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FURTHER DEVELOPMENT OF CROSS-LAMINATED TIMBER (CLT) – MECHANICAL TESTS ON 45° ALTERNATING LAYERS

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ABSTRACT: In this paper, a series of experimental bending and compression tests were performed on cross-laminated timber (CLT) products with ±45° alternating layers, to evaluate their performance against conventional panels of 90° orientation. Engineered wood products, such as CLT with ±45° alternating layers can provide opportunities for greater use in larger and more sustainable timber constructions. A total of 40 panels, manufactured in an industrial CLT production line with either of these two configurations, were tested and compared. Panels were evaluated in bending tests n=20 and the remaining ones in compression tests. Results showed that 35% increased the strength in the four-point bending tests for panels containing ±45° alternating layers compared with the 90° alternating layers. Compression strength was increased by 15%. Stiffness increased by 15% in the four-point bending and 30% in the compression. The results indicate that CLT containing ±45° alternating layers has increased strength and stiffness compared to 90° alternating layers. These findings suggest that further developments in CLT are feasible in advanced building applications.

KEYWORDS: Crosslam, X-lam, Panel configuration, CLT assembling, CLT manufacturing, Mass timber engineering, Experimental study, Destructive testing, Influence of orientation

1 INTRODUCTION

“Sustainable development seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future” [1]. The main idea of sustainable development for society is not to use more than can be replaced [2]. In Europe, nearly 40% of the total use of energy and materials, 40% of the waste and 40% of greenhouse gas emissions, originate from the building sector. Thus, the construction industry has a considerable impact on sustainable development [3].
Currently, the development of timber engineering demands a more flexible practice of wooden building materials and a renewed sense of sustainability. Engineered wood materials can include glued-laminated timber (Glulam), laminated veneer lumber (LVL), structural composite lumber (SCL) and, finally cross-laminated timber (CLT), which is increasingly used in wood construction worldwide [4].
When considered in conjunction with environmental concerns, the significance of wood-based constructions is even more positive compared to concrete and steel, which in turn will promote further advancements towards sustainable building solutions [5].
CLT is a widely used and established engineered wood panel, based on at least three solid timber board layers in orthogonal and adhesively bonded assemblies. This technology was first used and developed in the early ‘90s in Central Europe [6]. CLT is generally composed of several layers of an odd total number, keeping the wood fibers of each layer transverse to the adjacent layers, as shown in Figure 1. Higher dimensional stability and load-bearing capacity are two key advantages of CLT compared to regular construction timber [7].

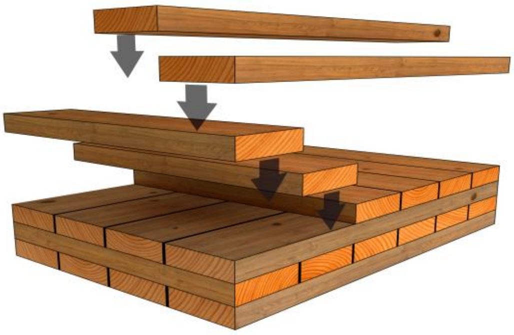

Figure 1: *Conventional assembly layup of cross-laminated timber (CLT 90°)*

Its in-and-out plane endurance, unlike traditional light-frame constructions, makes it progressively acknowledged as an appropriate construction material

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[8]. One of the critical issues in traditional wood-frame buildings is the floor span in regards to structural design performance. Even the performance of walls can be crucial, especially in high-rise buildings due to the additional vertical and lateral forces applied from wind loads. The growing interest in wood-based constructions and their comparatively low environmental footprint make this material an appealing option, but conventional wood construction methods are being challenged, especially in cases where larger and high-rise timber buildings are needed [5, 7].

