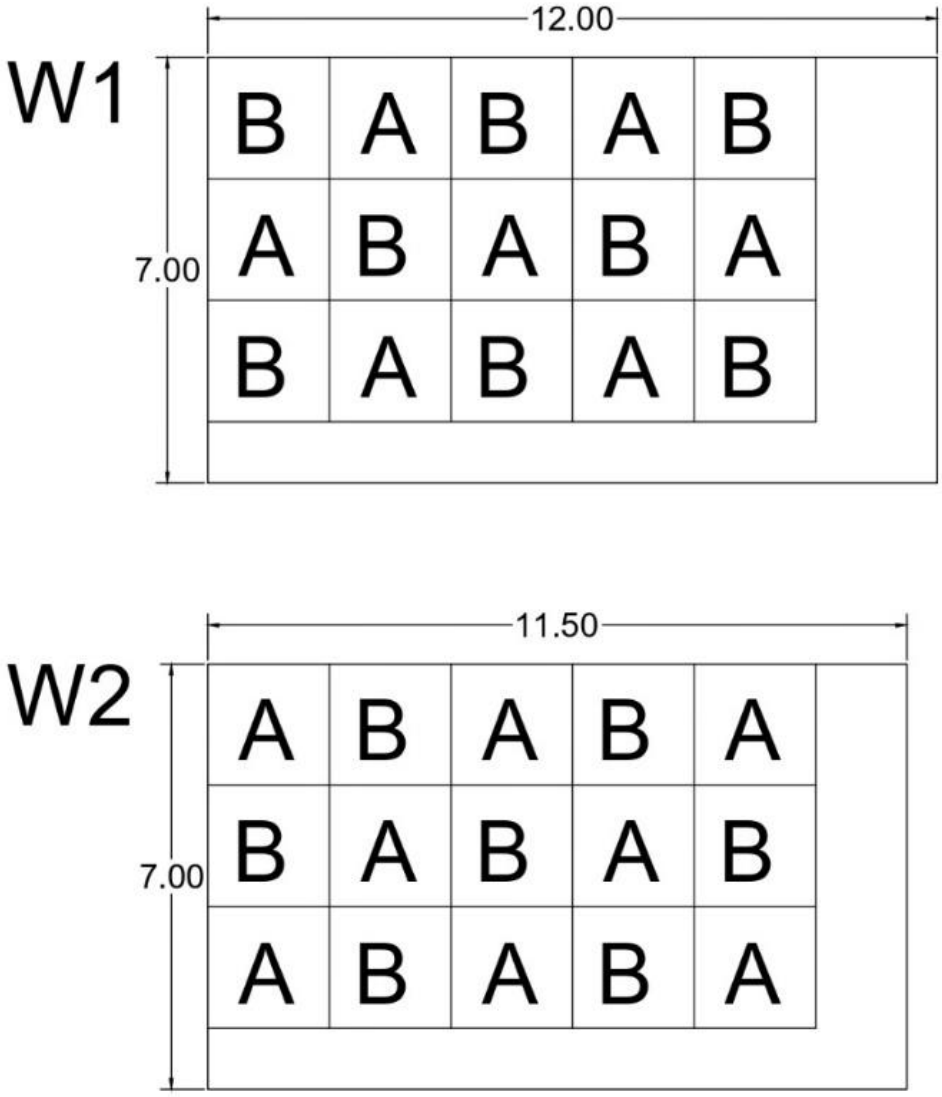

Fig. 29 Block shear test specimen cutting pattern for generic CLT

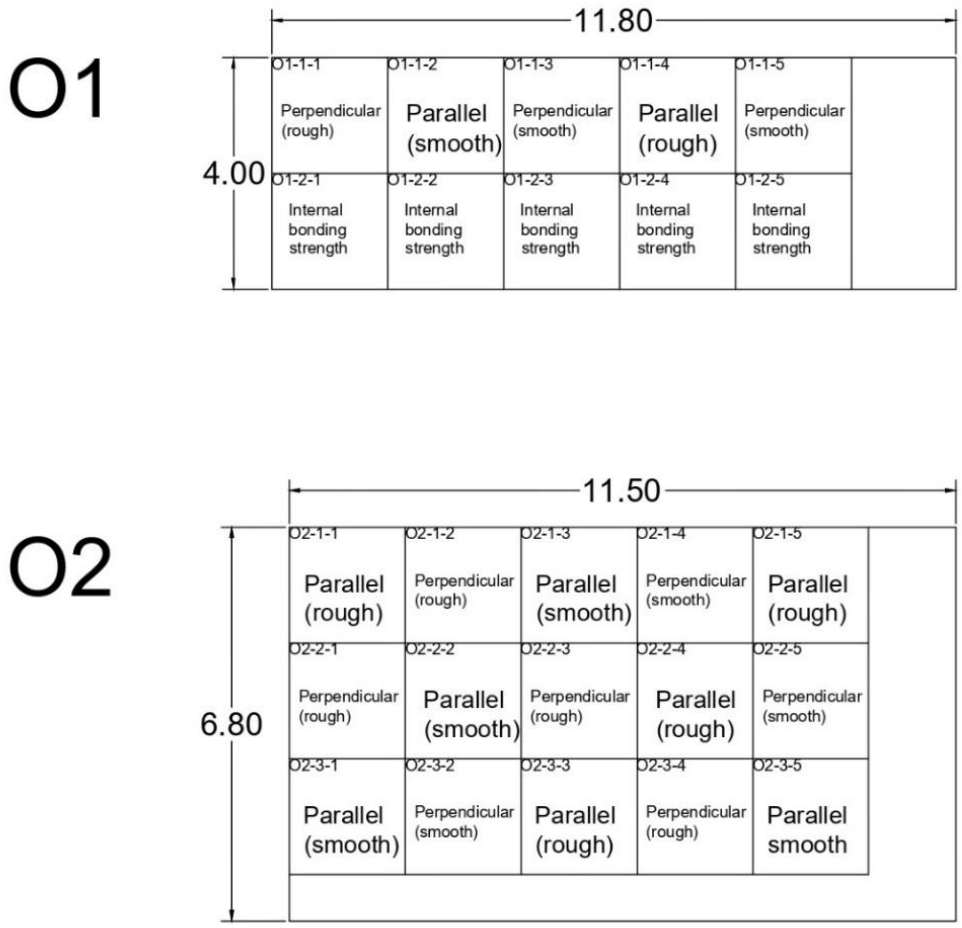

Fig. 30 Block shear test specimen cutting pattern for hybrid CLT

Fig. 31 Block shear test specimens of generic CLT

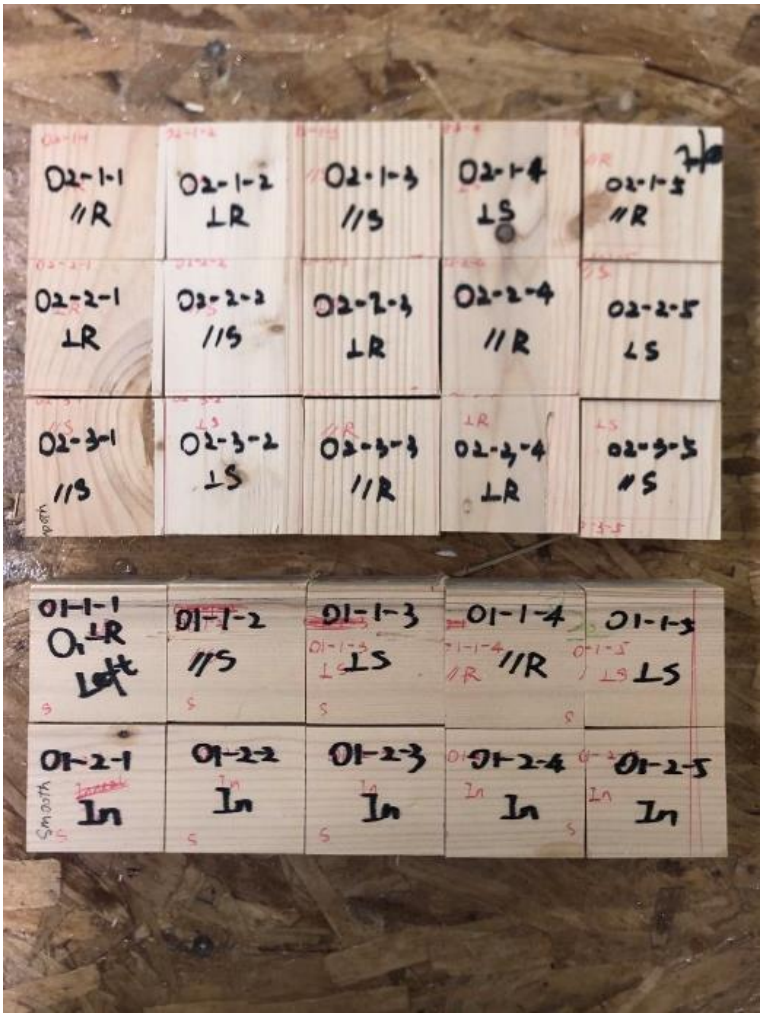

Fig. 32 Block shear test specimens of hybrid CLT

4 CLT panels were made. From generic CLT 1 (W1) and hybrid CLT 2 (O2) were used to make 6 specimens for long-span bending test in the major direction, 6 specimens for short-span shear test in the minor direction, 6 specimens for rolling shear test and block shear specimens. From generic CLT 2 (W2) and hybrid CLT 1 (O1) were used to make 6 specimens for long-span bending test in the minor direction and 6 specimens for short-span shear test in the major direction, 6 specimens for rolling shear test and block shear specimens.

The cutting patterns are shown in Fig. 33 and Fig. 34. These pictures show the position of specimens used in different tests and the orientation of cutting. During the cutting, the edge parts were removed, and the specimens were not cut along the bond line.

Table. 4 Amount of specimens under each type of testing condition

W1		W2	
Specimen type	Number	Specimen type	Number
Long-span bending test specimen in the major direction	6	Long-span bending test specimen in the minor direction	6
Short-span bending test specimen in the minor direction	6	Short-span bending test specimen in the major direction	6
Rolling shear test specimen	6	Rolling shear test specimen	6
Block shear test specimen	15	Block shear test specimen	15
O1		O2	
Specimen type	Number	Specimen type	Number
Long-span bending test specimen in the minor direction	6	Long-span bending test specimen in the major direction	6
Short-span bending test specimen in the major direction	6	Short-span bending test specimen in the minor direction	6
Rolling shear test specimen	6	Rolling shear test specimen	6
Block shear test specimen	10	Block shear test specimen	15

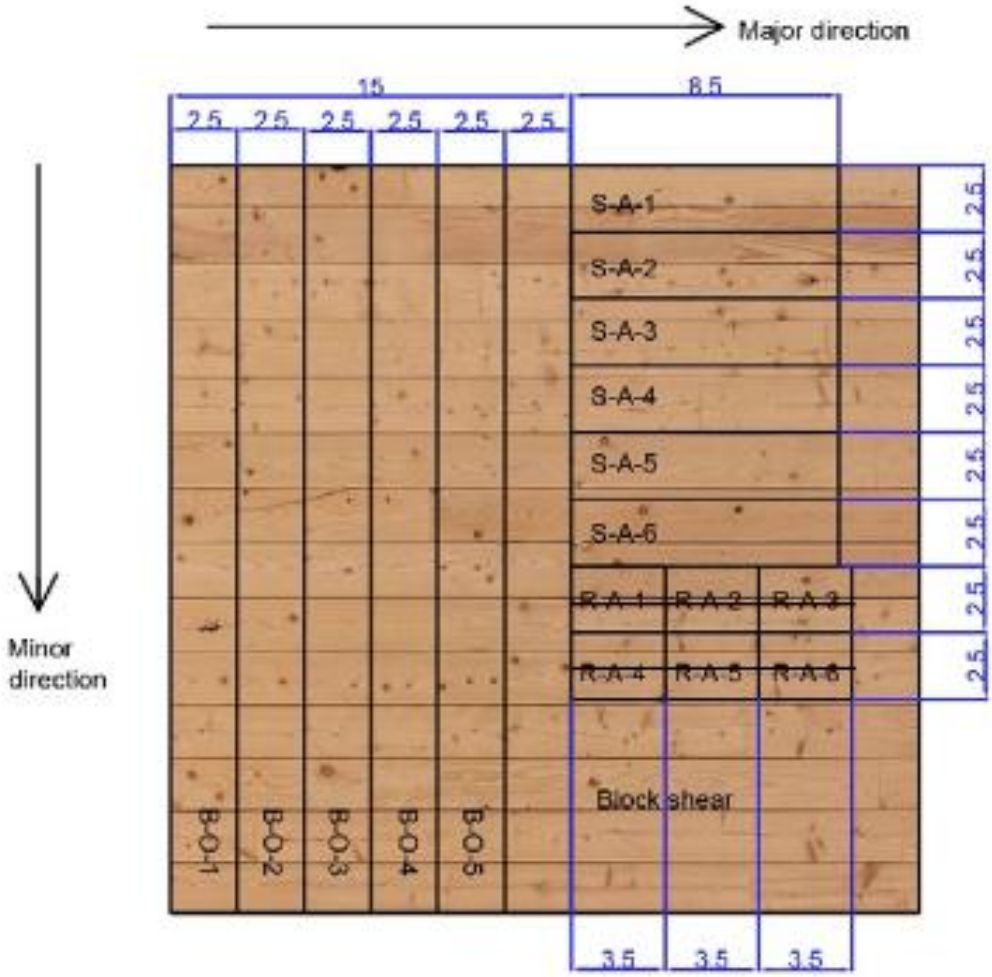

Fig. 33 Specimen cutting for panel: long-span bending test in the major direction and short-span shear test in the minor direction

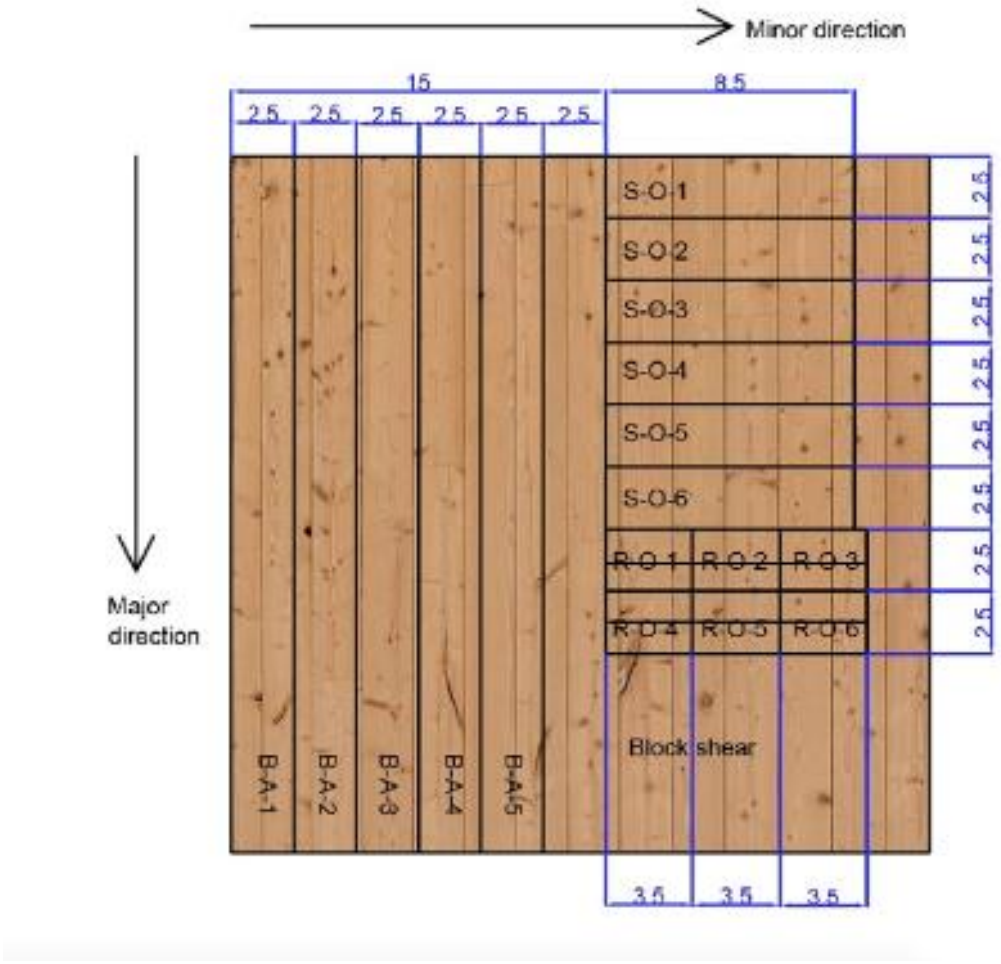

Fig. 34 Specimen cutting for panel: long-span bending test in the minor direction and short-span shear test in the major direction

2.3 Preparation of materials

2.3.1 Wood strips

According to design, there were 14 pieces of $11.0mm \times 50.8mm \times 711.2mm$ ($\frac{7}{16}$"×2" × 28") wood strips used in one SPF layer. In total 42 pieces of wood strips were needed to be cut from 2x6" lumber to make one three-layer generic CLT. Meanwhile, 28 pieces of wood strips were needed to be cut from 2x6" lumber to make one three-layer hybrid CLT. Two pieces of generic CLT and two pieces of hybrid CLT (transverse layer was made of OSB) were made so the total number of wood strips required was 224. Table 5 shows the details of the materials required in this project.

The strips were cut from the 2×6 lumber; the comparison of sizes between strip and lumber is shown in Table. 6 and the cutting pattern shown in Fig. 35 illustrates the cutting pattern for making wood strips from 2x6 lumber.

Table. 5 Amount of strips for each layer in specimens

Panel name	Top layer	Core layer	Bottom layer	Sum
W-CLT specimen 1	14	14	14	42
W-CLT specimen 2	14	14	14	42
W-CLT specimen 3	14	14	14	42
W-CLT specimen 4	14	14	14	42
hybrid CLT specimen 1	14	OSB	14	28
hybrid CLT specimen 2	14	OSB	14	28
Sum	84	56	84	224

Table. 6 Size of stirps and lumber materials

	Size (inch)	Size-Metric (mm)	Length (inch)	Length-Metric (mm)	Amount
Strips	7/16"x2"	11.0x 50.4	28"	711.2	224
Lumber	1.5" x 5.5"	38x 140			

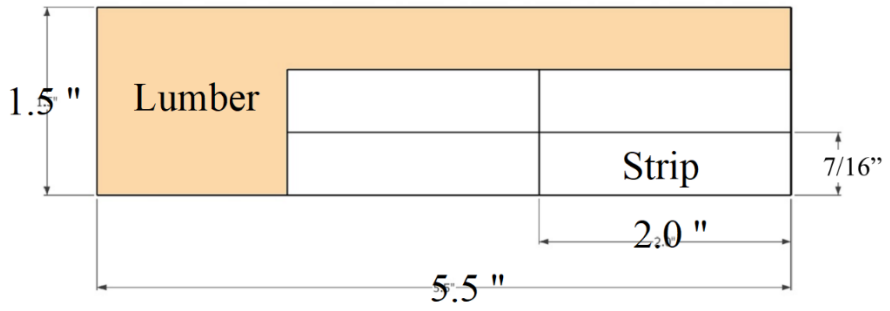

Fig. 35 Cutting pattern on the cross section of 2x6 lumber for making wood strips

2.3.2 The steps of making wood strips

The production process of how the wood strips were made is shown in Fig. 36.

- Step 1: Cutting length by removing big defects

  2"x6" dimensional lumbers were prepared. A 30” (762.0mm) strip was used to estimate the length and draw lines to mark where it should be cut to remove big defects like knots, decay and so on. Meanwhile, each wood strip was marked with a number. The strips were cut to a length of 30" allowing tolerance for edge cutting.

- Step 2: Trimming the thickness

  A table sawing machine was used to rip a board to make wood strips of a given thickness. The spacing between the fence and blade was adjusted to 1". A board was pushed through to make strips of a thickness of 1", which left some room for further sanding.

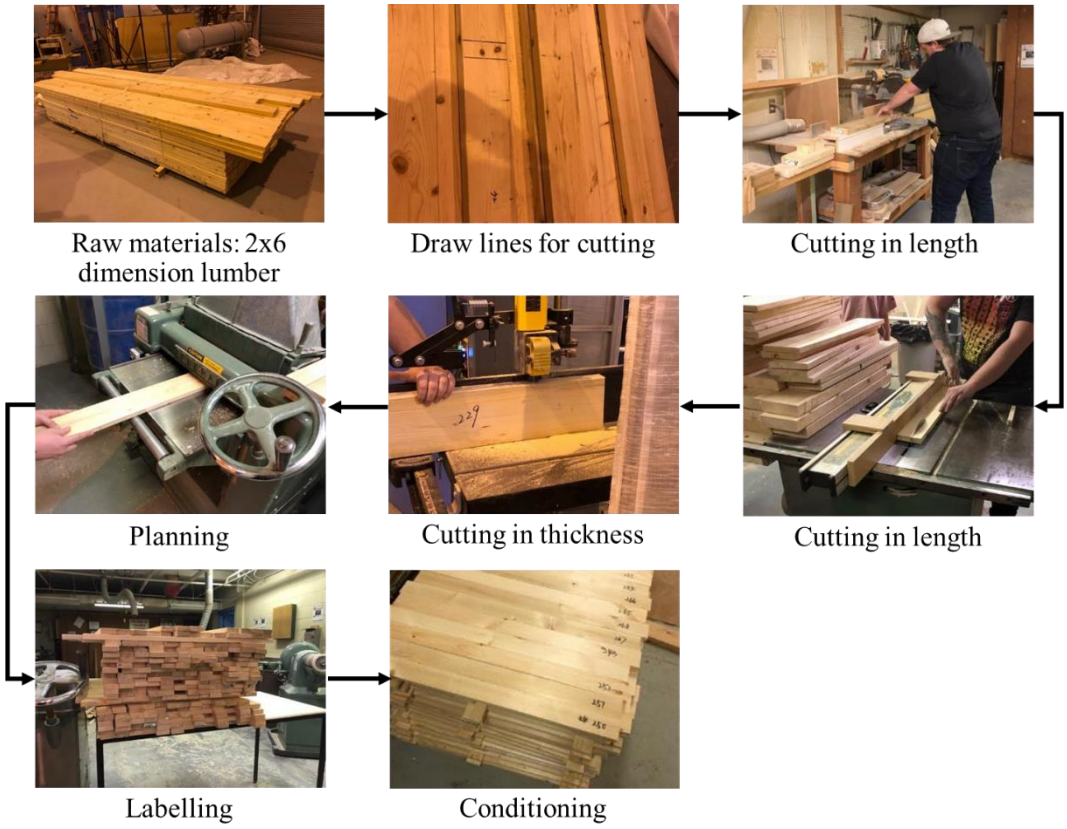

Fig. 36 The production process of wood strips

- Step 3: Making the width

  A table saw was used to cut the strips to a set width. The fence was set at 2” and then the lumber was pushed against the blade.

- Step 4: Planning

  A thickness sanded was used to smooth the surface and reduce the thickness. Both sides of each strip were planed 4 times. After this process, all the strips were 7/16" thick.

After these four processes, all strips were 7/16"x2"x30". The strips which were similar to “clear wood” were selected and the remainder were discarded. In total 270 pieces of strips were identified and marked with numbers.

All wood strips were conditioned in a dehumidification dry kiln for at least 7 days to equalize their MC, reaching their equilibrium moisture contents (EMC) of 12 ± 3%. The recommended moisture content differential shall be no more than 5% specified according to standard PRG 320 (APA, 2019).

2.3.3 Grouping of wood strips

After preparing the wood strips, the mass of each wood strip was measured to select and group wood strips according to the density for making CLT panels. Thus, all the laminations of CLT panels could have the similar density and mechanical properties. The normal distribution curve of mass is shown in Fig. 37. The average value was 226.70g and the standard deviation was 32.38 g. According to this curve, those strips with masses less than 191.00g or more than 280.36g were rejected.

These strips were made by the same machine so that the sizes of strips were assumed to be the same. But the actual size and moisture content could have some differences which could lead to density differences. To determine this, 30 strips were randomly selected, and their masses, sizes, and moisture contents were measured to calculate their density.

Appendix1.1 shows the details of 30 strips randomly selected for measuring sizes and masses. From this table, it can be found that the strips were of uniform size, except specimen 30 which was smaller. It was known that the density of wood was mainly affected by moisture content. In this exercise, it was found that the strips with high moisture content (19-23%) had a higher density around 0.3 g/cm^3while strips with low moisture content (12-15%) had a lower density around 0.25 g/cm^3. Specimen 30 was discards since its mass was less than 191g.

After grouping the strips according to their weight, the strips selected were divided into 6 groups (4 groups with relatively high weight were used in the surface layers and the

other two with relatively lower weight were used in the transverse layers). The groups in the individual type were kept with similar weight. Appendix1.2 shows the weight of each strip in 6 wood layers.

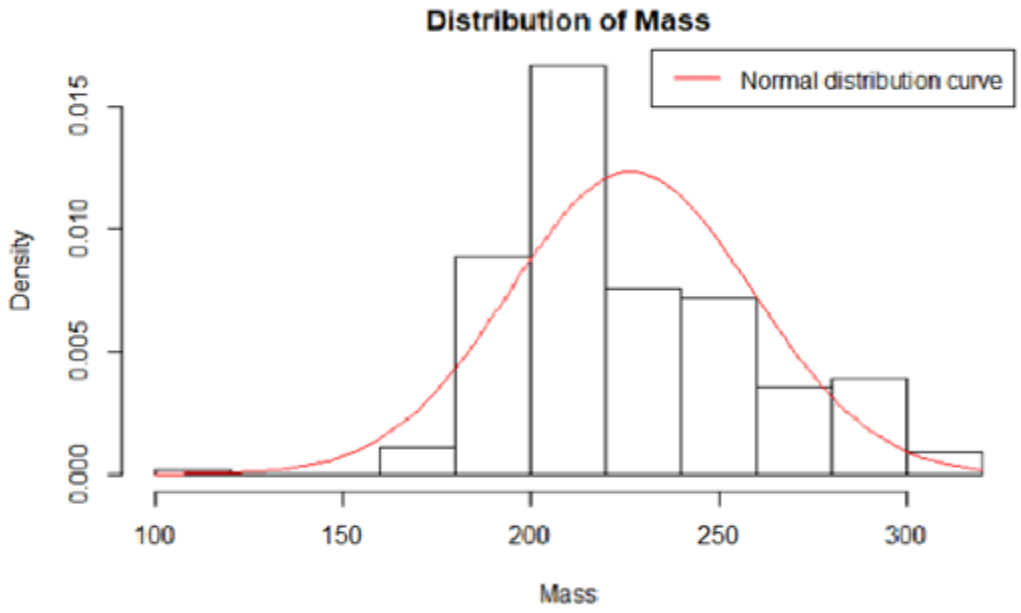

Fig. 37 Normal distribution curve of mass

2.3.4 OSB sheets

Two OSB sheets were required, which were 11.0mm ($\frac{7}{16}$") thick and 711.2mm (28") long and wide. Two OSB sheets were placed in the same conditioning chamber as wood strips to make sure that the moisture difference was within the recommended moisture content differential of no more than 5% as specified in PRG 320 (APA, 2019). In this project, OSB panels were to be treated using 600 sanding paper before bonding.

2.3.5 Application of adhesive

The spread rate of PUR (one-component polyurethane) ranges from 100-180g/m2 at optimal wood MC of 12% (Byeon *et al.*, 2020).

2.4: Fabrication of downsized CLT panels

2.4.1 Surface treatment

The surfaces of each wood strip were slightly sanded and then cleaned by removing dust prior to bonding. The surfaces of OSB were sanded using 600 mesh sanding paper and cleaned by removing dust prior to bonding as well.

2.4.2 Production of single layers

Edge bonding was applied between two laminations using single-component polyurethane with an application rate of $165 g/m^2$ which is the same application rate as face bonding. The lamination was clamped at a pressure of 0.20 N/mm², a temperature over 15°C, and relative humidity (RH) between 40% and 75% for two hours. During

curing, the temperature T was kept around 18°C and rel. humidity was kept lager or equal to 30 %. Each layer needed 24 hours for full curing.

2.4.3 Bonding

After producing the wood single layers, the thickness, width, length and weight of each layer were measured and recorded. The two OSB panels were measured too after surface sanding. The layers were divided into different panel groups. Table. 7 shows the detail of panel information.

Surface bonding was done between each layer using single-component polyurethane. Vacuum pressing (Fig. 38) was used in this lab. Panels were loaded under -100 ps for 2 hours and cured for 24 hours.

2.4.4 Making specimens

First, the edges of the panels were trimmed; then the left sides of the panels were cut according to Fig. 33 and Fig. 34 in “2.2 Design of downscaled CLT panels”. All the cutting avoided the position where the edge bonding was done.

Table. 7 Summary of layer information of 4 panels

Panel number	Layer information		Average thickness (mm)	Average length 1 (mm)	Average length2 (mm)	Weight (g)	Density (kg/m^3)
W1 (generic)	Top layer	12	11.05	714	714	2408	427.46
	Transverse layer	13	10.91	715	712	2073	373.24
	Bottom layer	4	11.22	712	714	2493	437.07
W2 (generic)	Top layer	6	11.01	720	714	2390	422.26
	Transverse layer	14	11.05	715	712	2068	367.62
	Bottom layer	9	11.03	714	714	2428	431.79
O1 (hybrid)	Top layer	1	11.04	713	713	2472	440.45
	Transverse layer	OSB1	10.54	731	732	3600	638.09
	Bottom layer	11	11	710	714	2548	456.93
O2 (hybrid)	Top layer	5	11.15	713	717	2450	429.82
	Transverse layer	OSB2	10.70	711	714	3474	639.85
	Bottom layer	10	10.99	715	713	2593	462.82

Fig. 38 Vacuum pressing

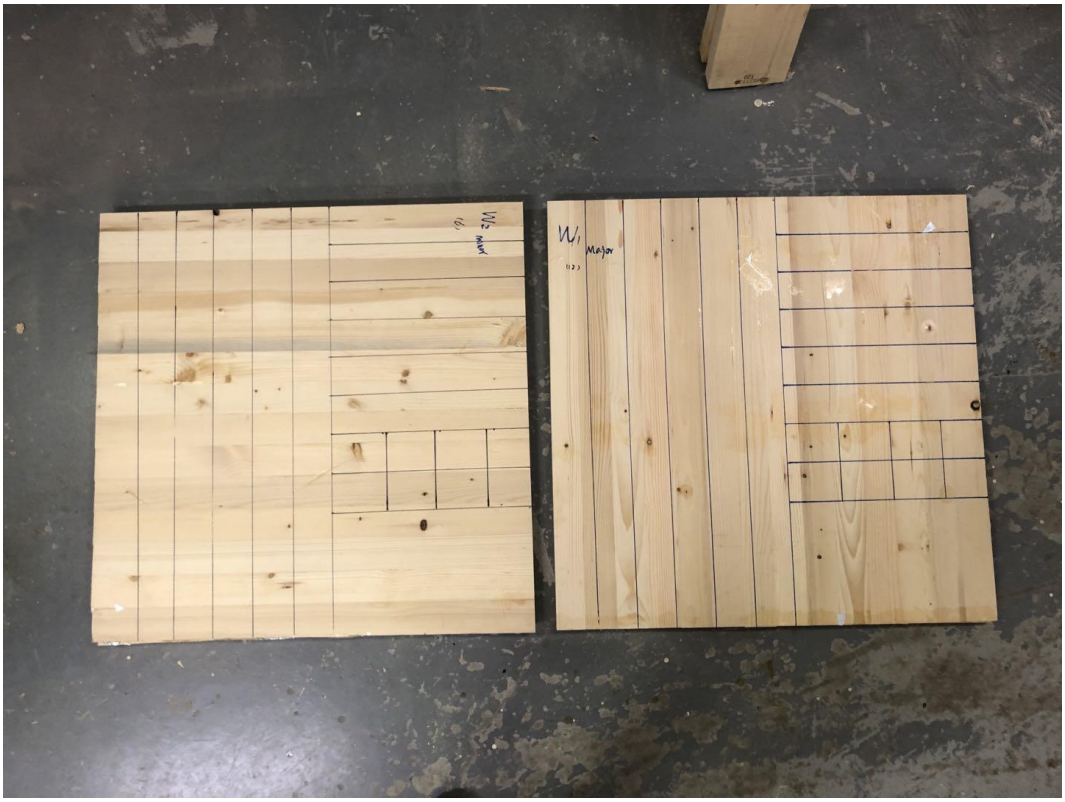

Fig. 39 Cutting pattern lines on panels

3 Testing of mechanical properties

3.1 Four-point long-span bending tests

Four-point long-span tests were conducted in accordance with ASTM D198 as shown in the Fig. 40 (ASTM International, 2015). The test span was $533.4mm$ (21") measured between the centerline of the supports. The loads were applied in the position that was $177.8mm$ (7") away from the supporting points and load span was $177.8mm$ (7"). LVDT was attached on each specimen. Each specimen was weighed and its dimensions were measured prior to the start of a test. A load rate of 5 mm/min was used to ensure the failure of a specimen within 6–20 min as specified by ASTM D198 (ASTM International, 2015). After loading, small blocks were cut from each specimen, which were oven-dried for at least 24h at 105^{o}C to determine the average moisture content at the time of testing.