Recent architectural and engineering research has indicated that in high-rise building construction; wood could be a suitable material if it is appropriately engineered. Suggested solutions include buildings made of nearly 80% timber by volume for constructions of 40-floors or more, where the primary structural material could be a glulam reinforced CLT combined with concrete and steel. However, building these larger timber structures introduces challenges, such as the management of greater spans and intersections which demand an increased material per unit area factor compared with traditional methods. Furthermore, floors in this type of high-rise buildings, equal nearly 70% of the total used materials. Thus, it is significant to enhance the physical properties of these engineered wood products to guarantee the availability of sustainable and competitive, low-carbon-emitting materials suitable for the affordable building needs of the future [5]. CLT products fit this function; however, cost represents a major obstacle for further penetration of this product into wood-based high-rise buildings. The question to explore is whether there is another more suitable way to align the boards in CLT to achieve the required mechanical properties while using less wood.

The standard procedure of CLT construction includes a 0° / 90° laminate; which means that the board layers are interchangeably configured in a longitudinal and transverse order [7]. However, there is a potential for trying to distribute the forces more, along the fibers, taking advantage of the anisotropic properties of wood. In this study, the boards were aligned at 90° or ±45° in transverse layers. This alignment has not been evaluated on industrially manufactured CLT products; however; there is an established non-glued product using a ±45° orientation, developed by Thoma Holz100, which uses dowels to assemble the boards [9]. Gluing the boards instead of using dowels can offer improved mechanical properties (Figure 2).

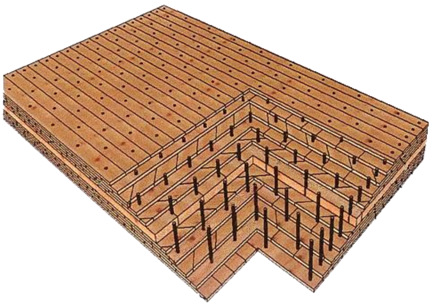

Figure 2: *Thoma Holz100 uses wooden dowels to assemble boards in orientations of ±45° [9]*

In the present study, the main objective is to compare CLT panels containing board grain directions aligned by alternating 90° and ±45°. The purpose is to determine the potential load-bearing layer capacity impact within the panel's main load-bearing direction. The intention is to distribute the load in the strongest wood direction by placing alternating boards at ±45°, so as to reduce the transversal load and minimizing the risk of rolling shear (Figure 3). In structural CLT applications, shear can be crucial [10].

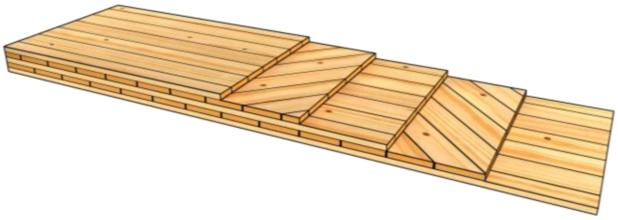

Figure 3: *Alternating transverse layers of a CLT panel layup in a ±45° configuration*

This study examines how the CLT panel configuration can improve its bending and compression properties. Destructive bending and compression tests were conducted in the main load-carrying direction in a flatwise panel layup, where each transverse layer was configured at 90° and compared with the ±45° configuration.

The main purpose of this work is to examine further the potential of CLT as it has been proposed for sustainable, high-endurance wood building construction. This was achieved by investigating the load-bearing capacity of CLT, regarding distribution and alignment of board enhancements in the main load direction, taking advantage of the material properties. Evaluation and comparison results were performed by examining the bending and compression properties of 90° and ±45° alternating transverse CLT layers.

The assumed advantages of using these CLT ±45° products are: (1) increased load-direction mechanical performance proposing it as load-bearing construction panel element, suitable in respect to in-plane shear; (2) more efficient use of wood material properties; and (3) making CLT panels a suitable material in specific demanding construction enterprises.

2 MATERIALS AND METHODS

2.1 MATERIALS

To produce traversable CLT panels consisting of layers alternating at 90° and ±45°, the European Norway Spruce (*Picea abies*) was chosen. An industrial CLT production line was used to manufacture the panels based on a custom process and manufacturing procedure in a factory located at Martinsons in Bygdsiljum, Sweden, as depicted in Figure 4. A Dynagrade was used to grade the machine strength of the boards, by measuring the physical impact resonant frequency mode, according to a standard methodology described in Dynalyze AB patent [11]. The structural timber strength and the quality class were LS15 and Q61, respectively, according to CEN/EN 14081 (2011) [12] and in compliance with C24-grade CEN/EN 338 (2009) [13]. Moisture content was 8% on average, as measured by the oven dry method conforming to CEN/EN 13183 (2003) [14]. The determined average density was 462 kg/m^3 conforming to ISO 3131 (1975) [15]. Edgewise and flatwise board pre-processing through a jointer were performed, and the dimension of each single board was 19 mm and 94 mm in thickness and width, respectively. No finger joints were contained in the boards. Since it was possible to adjust the production line saw to cut single full-length boards at 45° for the transverse layers, the amount of material used for the two different types of CLT corresponded approximately to each other and minimized the sawing waste.

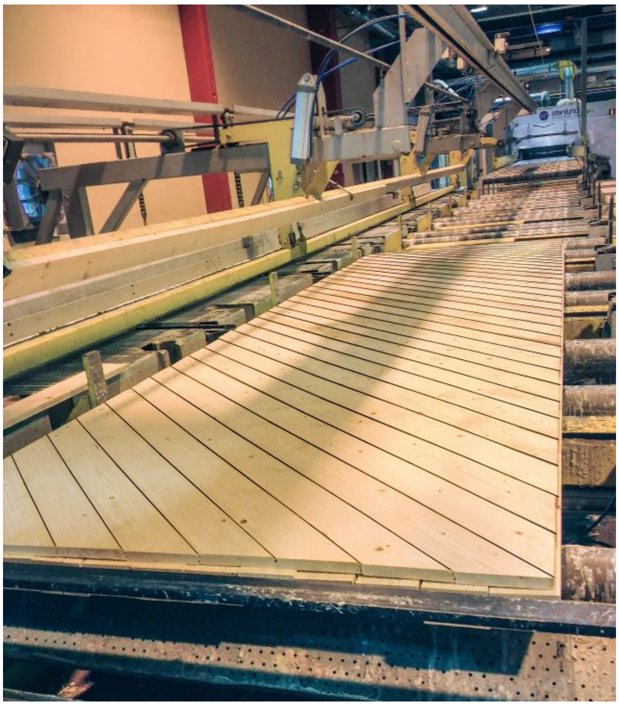

Figure 4: Industrial production line used for manufacturing conventional CLT 90° and modified CLT ±45° panels

An adhesive melamine-urea-formaldehyde (MUF) Cascomin 1247 alongside 2526 hardener, from Casco Adhesives AB (Netherlands), was used to glue the boards. The selected glue corresponds to glue type 1 according to CEN/EN 301 (2012) [16]. From the same vendor, an industrial separate ribbon spreader 6230, was used to apply glue on all the flat surfaces of the boards during fabrication, without edge bonding. The ratio of the used adhesive hardener was set to 29.2% and a total of 320 g/m² glue was applied.

To press the boards into panels, a single step procedure of applying pressure in both directions transversely to the CLT occurred with the use of a high-frequency press SM 6013 HFS made by Stenlund Maskiner AB. The duration of this production stage was 290 s and the production temperature of the panels reached 78 °C.

The manufactured CLT panel dimensions were 95 mm in thickness, 1200 mm in width and 4136 mm in length, after curing. A total of six panels were manufactured, consisting of alternating 90° and ±45° transverse layers: three panels with alternating layers arranged transversely at 90° (0°, 90°, 0°, 90°, 0°) and another three panels with alternating layers arranged at ±45° (0°, 45°, 0°, −45°, 0°). The produced CLT panels were fabricated with every second panel being a modified CLT with alternating ±45° layers, following a regular CLT, and so forth. For improving panel comparability, the production was performed in an overlapping and simultaneous fashion resulting in equally matched materials and environmental conditions. The industry manufacturer confirmed all the followed production line procedures and all carefully chosen manufacturing parameters were within the CLT standard ranges.