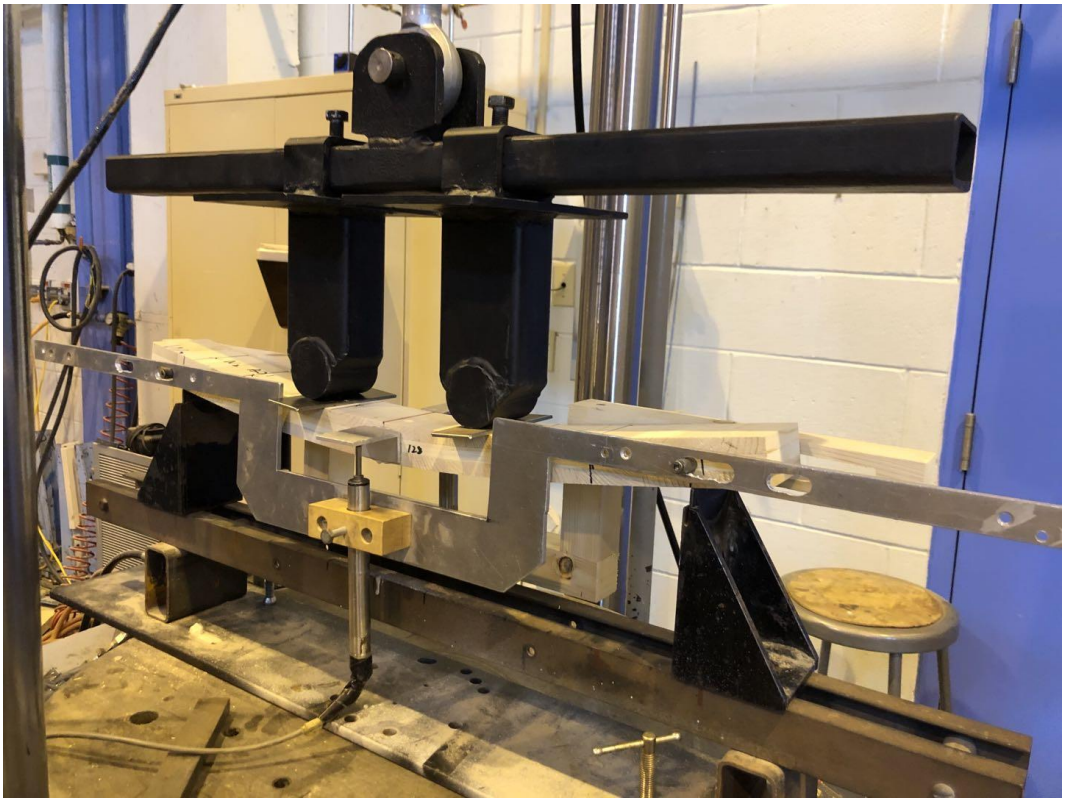

Fig. 40 Long-span bending setup

3.2 Three-point short-span bending tests

Three-point short-span bend tests were conducted in accordance with ASTM D198 (ASTM International, 2015) to assess shear strength. The setup is shown in shown in the Fig. 41. The load was applied at the middle of the $165mm$ $(6\frac{1}{2}")$ shear span with a single radius metal load head. The supports were identical to those employed in the flexural tests. LVDT was attached on each specimen . During each flexure test, each specimen was weighed and its dimensions were measured prior to the start of a test. A constant displacement rate of 2 mm/min was used, which produces failure after about 6-10 min. After loading, small blocks were cut from each specimen , which were oven-dried for at least 24h at 105^{o}C to determine the average moisture content at the time of testing.

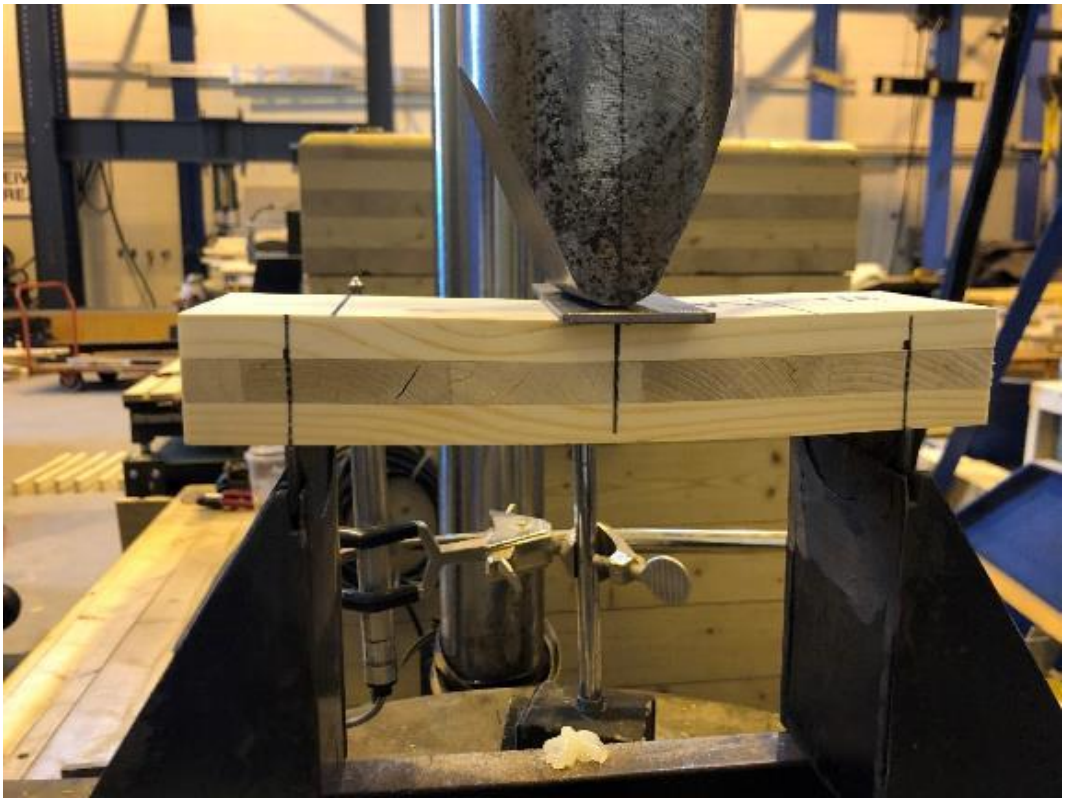

Fig. 41 Short-span bending setup

3.3 Rolling shear tests

Rolling shear tests were conducted in accordance with to Gong et al (2015). The loading rate was 0.5 mm/min. Rolling shear specimens were cut according to “2.2.2 Rolling shear test specimens ”. When specimens were too small for the LVDT to be attached, a 3D-printed fixture was used (Figs. 42, 43).

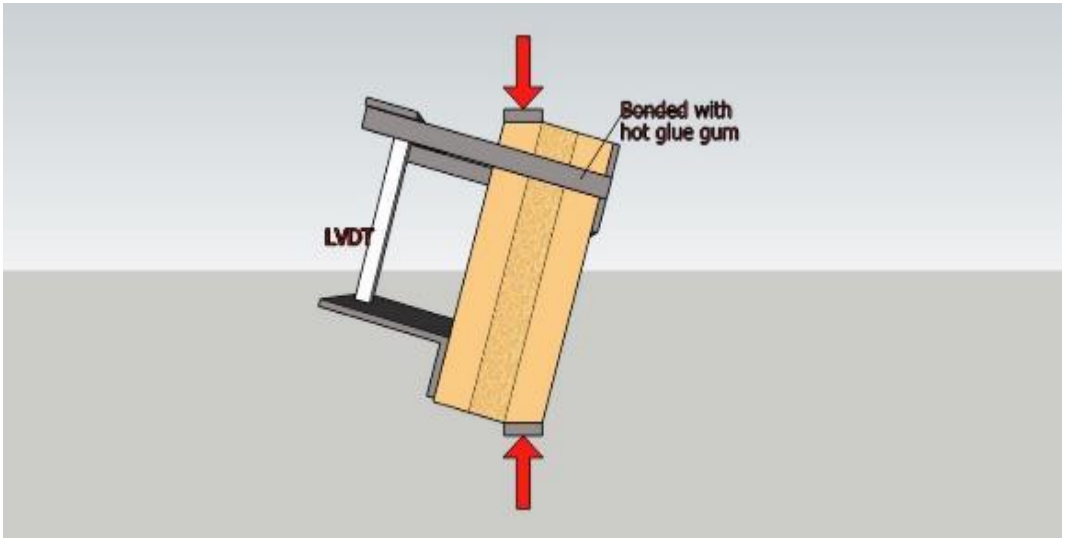

Fig. 42 Rollin shear fixture design

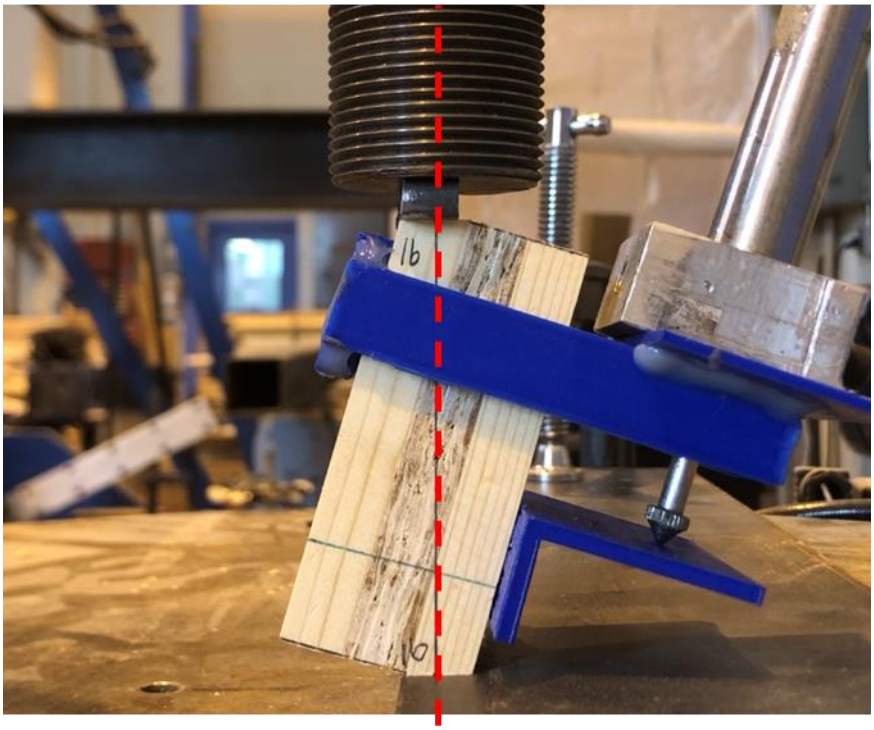

Fig. 43 Rolling shear bending setup

3.4 Block shear tests

Block shear tests were conducted in accordance with ASTM D905 (ASTM International, 2013) to assess bonding quality (Fig. 44). Block shear specimens were cut according to “2.2.3 Block shear test specimens ”. The loading rate was 1 mm/min. The percent of wood failure was estimated according to ASTM D5266（ASTM International, 2020）.

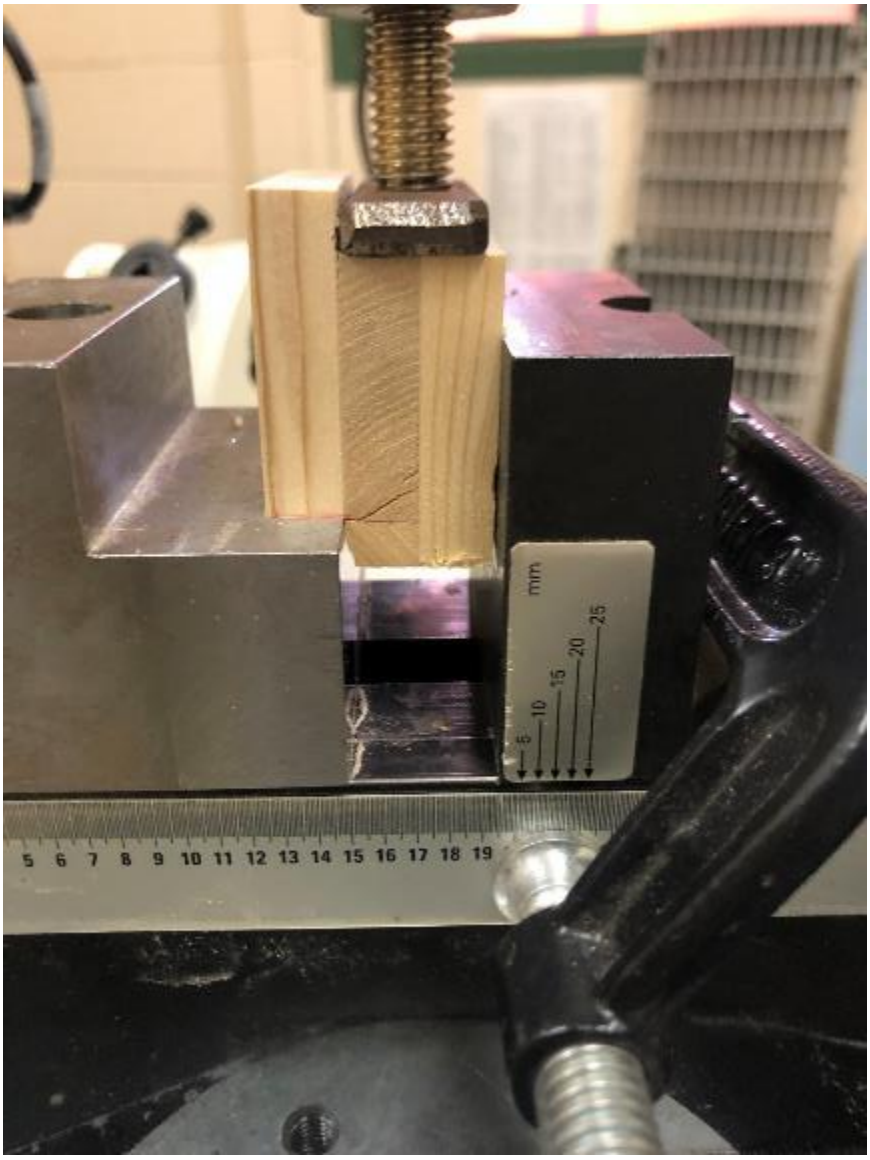

Fig. 44 Block shear test specimen

4 Results and discussion

4.1 MOE and MOR measured by the long-span bending tests

Usually when load is increasingly applied on a specimen, the specimen will have a certain amount of deformation. Therefore, the relationship between load and deflection can be used to describe the ability of a specimen to resist deformation subjected to an external force. Based on this the load-deflection curves were used to evaluate MOE and MOR. The load-deflection curves along with the typical failure modes are plotted in Fig. 45. Additionally, Fig. 46 shows the detailed failure mode of 4 typical specimens in different groups. In general, the failure showed a brittle mode.

As shown in Fig. 45, four curves all had a similar shape: increasing relatively linearly, reaching its peak and then decreasing suddenly. However, the curve of generic CLT in the major direction was the sharpest, followed by that of hybrid CLT in the major direction. The curve of generic CLT in the minor direction rose very slowly when compared with specimens in the major direction, followed by the curve of hybrid CLT in the minor direction which was the lowest curve in this diagram. According to formula (1), slope is closely related to MOE so this diagram can show that the generic CLT in the major direction had the highest MOE, followed by hybrid CLT in the major direction, generic CLT in the minor direction and hybrid CLT in the minor direction.