CLT panels were sawn using computer numerical control (CNC) in systematic sampling in two groups for a total of 40 samples. Each group included ten samples consisting of 90° configurations and ten samples of ±45°. One group was tested in destructive four-point bending and the other group for compression testing.

The sample dimension measurement fulfills the requirement of CEN/EN 325 (2012) [17]. The average final dimensions of the samples ready for the four-point bending test were 95 mm in thickness, 590 mm in width and 2000 mm in length. The average dimensions for the compression samples were 95 mm in thickness, 180 mm in width and 570 mm in length.

2.2 METHODS

The tests for evaluating the bending and compression properties of the samples followed the European standard CEN/EN 408 (2012) [18] which is certified for determining the stiffness and strength properties of CLT based on the CEN/EN 16351 standard (2015) [19]. All tests were performed at SP Technical Research Institute of Sweden in Skellefteå as shown in Figures 5 and 6.

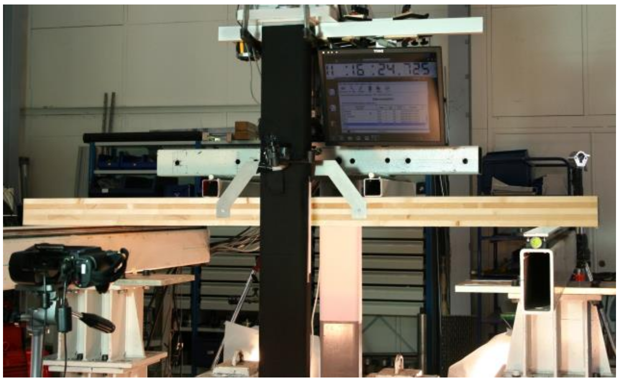

Figure 5: Experimental four-point bending test of CLT panels with an alternating layer configuration

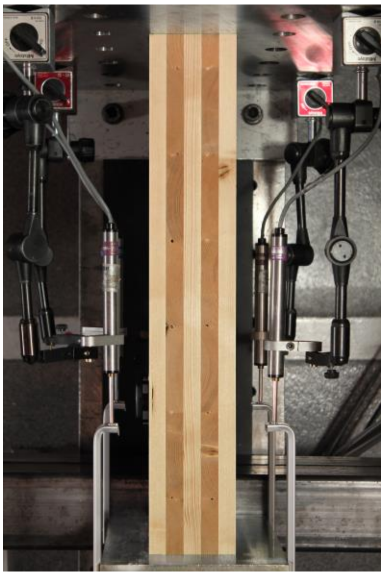

Figure 6: Experimental compression test of CLT panels

An accredited laboratory was used for all testing, having followed the SP standard operating procedures for calibrating all measuring devices and equipment. During testing, measurements were recorded at a frequency of 100 Hz. For local displacement bending measurement, the acceptance accuracy was ± 0.02 mm for the two 25-mm-long linear displacement micro-measurement sensors. In global displacement bending and compression measurement, the 50-mm-long displacement sensors had an accuracy of ± 0.04 mm. Global bending displacement was measured with two sensors placed on either side of the sample center. Global compression displacement was measured with four sensors, one at each of the four corners. The load cell was at ± 0.20% maximum output.

The mechanical bending properties studied in this work were measured by applying load with corresponding global and local displacement. The bending samples were tested in their major direction in a flatwise layup configuration. The global bending span was 1710 mm, and the distance between the two inner load points was 570 mm, with support widths at 50 mm, including a 5 mm edge radius.

In compression testing, the load was applied in the center axis from the sample CLT surface. Tested samples were placed between two stiff steel plates, with one spherically seated loading-head to counteract the compressive load without bending.