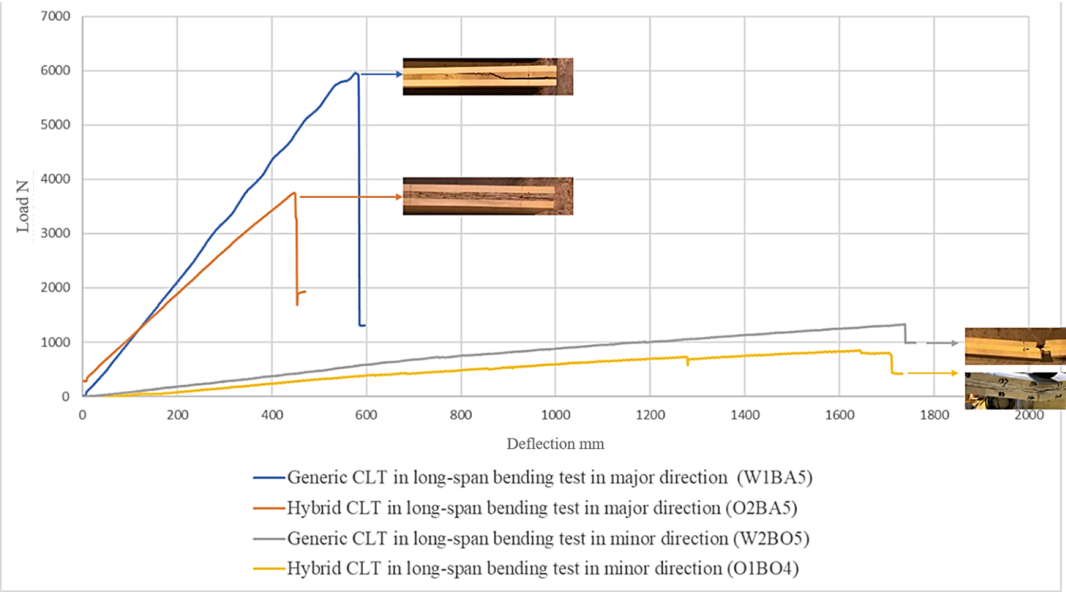

Fig. 45 Load-deflection curves of 4 different kinds of specimens in a long-span bending test

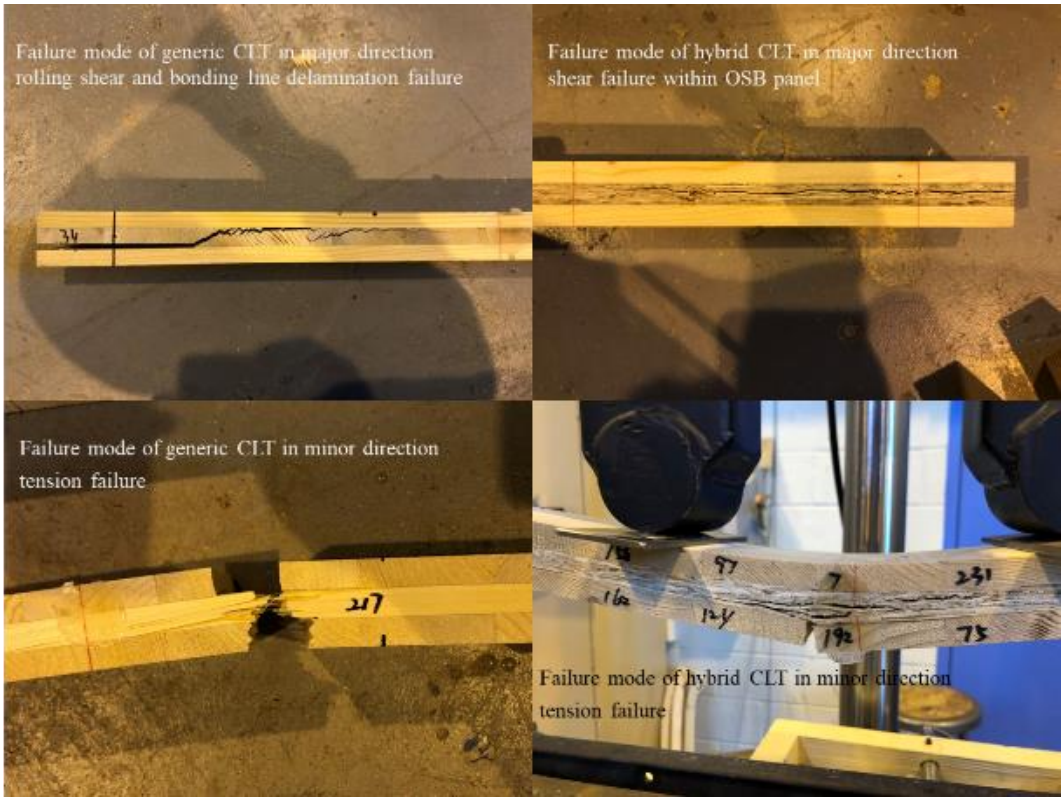

Fig. 46 Failure mode of specimens in long-span bending test

The highest turning point represents the maximum load the specimen could afford before failure, which is associated with MOR. Generic CLT in the major direction had the highest peak and it was approximately two times higher than that the hybrid CLT had in the same direction. To some degree this may demonstrate that generic CLT had double the MOR than hybrid CLT in the major direction. The curves of specimens in the minor direction were much lower than those in the major direction (the height was less than one tenth of that of the curve of generic CLT in the major direction), showing that CLT had a dramatically high MOR in the major direction. It was also worth mention that specimens in the major direction took less time to reach their peaks. The loading speed was the same (5mm/s) so it can be concluded that the specimens in the major direction can exhibit less deformation than those in the minor direction under the same load before failure, while the specimens in the minor direction would undergo greater deformation.

Turning to Fig. 46, the picture on the top left shows the failure mode of generic CLT in the major direction. The typical failure was rolling shear failure in the transverse layer. A crack(s) was suddenly initiated perpendicularly to growth ring in the transverse layer, and then propagated along the growth ring direction and resulted in a separation along the growth ring(s). The crack stopped at the bonding surface resulting in bonding line delamination failure.

The image on the top right of Fig. 46 shows the failure mode of hybrid CLT in the major direction. The typical failure was shear failure within the transverse layer. It showed that the internal bonding quality of OSB panel was lower than both internal shear resistance

of lumber and bonding lines quality between lumber and OSB panel. The results of block shear test supported this interpretation.

The image on the bottom left right of Fig. 46 shows the failure mode of generic CLT in the minor direction. The typical failure was tension failure. A crack(s) was suddenly initiated alone the growth ring in the bottom layer, and then propagated upwards to the core layer, and finally resulted in failure.

The image on the bottom right of Fig. 46 shows the failure mode of hybrid CLT in the minor direction. The typical failure was tension failure. A crack(s) suddenly initiated alone the growth ring in the bottom layer, and then propagated upwards to the core layer, led to OSB splintering tension failure and finally resulted in failure.

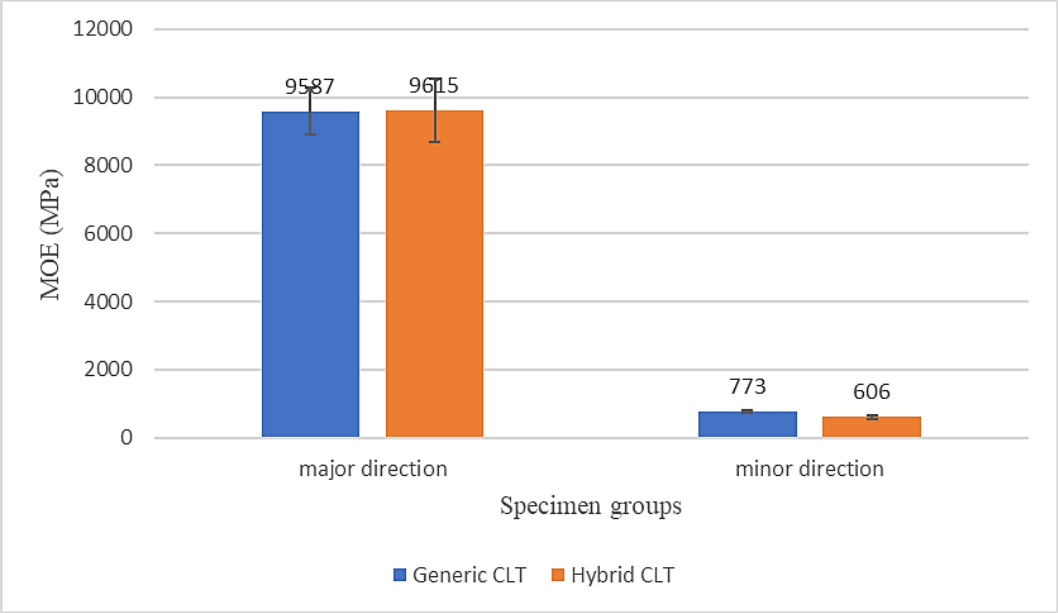

Fig. 47 MOE of long-span bending test specimens in two directions

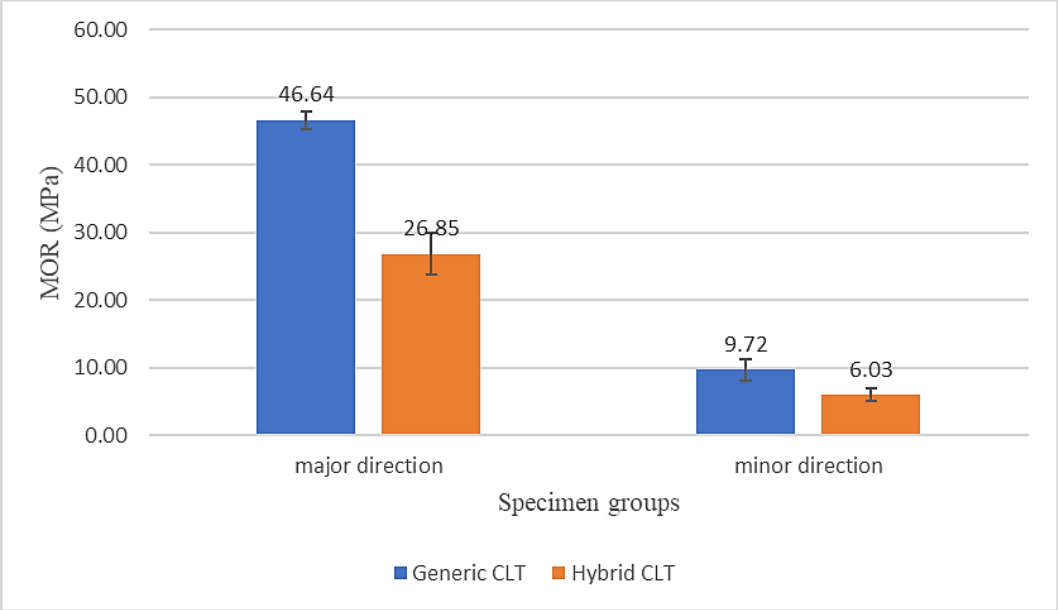

Fig. 48 MOR of long-span bending test specimens in two directions

Figs. 47-48 shows the average MOE and MOR of 4 different types of specimens in two directions and Appendix 1.3 gives the summary of test results and Appendix 1.4 gives the analysis of test results. The detailed failure mode of each specimen is shown in Appendix 1.7. After comparison, the following could be found:

- In terms of average MOE, there was not a significant difference between hybrid and generic CLT in the either major or minor directions, which showed that using OSB as the transverse layer material can provide a similar performance with lumber within the elastic deformation. It was weaker than LSL whose MOE was 13% higher than generic CLT (Wang et al. (2015)). And it was stronger than LVL whose MOE was 8.7% lower than generic CLT (Wang et al. (2017)). With regard to cost, OSB can be seen as a cost-efficient alternative material used in transverse layer within elastic deformation.

  However, hybrid CLT had higher standard deviation than generic CLT. This may be for the following reason: first as can be seen in Fig. 46, the failure mode of hybrid CLT was typified by tension failure within the OSB panels. Compared with lumber, OSB was more uneven because the wood strands with different sizes were bonded randomly during production. So the bonding quality varied from area to area. Although the failure usually happened on the center of the OSB (in the major direction) or on the bottom of the OSB panel (in the minor direction), the different parts in one OSB panel would display different properties. In this situation, 6 specimens may not be enough to allow an accurate estimation of MOE of hybrid

CLT in long-span bending test. So more tests need to be done in the future to figure out the relationship between these two kinds of CLT.

In terms of average MOR, hybrid CLT had much lower value that those of generic CLT, 42.4% lower in the major direction and 38.0% lower in the minor direction. Also it was weaker than LSL whose MOR was 24% higher than that of generic CLT (Wang et al. (2015)) and LVL whose MOR was 10.1% lower than generic CLT (Wang et al. (2017)).

The reason that led to this difference could be that after elastic deformation, it was easier for OSB to crack under increasing load because OSB was composed of wood strands with glue. In the block shear tests, it was found that the average internal bonding quality of OSB panels was 1.64 kPa while the bonding quality of lumber was over 2 kPa. Since the internal bonding quality of OSB panel was lower than both internal shear resistance of lumber and bonding lines between lumber and OSB panel, it was easier for failure to be initialed within the OSB panels.

- According to tests in the major and minor directions, generic CLT and hybrid CLT all had much better properties in the major direction than in the minor direction. The reason was that strips applied in the major direction on the surface layers were much stronger than those applied in the minor direction on the surface layers. Under the tensile force, it was easier for lumber in the radical direction or edge bonding line to split than lumber in the longitudinal direction which observations

was in agreement with Gong, M. (2019, 10). Furthermore Wang et al. (2014) and Davids et al. (2017) also reached the similar conclusion about MOE and MOR differences of specimens in the major and minor directions.

4.2 MOE and MOR measured by the short-span bending tests

The short-span bending tests are used to evaluate the shear properties of a material. However, just for the comparison purpose, the MOE and MOR under the short-span bending are still presented. The load-deflection curves along with the typical failure modes are plotted in Fig. 49 Additionally Fig. 50 shows the detailed failure mode of 4 different types of specimens in two directions.

As shown in Fig. 49, four curves all had the similar shape: increasing relatively linearly, reaching its peak and then decreasing suddenly. However, the curve of hybrid CLT in the major direction was the sharpest, followed by that of generic CLT in the major direction. The generic CLT in the minor direction and hybrid CLT in the minor direction ranked the third and the fourth respectively. According to formula (3), slope is closely related to MOE so this diagram can show that the hybrid CLT in the major direction had the highest MOE, followed by generic CLT in the major direction, generic CLT in the minor direction and hybrid CLT in the minor direction.

The peak of each curve represents the maximum load the specimen can afford before failure, which is associated with MOR. Generic CLT in the major direction had the

highest peak and it is higher than that of the hybrid CLT in the major direction. The curves of specimens in the minor direction were much lower than those in the major direction, showing that CLT had a noticeable high MOR in the major direction. However, different form Fig. 45 “load-deflection curves of 4 different kinds of specimens in short-span bending test”, the specimens tested in the major direction took longer to reach their peak. On the one hand this demonstrated that like the specimens in the long-span bending test, specimens in the major direction can display less deformation than those in the minor direction under the same load. On the other hand, specimens in minor direction can’t perform a larger deformation than specimens in the major direction. This was totally consistent with the conclusion in long-span bending test. It may be because in long-span bending test the moment in the center of the specimen was much higher due to the long length. The higher moment the specimen had, the bigger deformation it would exhibit.