The standard CEN/EN 408 (2012) [18] describes and defines the used experimental methods for determining mechanical properties in bending and compression. Determined CLT properties were the modulus of rupture (MOR), the global modulus of elasticity (MOE) in bending and compression, and the local MOE in bending.

Global bending MOE was examined by measuring the displacement around the neutral axis over the full panel span 18 × h between the two outer supports; thereby, it is possible to study the effects of shear in bending. The local displacement defined the local MOE, which was reviewed as a span length 5 × h, measured from the center of the neutral axis. In compression, the displacement measured over the full sample length was 6 × h. All presented stiffness values were established on 10% and 40% of the ultimate load. MOE and MOR calculations were based on the determined measurement values from the gross cross-section of tested samples according to CEN/EN 408 (2012) [18].

Another metric used was the 5th percentile value also identified as 5-percentile or 5%-quantile and corresponds to the lower one-sided 75% confidence level (CL). The 5th percentile declares the value of the 5% of the test values that are lower and within the suggested CL in accordance with timber structure standard CEN/EN 14358 (2006) [20].

3 RESULTS AND DISCUSSION

3.1 FOUR POINT BENDING TEST

Test results are reported on 40 CLT panels to investigate and analyze measurement uncertainty by also reporting standard deviation (SD). The number of 40 CLT panels is considered enough to prove the stability or variability of the test measurements and is similar to previous evaluation works [21].

Table 1 reviews the bending characteristics of the tested CLT samples which include performance results with respect to the four-point bending global and local modulus of elasticity (MOE) and modulus of rupture (MOR) in the two different CLT configurations. Results also include the 5th percentile values which are considered as a metric indication of their design value as load-bearing building materials.

***Table 1:** Four-point bending test for CLT with 90° and ±45° alternating transverse layers*

CLT type		MOE Global (MPa)	MOE Local (MPa)	MOR (MPa)
90°	Ave.	8243.0 (5.3)	9353.6 (5.8)	35.2 (9.7)
	5th percentile	7357.2	8269.6	28.3
±45°	Ave.	9517.2 (2.2)	10568.0 (2.6)	47.5 (6.1)
	5th percentile	9087.4	9997.3	41.8

Values in parentheses are sample coefficient of variation (COV)

3.1.1 Global and Local Modulus of Elasticity (MOE)

Based on Table 1, the 90° alternating CLT layers average global MOE was 8243.0 MPa, the COV was 5.3%, and the 5th percentile design value was 7357.2 MPa. However, for the panels with ±45° alternating CLT, the average global MOE was 9517.2 MPa, the COV 2.2%, and the 5th percentile design value was 9087.4 MPa.

By comparing the aforementioned values of the two different CLT, the global MOE average value for the ±45° alternating CLT layers increased by 15.5%. Its value of COV decreased by 59.1% and the 5th percentile design value increased by 23.5%.

Considering the local MOE, the average value for the 90° alternating CLT was 9353.6 MPa and the value of COV was 5.8% and finally, the 5th percentile design value was 8269.6 MPa. In the tests of the ±45° alternating CLT, the average local MOE was determined at 10568.0 MPa, the COV 2.6%, and the 5th percentile design value reached 9997.3 MPa.

When compared, the local MOE average value increased by 13.0%, and the COV decreased by 54.5% with the 5th percentile design value increasing by 20.9% for ±45° compared with 90°.

3.1.2 Modulus of Rupture (MOR)

Regarding the modulus of rupture, as shown in Table 1, the average value for the 90° alternating CLT was 35.2 MPa, with a COV 9.7%, and the 5th percentile design value was 28.3 MPa. The values for the ±45° alternating CLT, were 47.5 MPa for the average MOR, 6.1% for the COV, and 41.8 MPa for the 5th percentile design value.

In the ±45° and 90° CLT comparison, the average value of the MOR was increased by 35.0%. A 37.3% decrease was observed in the COV and a 47.8% increase in the 5th percentile design value.