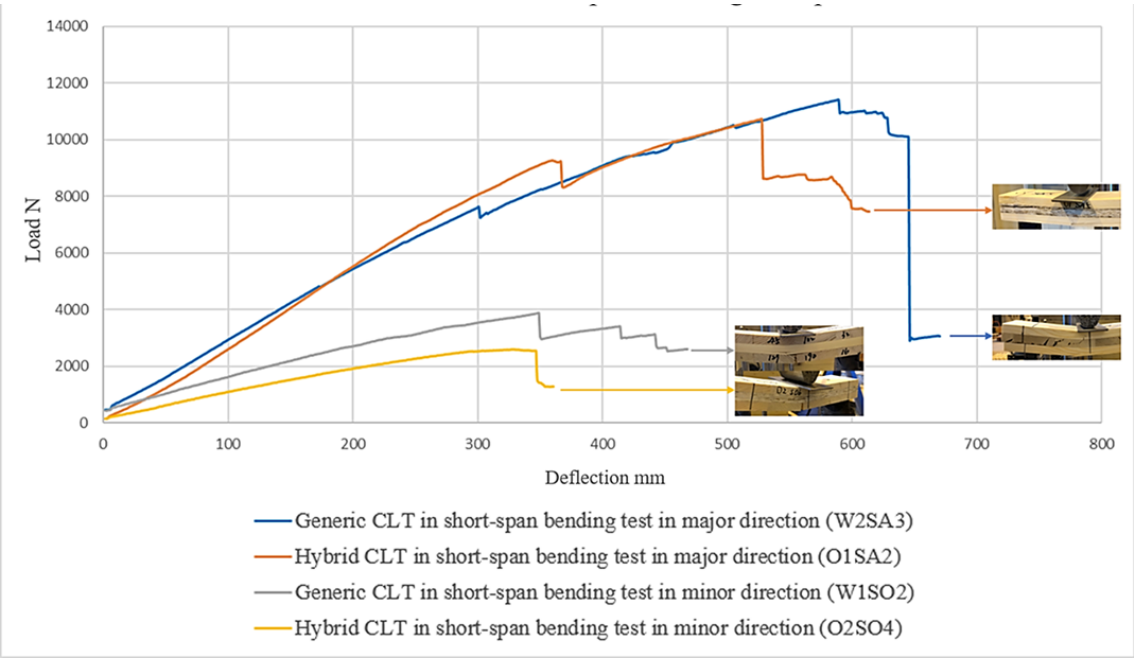

Fig. 49 Load-deflection curves of 4 different kinds of specimens in short-span bending test

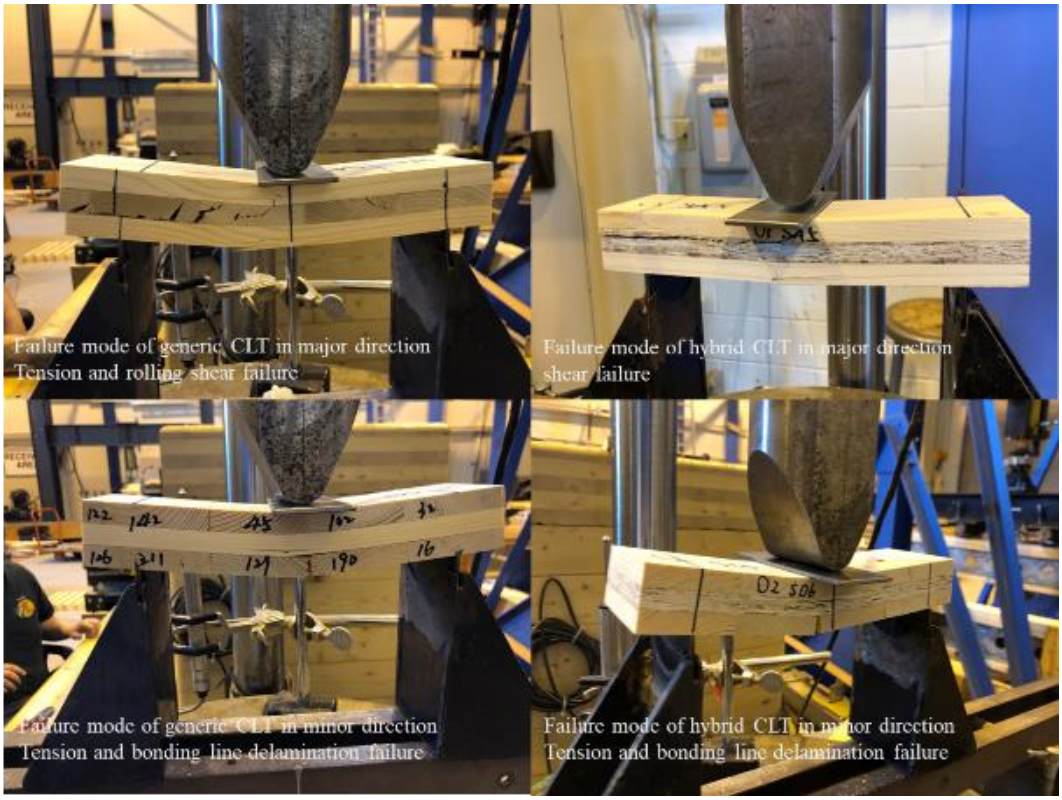

Fig. 50 Failure mode of specimens in short-span bending test

The top left of Fig. 50 shows the failure mode of generic CLT in the major direction. The typical failure was rolling shear and tension failure in the transverse layer. A crack(s) was suddenly initiated perpendicularly to growth ring in the transverse layer, and then propagated along the growth ring direction and resulted in a separation along the growth ring(s). During this period, the bottom of this specimen also had a spitting tension failure, which may be resulted from rolling shear: the internal deformation of the transverse layer accelerated bottom tension failure and the failed transverse layer did not have enough strength to resist the load any more after rolling shear.

The image on the top right of Fig. 50 shows the failure mode of hybrid CLT in the major direction. The typical failure was shear failure within the transverse layer. The OSB in the transverse layer failed first and then the tension failure appeared on the lumber on the bottom. This showed that the internal bonding quality of OSB panel was lower than both internal shear resistance of lumber and bonding lines between lumber and OSB panel. The results of the block shear test supported this interpretation.

The image on the bottom left of Fig. 50 shows the failure mode of generic CLT in the minor direction. The typical failure was tension and bonding line delamination failure. A crack(s) was suddenly initiated alone the growth ring in the bottom layer, and then propagated upwards to the transverse layer, resulting in bonding line delamination. During this period, the lumber in the transverse layer also underwent a tension failure.

The image on the bottom right of Fig. 50 shows the failure mode of hybrid CLT in the minor direction. The typical failure was tension and bonding line delamination failure. A

crack(s) was suddenly initiated alone the growth ring in the bottom layer, and then propagated upwards to the transverse layer, resulting in tension failure in the transverse layer.

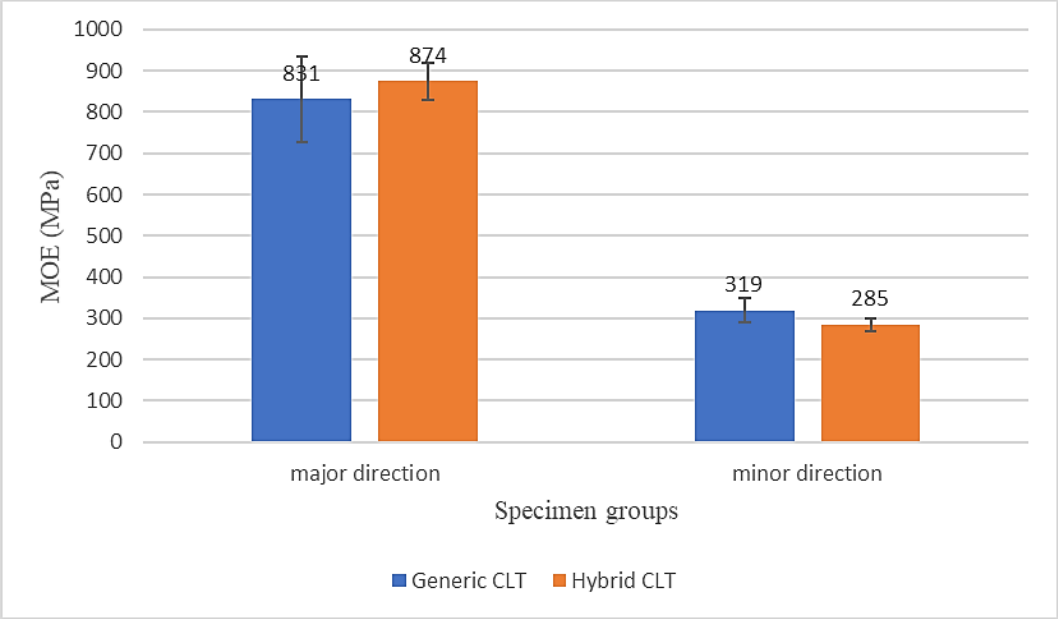

Fig. 51 MOE of short-span bending test specimens in two directions

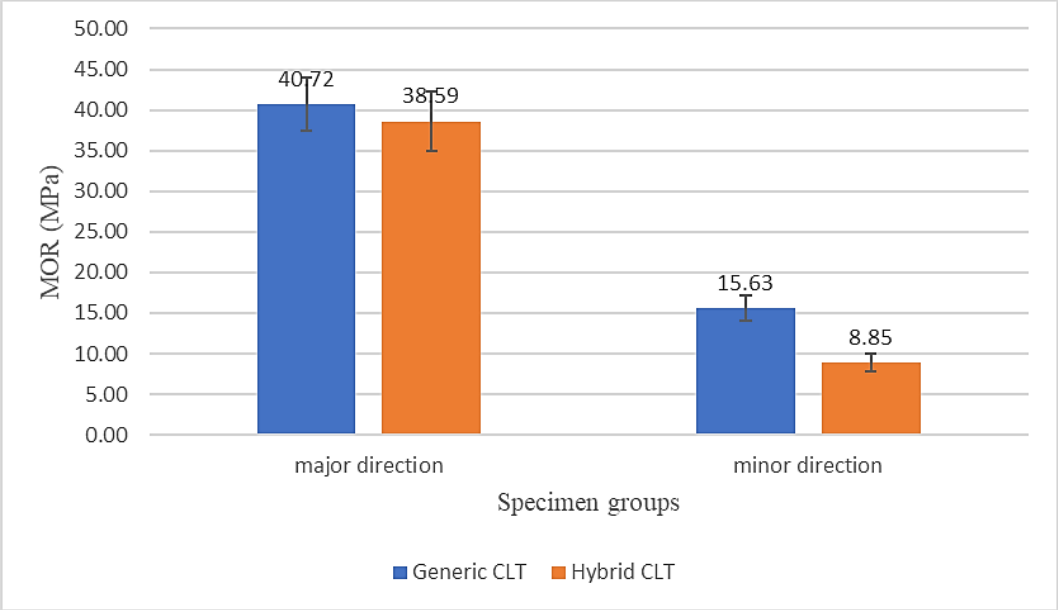

Fig. 52 MOR of short-span bending test specimens in two directions

Figs. 51-52 shows the MOE and MOR of 4 different types of specimens in two directions and Appendix 1.5 gives the summary of test results and Appendix 1.6 gives the analysis of test results. The detailed failure mode of each specimen is shown in Appendix 1.7. After comparison, it could be found:

- In terms of MOE, hybrid CLT had higher MOE (5.2%) in the major direction and lower MOE (10.7%) in the minor direction than generic CLT. This showed that within elastic deformation, hybrid CLT can bear more load in the major direction. What is more, in long-span bending test in the major direction, the hybrid CLT had a similar MOE with generic CLT.

- In terms of MOR, in the major direction these two kinds of specimens had similar value. However, hybrid CLT had much lower value that those of generic CLT, 43.4% lower in the minor direction. The reason that led to this difference was that: after elastic deformation, it was easier for OSB to crack under increasing load because OSB was composed of wood strips with glue, which can be shown in the load-deflection curves (see Fig. 49). The internal bonding quality of OSB panel was lower than both internal shear resistance of lumber and bonding lines between lumber and OSB panel. The result of block shear test can prove it too.

- According to tests in the major and minor directions, generic CLT and hybrid CLT all had a much better properties in the major direction than in the minor direction. The reason was that strips applied in the major direction on the surface layers were

much stronger than those applied in the minor direction on the surface layers with glue. Under the tensile force, it was easier for lumber in the radical direction or edge bonding line to split than lumber in the longitudinal direction, which was same with Gong (2019). Moreover, Wang et al. (2014) and Davids et al. (2017) also reached the similar conclusion about MOE and MOR differences of specimens in the major and the minor direction.

4.3 Shear strength measured by the short-span bending tests

Fig. 51 shows the maximum shear strength of 4 different types of specimens in two directions and Appendix 1.8 gives the summary of test results.

- In the major direction, there was not a significant difference between generic CLT and hybrid CLT (4.10 MPa for generic CLT and 3.83MPa for hybrid CLT). However, in the minor direction, the maximum shear strength of hybrid CLT was 0.87 MPa, 44.1% lower than that of generic CLT (1.56MPa). This demonstrated that in the major direction hybrid CLT could bear similar shear strength with generic CLT but in the minor direction using of OSB decreased the maximum shear strength a lot.

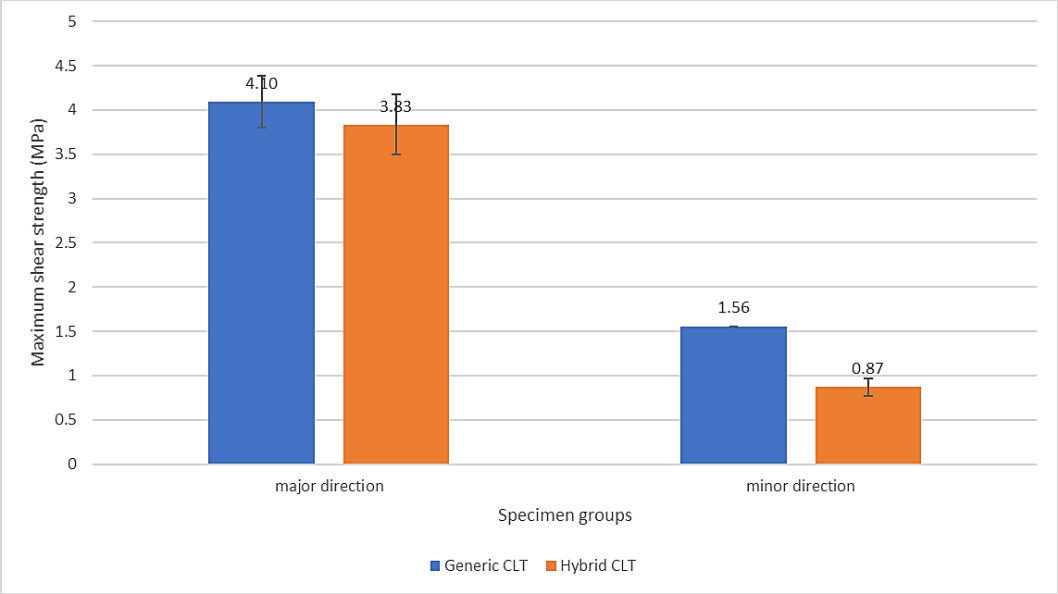

Fig. 53 Maximum shear strength of short-span bending test specimens in two directions

4.4 Rolling shear modulus and strength

Table. 8 shows the summary of rolling shear test results and Fig. 55 shows the failure modes of specimens in rolling shear tests. The detailed test result is shown in Appendix 1.9. However, after analyzing the data, the slopes of stress-strain diagrams varied from specimen to specimen. Thus, neither the slope nor the shear modulus can be calculated. The 3D-printed fixture may cause this problem: when the machine went down along with the load increasing, the surface layer went down too (which was unexpected), making the fixture touch the platform. This made the LVDT cannot record the strain accurately.

- In the major direction, the SPF wood used had a 14.5% higher average rolling shear strength than OSB used. In Wang et al. (2014), the LVL had a 24.1% lower rolling shear strength than lumber. This suggests that OSB had a better performance than LVL in terms of rolling shear strength improvement.
- From Table 8, it can be found that the COV of rolling shear strength of OSB is only about half of that of wood. This suggests OSB has a more uniform structure than the wood used. It is true since OSB is engineer-designed and manufactured.

- It was evident in Fig. 55 that the failure modes of hybrid CLT were all internal shear failure. This showed that internal shear resistance of OSB was the main reason of hybrid CLT failure. In 4.3 block shear tests, the internal bonding quality was 1.64 kPa which was lower than lumber-to-lumber bonding (generic CLT surface bonding) and lumber-to-OSB bonding when load parallel applied (hybrid

CLT surface bonding). The lower shear strength in the core of OSB could be due to the small dimensions of strands used.

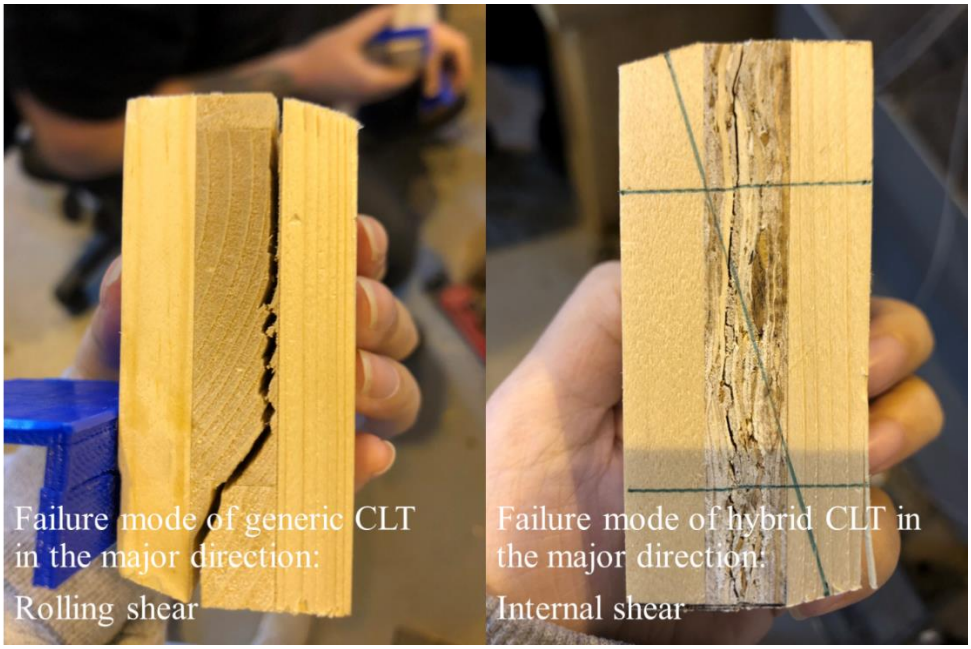

Fig. 54 Failure mode of specimens in rolling shear tests

Table. 8 Summary of the rolling shear test results

	Pmax				Rolling shear strength			
	Count	Average (kN)	Sd (kN)	COV	Count	Average (MPa)	Sd (MPa)	COV
Lumber	6	5.28	1.6	30.30%	6	1.31	0.39	30.00%
OSB	6	4.53	0.68	15.00%	6	1.12	0.17	15.10%

4.5 Block shear strength

Table. 9 shows the summary of block shear test results. The detailed test result are shown in Appendix2.0.

- In terms of hybrid CLT specimens, it was obvious that block shear specimens with load parallelly applied had higher resistance than did specimens with load perpendicularly applied. It was because that when load parallelly applied on specimens, the OSB was put in its minor direction. As shown in Figs. 56-57, there were many small wood strands in the minor direction, which meant that it had more glue applied and small strands were bonded together more closely, leading to stronger properties. In the meantime, when load perpendicularly applied on specimens, the OSB was put in its major direction. There were small number of big wood strands in the major direction, which mean it had less glue applied, leading to weaker properties.

- Also, it was worth mention that the percentage of wood failure of hybrid CLT with load perpendicularly applied was very low, especially in the perpendicular rough group, in which almost all specimens had 0% wood failure. It may indicate that lumber-OSB bonding was different in block shear test: when load was applied perpendicular to grain the bonding quality was higher while when load was applied parallel to grain the bonding quality was lower.

- OSB had two different surfaces: smooth surface and rough surface. The results in

Table 9 suggested that the bonding quality on the rough surface was higher than smooth surface when load was parallelly or perpendicularly to grain applied. It was because the glue can have more area to bond materials together on the rough surfaces. That was why surface sanding was important in surface treatment before applied glue.

- In terms of generic CLT specimens, the bonding qualities of these four different bonding groups were different, indicating that manual glue-apply in this lab cannot make every panel even. It may cause inaccurate results.

Table. 9 Summary of the block shear test results

	Rough surface		Smooth surface		Internal
	Perpendicular	Parallel	Perpendicular	Parallel	
Average (kPa)	1.48	3.08	1.21	2.31	1.64
Sd (kPa)	0.31	0.57	0.32	0.57	0.42
Percentage of wood failure	4%	76%	60%	100%	100%
	W1A	W1B	W2A	W2B	
Average (kPa)	2.78	3.39	2.09	2.32	
Sd (kPa)	0.71	0.69	0.34	0.20	
Percentage of wood failure	98%	86%	100%	100%	

Fig. 55 Cross section of hybrid CLT failure with load perpendicularly applied

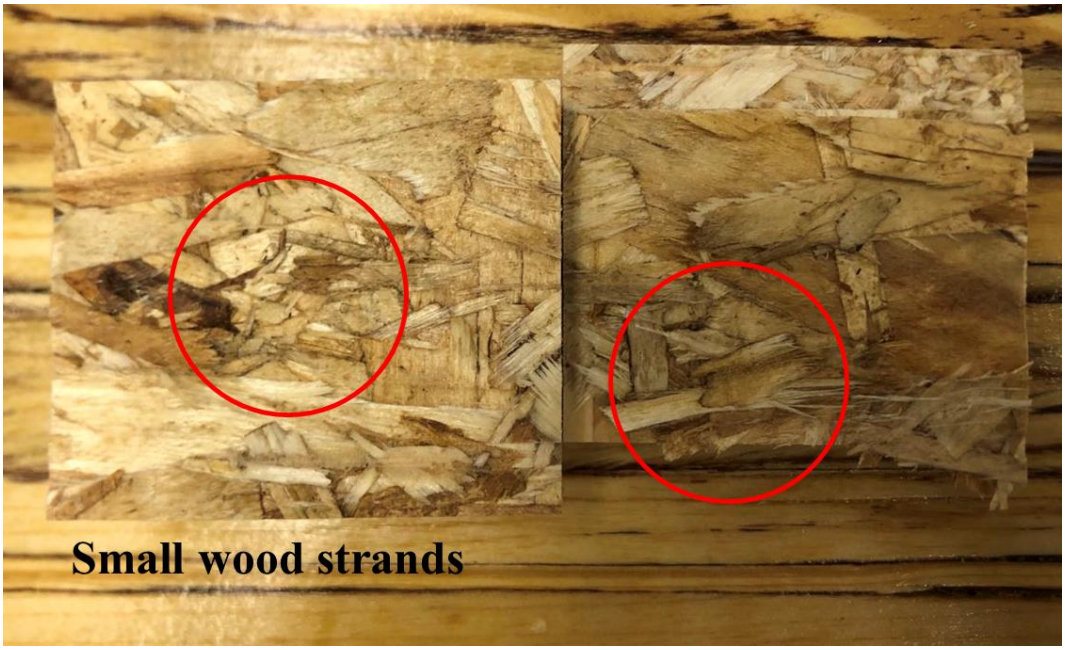

Fig. 56 Cross section of hybrid CLT failure with load parallelly applied

4.6 Summary

To sum up, using OSB as the transverse layer material can reach a similar or better performance with lumber within elastic deformation and it could reach a similar maximum shear strength in the major direction. However, after that it failed faster than generic CLT. So, this study suggested that use of OSB as transverse layer (the major direction of OSB was perpendicular to the major direction of CLT) in fabrication of CLT could reach a similar performance in effective MOE but it could not improve its performance noticeably .Also in terms of MOR in the both major and minor directions, rolling shear test, the use of OSB as transverse layer couldn't improve or reach a similar performance when compared with generic CLT.

Additionally, compared with other material used in transverse layer in hybrid CLT, OSB was better than LVL and weaker than LSL. Moreover, OSB has a very high yield of raw materials, which can reach as much as 90%, and the wood strands are usually made from small diameter and fast-growing trees. Thus, OSB has a great potential to be an alternative material used in transverse layer in hybrid CLT to make CLT more cost-efficient and reduce the raw material quality requirement.

5 Conclusions and Recommendations

Based on the results and discussion, the following conclusions could be drawn:

- In the long-span bending test, there was not a significant difference between MOE of hybrid and generic CLT in the either major or minor direction. In the major direction, MOE of generic CLT was 9,587MPa and MOE of hybrid CLT was 9,615MPa; in the minor direction, MOE of generic CLT was 773MPa and MOE of hybrid CLT was 606MPa.

  However, hybrid CLT had much lower MOR than that those of generic CLT, 42.4% lower in the major direction (26.85MPa for hybrid CLT and 46.64MPa for generic CLT) and 38.0% lower in the minor direction (6.03MPa for hybrid CLT and 9.72MPa for hybrid CLT).

- In the short-span bending test, MOE of hybrid CLT in the major direction was 874MPa, 5.2% higher than that of generic CLT (831MPa). In the meantime, MOE of hybrid CLT in the minor direction was 285MPa, 10.7% lower than that of generic CLT in the minor direction (319MPa).

  Hybrid CLT had a similar MOR with generic CLT in the major direction (38.59MPa for hybrid CLT and 40.72MPa for generic CLT) and 43.4% lower in the minor direction (8.85MPa for hybrid CLT and 15.63MPa for generic CLT).

- In terms of the maximum shear strength, there was not a significant difference between the SPF wood used and OSB (4.10 MPa for wood and 3.83 MPa for OSB).

- In the rolling shear test, lumber had 14.5% higher rolling shear strength (1.31MPa) than OSB (1.12MPa).

- In the block shear test, the result found that the internal bonding strength of OSB was 1.64 kPa, lower than lumber-to-lumber and lumber-to-OSB bonding strength. Furthermore, 83% specimens in long-span bending test in the major direction, 100% specimens in short-span bending test in the major direction and 100% specimens in rolling shear test failed due to shear failure inside of the OSB. This indicated the low internal bonding strength of OSB may be the main reason of hybrid CLT failure. The further labs could focus on this to improve the properties of hybrid CLT with OSB.

Based on the findings from this thesis project, the following recommendations would be made:

- Since only the downsized CLTs were tested and analyzed in this project, the full-size specimens may have some differences. Thus, the full-size specimens are suggested to be made and tested.

- There were only 6 specimens tested in this project. The results showed the hybrid

CLT specimens had a higher standard deviation than generic one. Thus, increasing the number of specimens will generate more convincing results.

References

APA. 2020. APA Publication Search - APA – The Engineered Wood Association. [online] Available at: <https://www.apawood.org/publication-search?q=W410&tid=1> [Accessed 28 April 2020].

APA. 2019. PRG 320: Standard for performance rated cross laminated timber - APA – The Engineered Wood Association. [online] Available at: <https://www.apawood.org/ansi-apa-prg-320> [Accessed 28 April 2020].

ASTM International. 2013. Standard test method for strength properties of adhesive bonds in shear by compression loading. Designation: D905-08, American Society of Testing and Materials, ASTM International, West Conshohocken, PA, USA.

ASTM International. 2015. Standard test methods of static testing of lumber in structural sizes, Designation: D198-15, American Society of Testing and Materials, ASTM International, West Conshohocken, PA, USA.

ASTM International. 2020. Standard practice for estimating the percentage of wood failure in adhesive bonded joints. Designation: D5266 − 13 (Reapproved 2020), American Society of Testing and Materials, ASTM International, West Conshohocken, PA, USA.

Block, I., 2019. Mjøstårnet in Norway becomes world's tallest timber tower. [online] Dezeen. Available at: <https://www.dezeen.com/2019/03/19/mjostarne-worlds-tallest-timber-tower-voll-arkitekter-norway/> [Accessed 2 May 2020].

Brandner, R. (2014). Production and technology of cross laminated timber (CLT): A state-of-the-art Report. Focus Solid Timber Solutions - European Conference on Cross Laminated Timber (CLT), May 2013, 3–36.

Brandner, R., Flatscher, G., Ringhofer, A., Schickhofer, G., & Thiel, A. (2016). Cross laminated timber (CLT): overview and development. European Journal of Wood and Wood Products, 74(3), 331–351. https://doi.org/10.1007/s00107-015-0999-5

BSI. 2018. Timber structures – Cross laminated timber – requirements, Designation: prEN 16351, British Standards Institution, BSI, Gunnersbury, West London, UK.

Byeon, J. W., Kim, T. H., Yang, J. K., Byeon, H. S., & Park, H. M. (2018). Static bending performances of cross-laminated wood panels made with tropical and temperate woods. Journal of the Korean Wood Science and Technology,

46(6), 726–734. https://doi.org/10.5658/WOOD.2018.46.6.726

Canadian Standards Association. 2019. Engineering design in wood. CSA O86:19, Canadian Standards Association, Toronto, ON, Canada.

Chapman, K. M. (2006). Wood-based panels: particleboard, fiberboards and oriented strand board. Primary Wood Processing: Principles and Practice, 9781402043932, 427–475. https://doi.org/10.1007/1-4020-4393-7_12

Choi, C., Kojima, E., Kim, K. J., Yamasaki, M., Sasaki, Y., & Kang, S. G. (2018). Analysis of mechanical properties of cross-laminated timber (CLT) with plywood using Korean Larch. BioResources, 13(2), 2715–2726. https://doi.org/10.15376/biores.13.2.2715-2726

Davids, W. G., Willey, N., Lopez-Anido, R., Shaler, S., Gardner, D., Edgar, R., & Tajvidi, M. (2017). Structural performance of hybrid SPFs-LSL cross-laminated timber panels. Construction and Building Materials, 149, 156–163. https://doi.org/10.1016/j.conbuildmat.2017.05.131

Deutsches Patentund Markenamt. (1965). "Dokument US000003164511A" (PDF). DEPATISnet. [online] Available at: < https://depatisnet.dpma.de/DepatisNet/depatisnet?window=1&space=menu&content=treffer&action=pdf&docid=US000003164511A> [Accessed 28 April 2020].

Ehrhart, T., Brandner, R., Schickhofer, G., & Frangi, A. (2015). Rolling shear properties of some European timber species with focus on cross laminated timber (CLT): Test configuration and parameter study; Paper 48-6-1. 2nd Meeting of the International Network on Timber Engineering Research - Meeting Forty-Eight.

Forest Products Laboratory - USDA. (2010). Wood Handbook: wood as an engineering material. USDA - General Technical Report, General Te, 508. https://doi.org/General Technical Report FPL-GTR-190

Gagnon, S. and Pirvu, C. (2019). CLT handbook. FPInnovations, Montreal, QC, Canada. 812 p.

Gong, M. (2015). Planar shear properties of hardwood cross layer in hybrid cross laminated timber. In: Proceeding of 5th International Scientific Conference on Hardwood Processing 2015, Quebec, QC, Canada. pp.85-90.

Gong, M. (2019). Lumber-based mass timber products in construction. In: IntechOpen Limited, 10 Lower Thames Street, London, UK.

Gong, M. (2019, 10). Material for civil engineering - engineered wood products. University of New Brunswick, Fredericton, NB, Canada. Retrieved from T05 Engineered Wood Products.

Li, H., Wang, L., Wei, P., Wang, J., Wei, Y. (2019). Development status of cross-laminated timber and bamboo-wood composite cross-laminated timber in China. In: Journal of Northwest Forestry University 34(5): 240-246.

Ma, ZY. (2018). Effect of surface treatments on the bond quality of laminated OSB products, Master's Thesis Report, University of New Brunswick, Fredericton, NB, Canada.

Mohammad M, Gagnon S, Douglas BK, Podesto L. (2012). Introduction to cross laminated timber. Wood Design Focus 22(2):3-12.

Park, H. M., Fushitani, M., Sato, K., Kubo, T., & Byeon, H. S. (2006). Bending creep performances of three-ply cross-laminated woods made with five species. Journal of Wood Science, 52(3), 220–229. https://doi.org/10.1007/s10086-005-0750-7

Patloka, J., Kratochvilova, E., & Slanhof, J. (2019). The effect of oriented strand board substrate treatments on the adhesion of cement adhesives and coatings. IOP Conference Series: Earth and Environmental Science, 362(1). https://doi.org/10.1088/1755-1315/362/1/012082

Wang, Z., Fu, H., Dai, H., Na, B., Lu, X. (2014). Experimental study on mechanical properties of cross-laminated timber with different tree species. In: Journal of Central South University of Forestry & Technology.34(12),pp.141-145

Wang, Z., Fu, H., Gong, M., Luo, J., Dong, W., Wang, T., & Chui, Y. H. (2017). Planar shear and bending properties of hybrid CLT fabricated with lumber and LVL. Construction and Building Materials, 151, 172–177. https://doi.org/10.1016/j.conbuildmat.2017.04.205

Wang, Z., Gong, M., & Chui, Y. H. (2015). Mechanical properties of laminated strand lumber and hybrid cross-laminated timber. Construction and Building Materials, 101, 622–627. https://doi.org/10.1016/j.conbuildmat.2015.10.035

Wang, Z., Lu, Y., Xie, W., Gao, Z., Ding, Y., & Fu, H. (2019). Shear stress analysis and interlayer shear strength test of cross laminated timber (CLT) beam. Scientia Silvae Sinicae, 55(2), 152-158.