Average four-point bending values and the respective standard deviation for global and local MOE, as well as for MOR are displayed in Figure 7. The comparisons indicate that the strength and stiffness of CLT containing the ±45° alternating layers are increased compared with all of the values of the 90° conventional CLT. Moreover, the SD was less for the ±45° CLT due to the increased interaction contribution from the ±45° layers.

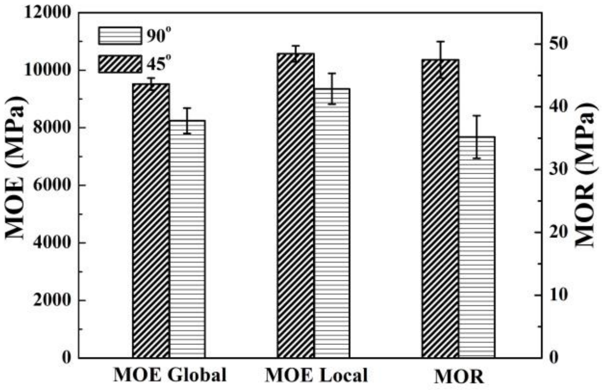

Figure 7: *Comparison of the average four-point bending values and their standard deviations (SD) for MOE global, MOE local, and MOR for both 90° and ±45° alternating CLT*

3.1.3 Failure Modes

Failure types differed among CLT samples in the four-point bending tests and appeared in single or multiple instances in the same tested sample. The most prominent failures can be categorized in the following three modes: (1) bending failure due to the tension of the lowest outer layer, as shown in Figure 8, with both types of CLT being affected; (2) failure due to rolling shear, which occurred when there was shear stress transverse to the grain and appeared more in 90° layers, as shown in Figure 9; and (3) failure due to longitudinal shear, caused by the parallel shear stress of grain and observed in CLT ±45°, shown in Figure 10.

Figure 8: *Bending failure due to tension in the lowest outer layer*

Figure 9: *Failure caused by initial rolling shear near to bondlines appeared as shear stress transverse to the grain*

Figure 10: *Failure due to longitudinal shear occurred as shear stress parallel to the grain*

In this study, failure combinations were also observed through the tests, like the combination of longitudinal shear and initial rolling shear as illustrated in Figure 11. In this study, there is a 45° shear which is a combination of rolling and longitudinal shear in the ±45° transverse layers. When comparing these kinds of failures with Figure 9 which shows a 90° sample, the observed appearance was similar apart from the board orientation.

Figure 11: *Failure due to a combination of longitudinal shear and initial rolling shear near to the bondlines*

3.2 COMPRESSION TEST

Table 2 summarizes the compression properties of the two different layered CLT samples. The evaluation metrics included the global compression MOE and MOR. The design value of the 5th percentile was determined for both CLT types as an indication to characterize their load-bearing capacity as construction materials.

Table 2: *Compression test for CLT with 90° and ±45° alternating transverse layers*

CLT type		MOE Global (MPa)	MOR (MPa)
90°	Ave.	5533.0 (10.6)	26.3 (9.5)
	5th percentile	4393.2	21.4
±45°	Ave.	7167.2 (6.6)	30.2 (2.6)
	5th percentile	6230.4	28.5

Values in parentheses are sample coefficient of variation (COV)

3.2.1 Modulus of Elasticity (MOE)

The results of the compression tests are listed in Table 2. For the 90° CLT layers, the average MOE was 5533.0 MPa, the COV was 10.6%, and the 5th percentile design value was 4393.2 MPa. For the ±45° layer setup, the average global MOE was 7167.2 MPa, with the COV being 6.6%, and finally, the value of 6230.4 MPa defined the 5th percentile design value.

When comparing the two types of CLT, a 29.5% increase was achieved for the average global MOE while the COV value decreased by 37.3%. The 5th percentile design value increased by 41.8%, favoring the ±45° alternating CLT type.