Appendixes

Appendix 1.1 Specific size, mass and moisture content of last 30 strips

Number	Mass (g)	Length (mm)	Width (mm)	Depth (mm)	Volume (mm^2)	MC (%)	Density (g/mm^2)
1	207.38	762	2.01	0.55	835.98	12.28	0.25
2	236.66	762	2.06	0.53	831.95	18.00	0.28
3	232.73	762	2.02	0.54	825.03	16.95	0.28
4	212.57	762	2.01	0.55	836.27	13.83	0.25
5	303.73	762	2.03	0.54	828.71	22.00	0.36
6	221.64	762	2.04	0.54	842.94	15.73	0.26
7	219.39	762	2.03	0.55	847.26	16.45	0.26
8	247.87	762	2.02	0.54	834.27	17.95	0.30
9	247.58	762	2.06	0.55	856.33	15.93	0.29
10	212.08	762	2.04	0.54	835.08	13.23	0.25
11	251.00	762	2.04	0.54	829.61	13.08	0.30
12	242.64	762	2.01	0.53	815.23	19.40	0.30
13	218.71	762	2.05	0.54	843.95	17.05	0.26
14	199.35	762	2.03	0.54	831.39	12.50	0.24
15	233.20	762	2.04	0.54	839.42	16.90	0.28
16	202.30	762	2.03	0.55	848.51	16.60	0.24
17	258.18	762	2.05	0.54	836.80	18.30	0.31
18	241.34	762	2.00	0.54	818.50	15.00	0.30
19	187.91	762	2.04	0.54	843.98	11.18	0.22
20	223.39	762	2.03	0.54	838.50	18.23	0.27
21	234.26	762	2.02	0.54	830.67	17.18	0.28
22	309.83	762	2.04	0.54	837.54	23.18	0.37
23	281.17	762	2.01	0.53	814.50	20.83	0.35
24	235.82	762	2.02	0.54	828.11	17.63	0.31
25	214.09	762	2.04	0.54	835.49	17.60	0.26
26	215.58	762	2.01	0.54	824.42	17.88	0.26
27	286.51	762	2.05	0.55	853.22	11.58	0.34
28	195.16	762	2.04	0.54	832.38	13.13	0.23
29	192.80	762	2.01	0.54	822.89	12.33	0.23
30	188.93	762	1.99	0.53	796.10	16.03	0.24

Appendix 1.2 Summary of weight of strips in 6 wood layers

Surface layers									
Panel 1		Panel 4		Panel 5		Panel 6		Panel 9	
Number	Weigh t (g)	Number	Weigh t (g)	Number	Weigh t (g)	Number	Weigh t (g)	Number	Weigh t (g)
125	200.16	6	182.55	55	246.31	84	212.55	224	197.94
178	198.55	29	215.91	105	227.63	161	218.64	19	208.86
148	211.4	106	207.21	44	209.07	61	218.02	227	207.9
157	198.64	211	210.42	66	205.87	8	270.08	199	220.88
156	202.63	129	237.51	168	210.56	145	207.34	46	211.72
97	271.55	190	209.47	43	232.66	103	244.47	54	197.92
7	266.37	16	238.51	180	198.92	14	242.6	176	198.25
231	256.45	24	284.21	104	211.31	49	188.21	50	213.06
58	205.12	80	200.11	184	205.24	150	214.43	111	260.99
133	213.24	228	245.01	86	245.92	122	201.25	52	274.36
196	228.44	164	208.67	70	211.88	17	187.05	101	198.91
140	212.54	159	258.17	67	255.85	92	214.35	94	202.63
165	265.49	177	231.68	119	206.02	15	207.68	120	202.92
1	200.16	186	219.95	3	209.01	194	210.83	238	273.42
Average	**223.62**	**Average**	**224.96**	**Average**	**219.73**	**Average**	**216.96**	**Average**	**219.27**
Sd	**28.41**	**Sd**	**26.25**	**Sd**	**18.39**	**Sd**	**22.29**	**Sd**	**28.22**
COV	**12.7%**	**COV**	**11.7%**	**COV**	**8.4%**	**COV**	**10.3%**	**COV**	**12.9%**
Surface layers						Transverse layers			
Panel 10		Panel 11		Panel 12		Panel 13		Panel 14	
Number	Weigh t (g)	Number	Weigh t (g)	Number	Weigh t (g)	Number	Weigh t (g)	Number	Weigh t (g)
143	207.5	172	213.42	83	215.09	146	188.32	108	166.4
171	225.22	69	196.92	59	190.93	189	167.81	21	197.26
57	204.15	53	210.23	89	213.17	96	213.17	167	187.24
131	239.16	88	198.25	36	234.09	179	183.57	160	187.17
117	208.28	162	240.57	64	167.57	239	177.83	234	191.4
68	254.25	124	201.71	35	214.51	72	173.88	229	163.34
65	252.16	192	204.96	112	240.7	109	189.16	37	173.17
194	210.83	75	291.73	16	203.49	170	185.54	203	183.39
147	256.15	130	244.47	32	213.47	222	189.42	226	197.97
212	233.31	98	274.29	102	238.38	214	205.49	173	189.56
202	174.84	118	268.71	45	266.31	174	184.44	217	196.64
213	192.46	144	208.71	142	228.48	126	193.74	31	197.45
40	268.24	87	277.45	122	201.25	181	186.69	128	165.67
33	243.2	18	247.26	12	201.53	34	191.75	235	211.3
Average	**226.41**	**Average**	**234.19**	**Average**	**216.36**	**Average**	**187.92**	**Average**	**186.28**
Sd	**27.46**	**Sd**	**33.45**	**Sd**	**24.33**	**Sd**	**11.57**	**Sd**	**14.36**
COV	**12.1%**	**COV**	**14.3%**	**COV**	**11.2%**	**COV**	**6.2%**	**COV**	**7.7%**

Appendix 1.3 Summary of long-span bending test results

Long-span bending test in the major direction				Long-span bending test in the minor direction			
Specimen	MOE (MPa)	MOR (MPa)	Failure mode	Specimen	MOE (MPa)	MOR (MPa)	Failure mode
W1BA1	8270	19.32	rolling shear+ bonding line delamination failure	W2BO1	823	11.65	tension failure
W1BA2	9254	48.84	rolling shear+ bonding line delamination failure	W2BO2	733	8.49	tension failure
W1BA3	8934	46.42	rolling shear+ bonding line delamination failure	W2BO3	785	10.62	tension failure
W1BA4	10099	46.34	rolling shear+ bonding line delamination failure	W2BO4	771	10.03	tension failure
W1BA5	10539	45.52	rolling shear failure	W2BO5	860	8.29	tension failure
W1BA6	9111	46.1	rolling shear+ bonding line delamination failure	W2BO6	754	7.81	tension failure
Average	**9587**	**46.64**		**Average**	**773**	**9.72**	
Sd	**694.94**	**1.28**		**Sd**	**33.8**	**1.56**	
COV	**7.2%**	**2.7%**		**COV**	**4.4%**	**16.0%**	
O2BA1	9627	26.93	shear failure	O1BO1	592	5.72	tension failure
O2BA2	10589	29.49	shear failure	O1BO2	566	6.01	tension failure
O2BA3	9008	21.39	shear failure	O1BO3	540	6.48	tension failure
O2BA4	10478	25.45	shear failure	O1BO4	639	6.57	tension failure
O2BA5	8140	29.22	shear failure	O1BO5	604	4.33	tension failure
O2BA6	9846	28.6	shear failure	O1BO6	696	7.09	tension failure
Average	**9615**	**26.85**		**Average**	**606**	**6.03**	
Sd	**926.56**	**3.08**		**Sd**	**55.5**	**0.96**	
COV	**9.6%**	**11.5%**		**COV**	**9.2%**	**15.9%**	

Note: W1BA1 is weak due to position (edge),W2BO5 has LVDT problem during load applying. These two specimens were not taken into analysis.

Appendix 1.4 Summary of the long-span bending test average results

In the major direction								
	MOE				MOR			
	Count	Average (MPa)	Sd (MPa)	COV	Count	Average (MPa)	Sd (MPa)	COV
Generic CLT	6	9587	694.94	7.2%	6	46.64	1.28	2.7%
Hybrid CLT	6	9615	926.56	9.6%	6	26.85	3.08	11.5%
In the minor direction								
	MOE				MOR			
	Count	Average (MPa)	Sd (MPa)	COV	Count	Average (MPa)	Sd (MPa)	COV
Generic CLT	6	773	33.8	4.4%	6	9.72	1.56	16.0%
Hybrid CLT	6	606	55.5	9.2%	6	6.03	0.96	15.9%

Appendix 1.5 Summary of the short-span bending test results

Short-span bending test in the major direction				Short-span bending test in the minor direction			
Specimen	MOE (MPa)	MOR (MPa)	Failure mode	Specimen	MOE (MPa)	MOR (MPa)	Failure mode
W2SA1	922	40.84	tension+ rolling shear failure	W1SO1	298	16.05	tension+ bonding line delamination failure
W2SA2	775	43.82	tension+ rolling shear failure	W1SO2	343	14.02	tension failure
W2SA3	755	40.19	tension+ rolling shear failure	W1SO3	304	13.93	tension+ bonding line delamination failure
W2SA4	999	45.14	tension+ rolling shear failure	W1SO4	359	18.01	tension+ bonding line delamination failure
W2SA5	787	37.44	tension+ rolling shear failure	W1SO5	329	15.75	tension+ bonding line delamination failure
W2SA6	748	36.87	tension+ rolling shear failure	W1SO6	282	16.03	tension+ bonding line delamination failure
Average	**831**	**40.72**		**Average**	**319.3**	**15.63**	
Sd	**104.34**	**3.31**		**Sd**	**29.48**	**1.52**	
COV	**12.6%**	**8.1%**		**COV**	**9.2%**	**9.7%**	
O1SA1	871	37.21	shear failure	O2SO1	299	10.32	tension failure
O1SA2	907	42.24	shear failure	O2SO2	293	9.17	tension+ bonding line delamination failure
O1SA3	853	37.06	shear failure	O2SO3	281	8.58	tension+ bonding line delamination failure
O1SA4	939	43.29	shear failure	O2SO4	303	9.36	tension+ bonding line delamination failure
O1SA5	869	38.45	shear failure	O2SO5	267	8.56	tension+ bonding line delamination failure
O1SA6	806	33.29	bonding line delamination failure	O2SO6	268	7.08	tension+ bonding line delamination failure
Average	**874**	**38.59**		**Average**	**285**	**8.85**	
Sd	**45.69**	**3.68**		**Sd**	**15.67**	**1.08**	
COV	**5.2%**	**9.5%**		**COV**	**5.5%**	**12.2%**	

Appendix 1.6 Summary of the short-span bending test average results

In the major direction								
	MOE				MOR			
	Count	Average (MPa)	Sd (MPa)	COV	Count	Average (MPa)	Sd (MPa)	COV
Generic CLT	6	831	104.34	12.6%	6	40.72	3.31	8.1%
Hybrid CLT	6	874	45.69	5.2%	6	38.59	3.68	9.5%
In the minor direction								
	MOE				MOR			
	Count	Average (MPa)	Sd (MPa)	COV	Count	Average (MPa)	Sd (MPa)	COV
Generic CLT	6	319	29.48	9.2%	6	15.63	1.52	9.7%
Hybrid CLT	6	285	15.67	5.5%	6	8.85	1.08	12.2%

Appendix1.7 Summary of failure moods of specimens in flexural tests

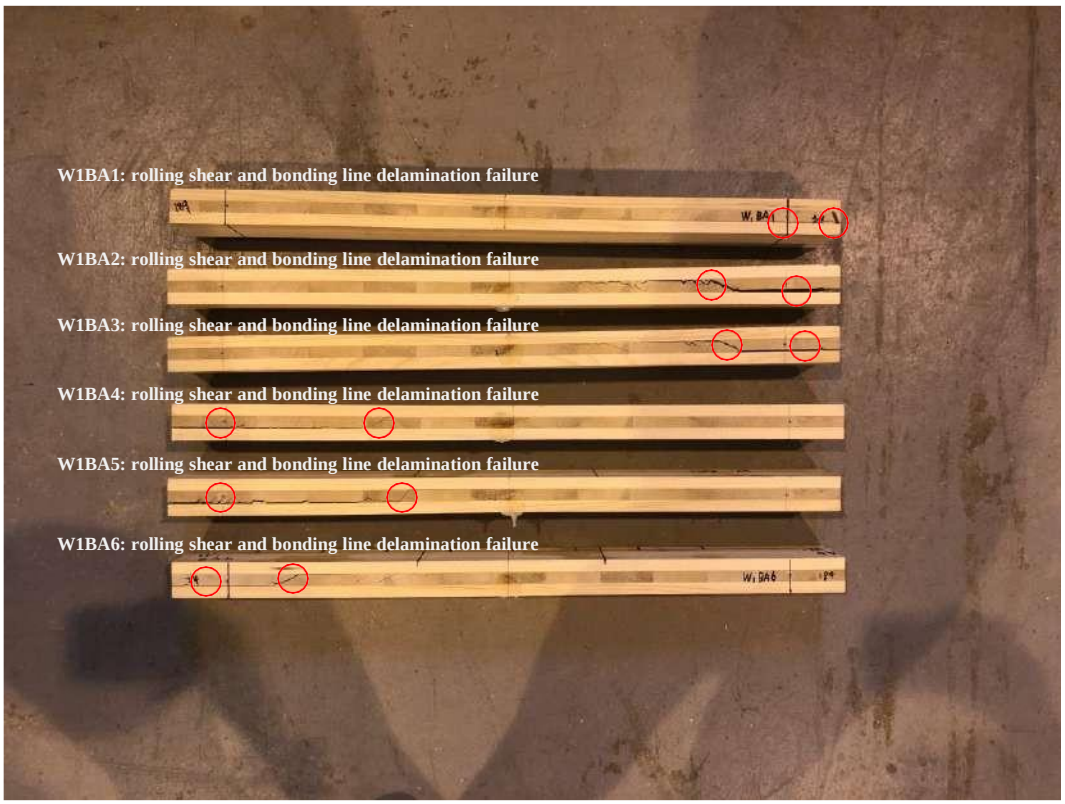

Fig. A1 Failure modes of generic CLT specimens in the major direction tested under the long-span bending

Fig. A2 Failure modes of hybrid CLT specimens in the major direction tested under the long-span bending

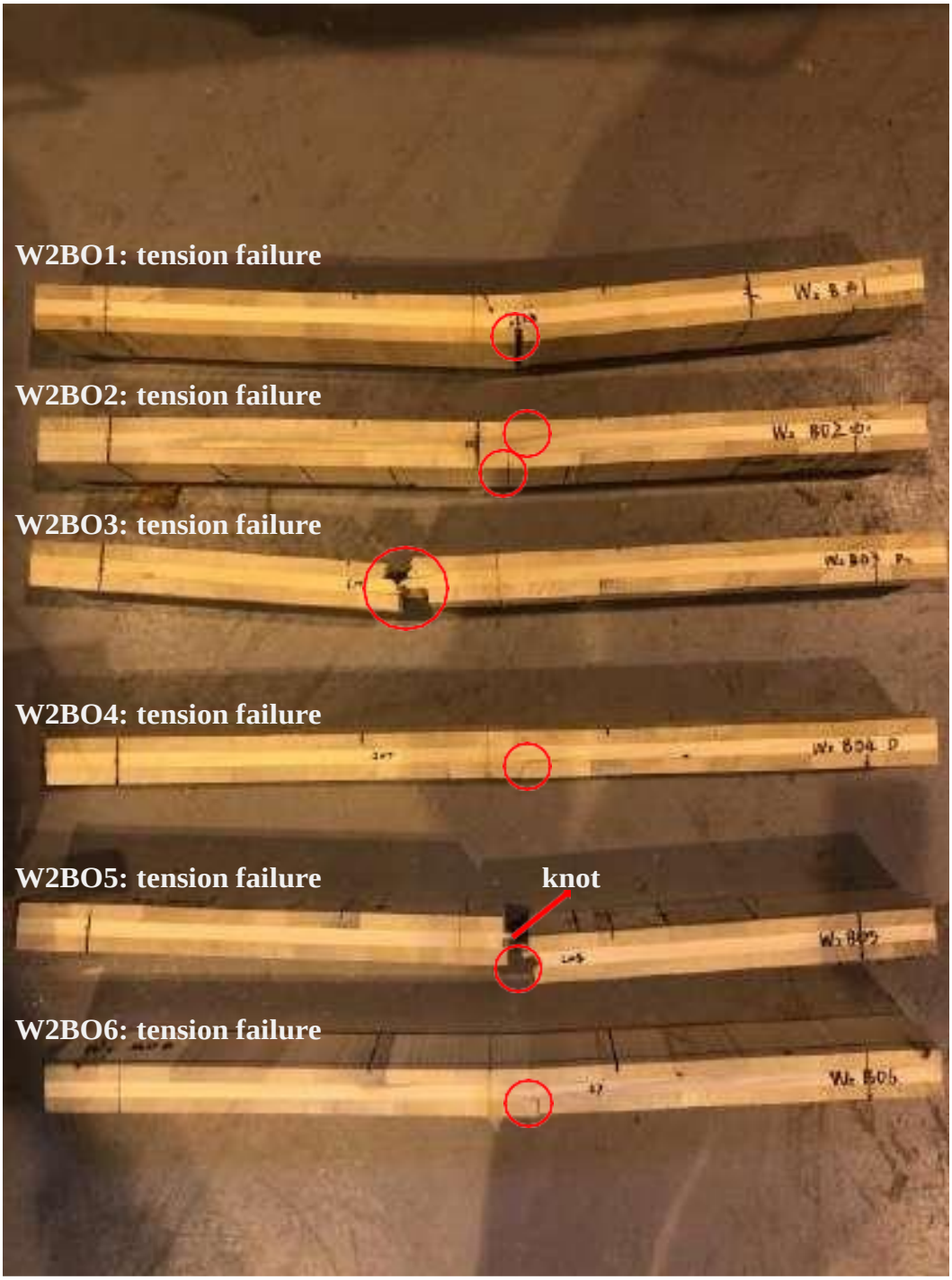

Fig. A3 Failure modes of generic CLT specimens in the minor direction tested under the long-span bending

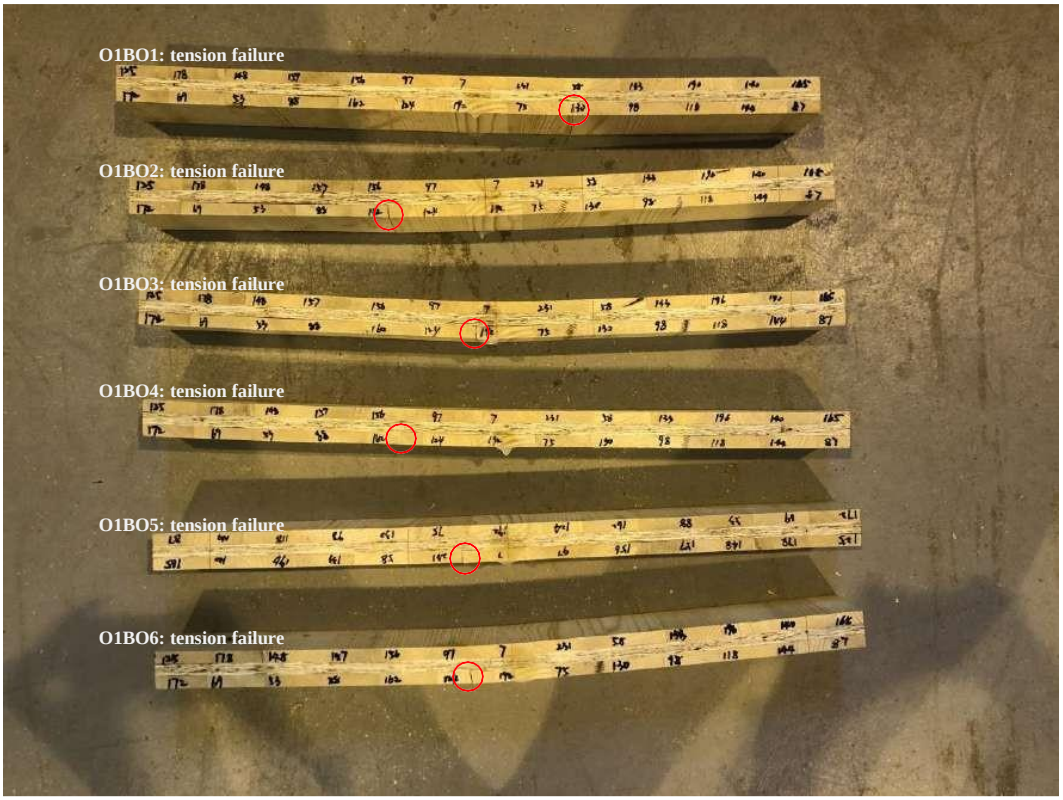

Fig. A4 Failure modes of hybrid CLT specimens in the minor direction tested under the long-span bending

Fig. A5 Failure modes of generic (left) and hybrid (right) CLT specimens in the major direction tested under the short-span bending

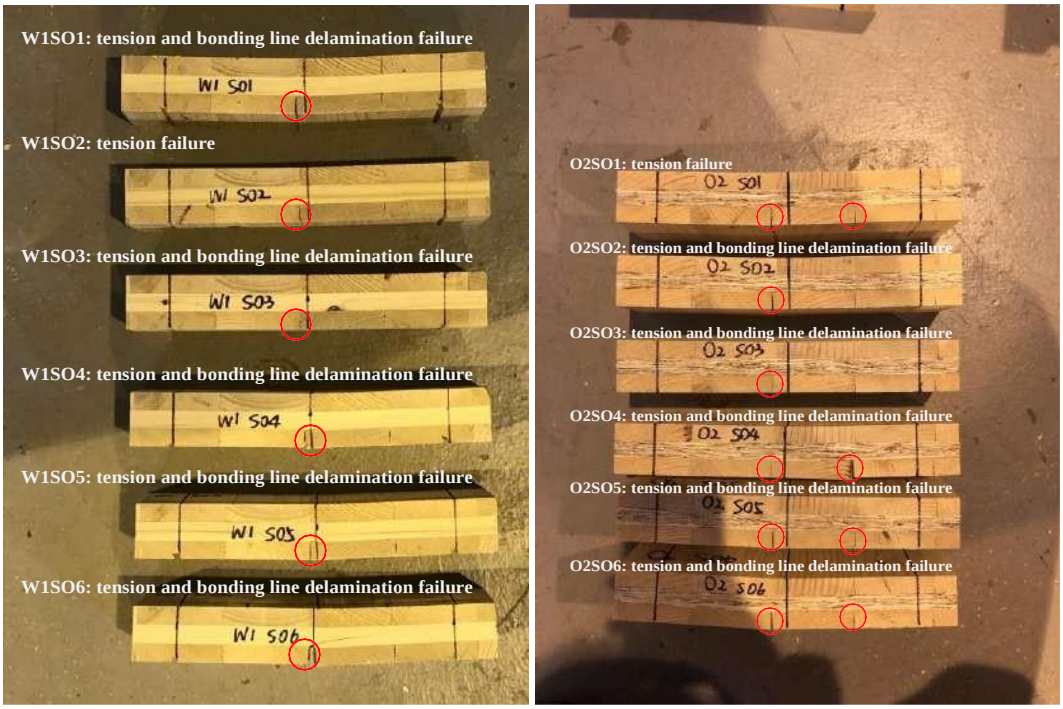

Fig. A6 Failure modes of generic (left) and hybrid (right) CLT specimens in the minor direction tested under the short-span bending

Appendix 1.8 Summary of maximum shear strength results

Specimen code	τ_{max}	Specimen code	τ_{max}
W2SA1	4.09	W1SO1	1.60
W2SA2	4.39	W1SO2	1.39
W2SA3	4.04	W1SO3	1.38
W2SA4	4.53	W1SO4	1.79
W2SA5	3.79	W1SO5	1.57
W2SA6	3.72	W1SO6	1.60
Average (MPa)	**4.10**	**Average (MPa)**	**1.56**
Sd (MPa)	**0.29**	**Sd (MPa)**	**0.14**
COV	**7.20%**	**COV**	**8.96%**
O1SA1	3.69	O2SO1	1.02
O1SA2	4.18	O1SA2	0.90
O1SA3	3.69	O1SA3	0.84
O1SA4	4.33	O1SA4	0.92
O1SA5	3.83	O1SA5	0.84
O1SA6	3.29	O1SA6	0.69
Average (MPa)	**3.83**	**Average (MPa)**	**0.87**
Sd (MPa)	**0.34**	**Sd (MPa)**	**0.10**
COV	**8.91%**	**COV**	**11.49%**

Appendix 1.9 Summary of rolling shear bending test results

Specimen	Pmax (N)	Rolling shear strength (MPa)	Specimen	Pmax (N)	Rolling shear strength (MPa)
W2RA1	5466	1.36	O1RA1	4774	1.19
W2RA2	6201	1.57	O1RA2	5132	1.27
W2RA3	5019	1.24	O1RA3	4021	0.99
W2RA4	3317	0.82	O1RA4	5456	1.35
W2RA5	3909	0.98	O1RA5	3817	0.94
W2RA6	7744	1.9	O1RA6	4006	0.99
Average	**5276**	**1.31**	**Average**	**4534**	**1.12**
Sd	**1597**	**0.39**	**Sd**	**681**	**0.17**
COV	**30.3%**	**29.8%**	**COV**	**15.0%**	**15.2%**
W1RO1	2076	0.51	O2RO1	1885	0.47
W1RO2	2560	0.64	O2RO2	1667	0.41
W1RO3	1968	0.48	O2RO3	2337	0.57
W1RO4	2267	0.56	O2RO4	2452	0.62
W1RO5	2681	0.66	O2RO5	1581	0.39
W1RO6	2201	0.54	O2RO6	2136	0.52
Average	**2292**	**0.57**	**Average**	**2010**	**0.5**
Sd	**277**	**0.07**	**Sd**	**357**	**0.09**
COV	**12.1%**	**12.3%**	**COV**	**17.8%**	**18.0%**

Appendix 2.0 Summary of block shear bending test results

Perpendicular rough (kPa)		Parallel rough (kPa)		Perpendicular smooth (kPa)		Parallel smooth (kPa)		Internal (kPa)	
O111	1.68	O114	3.53	O113	0.95	O112	3.09	O121	1.34
O212	1.47	O211	2.36	O115	1.07	O213	1.78	O122	1.26
O221	1.02	O215	3.7	O214	1.67	O222	2.04	O123	1.7
O223	1.84	O224	3.15	O225	1.16	O231		O124	1.57
O234	1.39	O233	2.65	O232		O235	2.35	O125	2.31
Average	**1.48**	**Average**	**3.08**	**Average**	**1.21**	**Average**	**2.31**	**Average**	**1.64**
Sd	**0.31**	**Sd**	**0.57**	**Sd**	**0.32**	**Sd**	**0.57**	**Sd**	**0.42**
COV	**20.9 %**	**COV**	**18.5 %**	**COV**	**26.4 %**	**COV**	**24.7 %**	**COV**	**25.6 %**
W1A (kPa)		W1B (kPa)		W2A (kPa)		W2B (kPa)			
1	2.38	1	4.08	1	2.26	1	2.51		
2	3.4	2	4.21	2	2.25	2	2.56		
3	1.73	3	3.01	3	1.76	3	2.23		
4	3.35	4	2.77	4	2.48	4	2.13		
5	3.03	5	2.9	5	1.69	5	2.19		
Average	**2.78**	**Average**	**3.39**	**Average**	**2.09**	**Average**	**2.32**		
Sd	**0.71**	**Sd**	**0.69**	**Sd**	**0.34**	**Sd**	**0.2**		
COV	**25.5 %**	**COV**	**20.4 %**	**COV**	**16.3 %**	**COV**	**8.6%**		

Appendix 2.1 Interlaminar shear strength measured by the short-span bending tests

Also, since CLT is laminated by the materials with different MOE, its shear strength is not in a linear relationship, which shows an abrupt change across a bonding line. So, in this project, the laminated shear strength diagrams were made in the short-span bending test to evaluate the shear resistance properties of each specimens**.** Wang et al. (2019) calculated the interlaminar shear strength of 3-layer CLT using Formula (1).

$$\begin{cases} \sigma_{xy} = \frac{My}{I(\frac{26}{27}+\frac{E_2}{27E_1})}, \ \frac{h}{6} \le |y| \le \frac{h}{2} \\ \sigma_{xy} = \frac{My}{I(\frac{26}{27}+\frac{E_2}{27E_1})} * \frac{E_2}{E_1}, \ 0 \le |y| \le \frac{h}{6} \end{cases} \quad (1)$$

Where,

$\boldsymbol{\sigma_{xy}}$ represents the interlaminar shear,

$\boldsymbol{E_1}$ represents MOE of surface layer,

$\boldsymbol{E_2}$ represents MOE of transverse layer,

M represents the moment at the center of the specimen, according to structural analysis it equals to $\boldsymbol{\frac{1}{4}P_{max} * L}$,

I represents the moment of inertia, for rectangular area $\boldsymbol{I = \frac{1}{12}bh^3}$,

H represents the height of the specimen,

B represents the width of the specimen.

The mean MOE of OSB panels used in this project was previously measured by UNB Wood Science Technology Centre, which were 5,087MPa and 3,490MPa in the major

and minor directions. The species of lumber used in this project was black spruce (*Picea mariana*). According to the Wood Handbook (Forest Products Laboratory, 2010), the MOE was 9500 MPa in the major direction (longitudinal $\boldsymbol{E_L}$). $\boldsymbol{E_T}$ could be estimated by the equation $\boldsymbol{E_L}$:$\boldsymbol{E_T}$=20:1 (Forest Products Laboratory, 2010). Thus, the MOE in the minor direction (tangential $\boldsymbol{E_T}$) was 475 MPa.

As shown in Fig. A7, for specimens in the major direction, the curves increased dramatically when $y = \frac{1}{3}h$ while the specimens in the minor direction had the contract tendency: the curves decreased noticeably when $y = \frac{1}{3}h$. This shows that the material with higher mechanical properties would bear more shear stress in CLT. The generic CLT in the major direction had the highest central shear stress, followed by hybrid CLT in the major direction, generic CLT in the minor direction and hybrid CLT in the minor direction.

It was also worth to mention that the curve of generic CLT in the minor direction had the most sudden change, the highest point was more than 10 times higher than the highest point within its transverse area ($\frac{1}{3}h \leq y \leq \frac{2}{3}h$). The reason was that longitudinal MOE is 20 times higher than tangential MOE, making CLT panels very unstable in the minor direction, especially in the transverse layer.

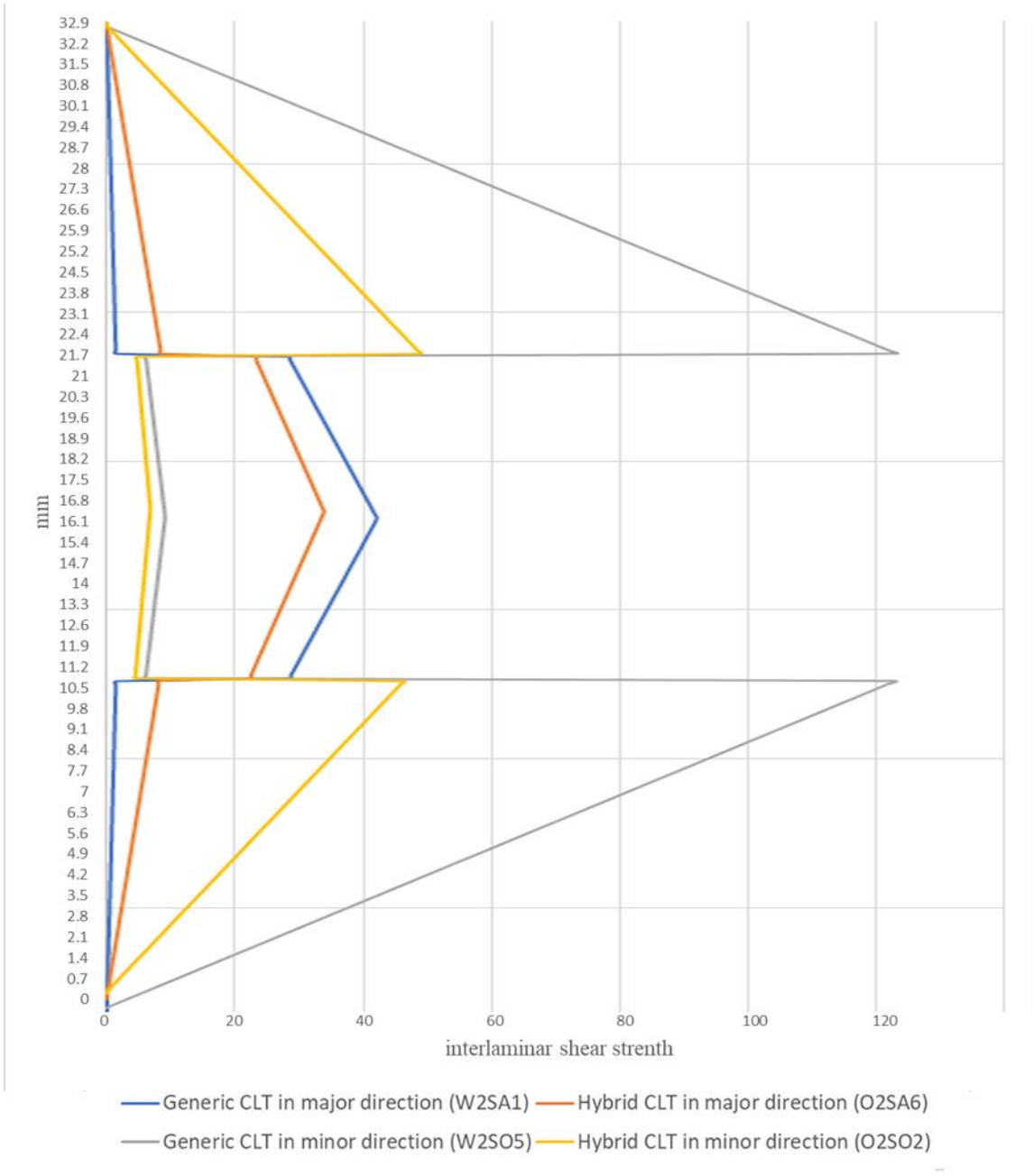

Fig. A7 Interlaminar shear strength curves of short-span bending test specimens

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1) Zhuo C, Gong M. 2020. Timber buildings and healthy living environment. International Wood Industry, 50(03): 8-13 (in Chinese).

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