3.2.2 Modulus of Rupture (MOR)

In the compression test of the 90° alternating CLT layers, as shown in Table 2, the average MOR was 26.3 MPa, the COV was 9.5%, and the 5th percentile design value was 21.4 MPa. Results for the ±45° alternating CLT were an average MOR of 30.2 MPa, COV of 2.6%, and 5th percentile value of 28.5 MPa.

In the two CLT type comparison, a 15.0% increase was achieved in the ±45° regarding average MOR, while a 72.4% decrease in the COV was observed. Thereto, the 5th percentile design value increased by 33.4%.

In Figure 12, the average compression values and the standard deviations (SD) of the two CLT types are depicted. This visual comparison displays that the strength and stiffness of ±45° alternating CLT were increased compared with the 90° alternating CLT values of global MOE and MOR. Moreover, the SD was less for ±45° than 90°.

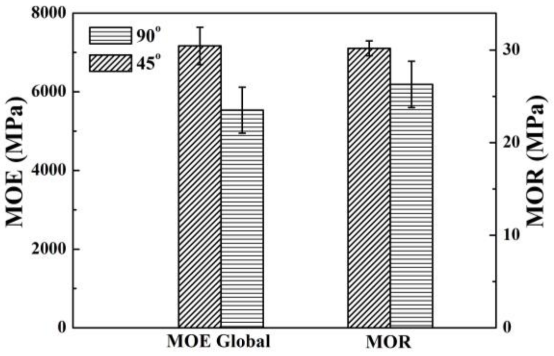

Figure 12: *Comparison of the average compression values and their standard deviations (SD) for the two types of CLT*

3.2.3 Failure Modes

Failure modes for compression tests differed among the two CLT configurations. Failure modes were more consistent for the ±45° alternating layers of CLT but more complex for the 90° CLT. The three most common failure modes can be seen in Figures 13-15. The failure caused by crushing and splitting between layers is presented in Figure 13. Crushing failure is shown in Figure 14 for 90° CLT. Shearing failure for ±45° alternating layers of CLT is shown in Figure 15.

Figure 13: *Compression sample, crushing and splitting failure in CLT 90°, sample top and side view*

Figure 14: *Failure due to crushing in CLT 90°, top and side view*

Figure 15: *Shearing failure in CLT ±45°, top and side view*

4 CONCLUSIONS

In this work, two different types of CLT products with 90° and ±45° alternating transverse layers were evaluated in four-point bending and compression tests. The experimental results have shown that CLT with ±45° alternating layer configuration exhibits increased mechanical characteristics when compared with the conventionally used 90° alternating layers.

The four-point bending strength MOR of 90° alternating layers increased by 35.0% while the global bending stiffness MOE increased by 15.5%. Especially, the 5th percentile value of MOR was increased by 47.8%.

Regarding the compression tests, the compression strength MOR increased by 15.0% while global bending stiffness MOE increased by 29.5% with the 5th percentile value for MOE being increased by 41.8% when comparing the two different configurations of CLT layers.

Furthermore, when investigating the mechanical bending and compression properties, a crucial statistical increase was observed in favor of the ±45° alternating CLT, with the SD being reduced regarding the marginal error, indicating greater predictability. This improvement is desired from a design point of view.

Bending failure modes were also investigated and three of them were identified as the most prominent: outer layer tensile failure which occurred in both sample types, rolling shear failure which was observed mostly in 90° samples, and failure in longitudinal shear which appeared in ±45° samples. Failure also occurred in combination. In bending there was a 45° shear which is a combination of rolling and longitudinal shear in the ±45° transverse layers. Failure modes were also observed in the compression samples: failure caused by crushing and splitting between layers and crushing only, with both failure modes being more common in 90° CLT. The failure mode for CLT ±45° was predominantly shearing.

Future sustainable constructions may use CLT ±45° since they can be beneficial in terms of structural engineering and design properties. The findings of the current work can lead to further CLT developments and improvements in the construction field. As they can be used as a load-bearing building material, helping the construction of larger spans with less material.

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