Bending Properties of Cross Laminated Timber (CLT) with a 45° Alternating Layer Configuration

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Bending tests were conducted with cross laminated timber (CLT) panels made using an alternating layer arrangement. Boards of Norway spruce were used to manufacture five-layer panels on an industrial CLT production line. In total, 20 samples were tested, consisting of two CLT configurations with 10 samples of each type: transverse layers at 45° and the conventional 90° arrangement. Sample dimensions were 95 mm × 590 mm × 2000 mm. The CLT panels were tested by four point bending in the main load-carrying direction in a flatwise panel layup. The results indicated that bending strength increased by 35% for elements assembled with 45° layers in comparison with 90° layers. Improved mechanical load bearing panel properties could lead to a larger span length with less material.

Keywords: Mass timber engineering; Massive timber; Crosslam; X-lam; Solid wood panel; Solid timber system; Rolling shear; CLT manufacturing; CLT assembly; Multi-layer; Sustainable construction material

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INTRODUCTION

Technological improvements in mass timber engineering have created a renewed sense of purpose and a more versatile use of wood as a building material. Combined with environmental issues, the importance of wood-based structures is becoming more evident compared with steel and concrete, which in turn will promote further advancements toward sustainable construction solutions (Fredriksson 2003; SOM 2013).

Cross laminated timber (CLT) is an engineered wood panel composed of at least three orthogonally and adhesively bonded layers of solid timber boards. This technology was introduced in the early 1990s in Central Europe (Schickhofer *et al.* 2009). In most cases, CLT has an odd number of layers, with wood fibers of each layer transverse to those of the neighboring layer (Fig. 1). The final outcome is a product with higher dimensional stability and load-bearing capacity compared with regular timber (Gagnon and Pirvu 2011).

Fig. 1. Conventional cross laminated timber (CLT)

CLT has considerable in-plane and out-of-plane resistance compared with traditional light-frame timber constructions, making it increasingly recognized as a suitable structural building material. In lower wood-frame buildings, the floor span can be a critical point in structural design performance. With high-rise buildings, the walls and columns need to resist higher vertical loads and additional lateral loads due to wind. The growing focus on timber-based structures, with their accompanied low environmental impact, has driven demand for the construction of large-scale and high-rise timber buildings (Gagnon and Pirvu 2011; SOM 2013).

Experimental tests on CLT have shown that positive outcomes and real-life events, such as the Kobe earthquake in 1995, demonstrate that these buildings can withstand severe forces vitally undamaged (Ceccotti *et al.* 2013).

Collaborative research conducted by architects and engineers has established that wood can be suitable for high-rise building construction. Concepts consisting of approximately 80% timber by volume for more than 40-floor buildings in which the main structural material is CLT reinforced with glulam, steel, and concrete have been suggested. Challenges to entire timber constructions include managing larger spans and connections, which can require more material per unit area. Floors require approximately 70% of all material in this type of high-rise buildings. Therefore, it is of growing importance to improve the properties of structurally engineered wood products to ensure a competitive and sustainable low carbon dioxide footprint material suitable as an affordable building architecture in the future (SOM 2013).

Currently, CLT is constructed as a 0°/90° laminate; that is, boards are alternately placed in a longitudinal and transverse order (Gagnon and Pirvu 2011). Due to the anisotropic properties of wood, there is a suitable potential for distributing the stresses more along the fibers. For Norway spruce, the modulus of elasticity and the shear modulus are about 25 times stronger in grain direction than in the transverse direction (Dinwoodie 2000). Therefore, stiffness and strength of the transverse layers must be considered in applications of conventional CLT with 90° transverse layers as rolling shear might govern the performance of the panel (Li *et al.* 2014). Thus, reducing the thickness of the transverse layers is not an alternative for reducing the risk of rolling shear.

The main point of this study is the comparison of two types of CLT panels consisting of boards either with grain direction aligned at ± 45° or at 90°, with the purpose of increasing the load-bearing capacity of the panel in the main load direction. The assumption is that by aligning alternating boards at 45°, the load will be distributed more in the strongest direction of the wood, thereby reducing the risk of rolling shear.

The purpose of this study is to examine a panel layup to improve the bending properties of CLT. Destructive bending tests of CLT in the main load-carrying direction in a flatwise panel layup, where every transverse layer is oriented at ± 45°, have not been tried (Fig. 2). A non-glued product exists with alternating ± 45° layers; however, the boards are assembled with wooden dowels instead of glue, a technique developed by Thoma Holz100 (ETA 2013). Assembling the boards with glue instead of dowels results in higher mechanical performance.

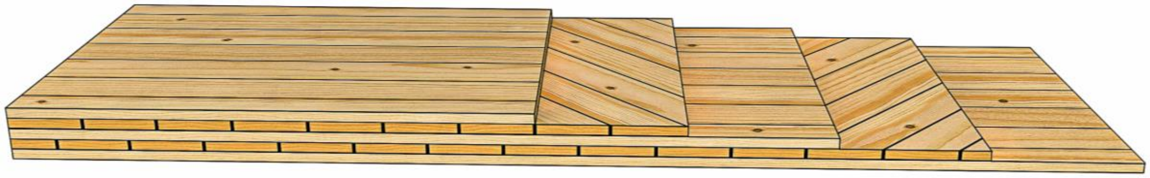

Fig. 2. CLT panel layup with ± 45° alternating transverse layer configuration

The major vision of this study was to further develop CLT for sustainable high-performance building construction. The specific objective was to optimize the CLT load-bearing capacity by enhancing the alignment and distribution of boards in relation to the main load direction from a material property perspective. Evaluation was conducted by comparing specific bending properties of 45° with 90° alternating transverse CLT layers.

The overall advantages expected of these CLT ± 45° products were: (1) more efficient use of resources by considering the material properties; (2) increased structural performance in the load direction when proposed as a load-bearing construction panel element, especially in regard to shear forces; and (3) CLT panels suitable for demanding construction purposes.

EXPERIMENTAL

CLT panels were manufactured on an industrial CLT production line under a modified process and production procedure at Martinsons in Bygdsiljum, Sweden (Fig. 3). European Norway spruce (*Picea abies*) from the local Bygdsiljum region was used. Boards were machine-strength graded using a Dynagrade, which measured the physical impact resonant frequency mode, similar to the method used with the Dynalyze AB patent (Larsson *et al.* 1998). The structural timber strength class was LS15, and the quality class was Q61 in accordance with CEN/EN 14081 (2011) and corresponding to C24-grade CEN/EN 338 (2009). The average moisture content was 8% as determined by the oven dry method according to CEN/EN 13183 (2003). The average density was 462 kg/m^3 according to ISO 3131 (1975). After prior board processing both edgewise and flatwise through a jointer, the dimensions of each individual board were 19 mm in thickness and 94 mm in width. The boards contained no finger joints. The amount of material used for the two different types of CLT corresponded to each other, through it was possible to adjust the production line saw to cut individual long boards in 45° for the transverse layers, thereby minimizing sawing waste.

Boards were glued using the melamine-urea-formaldehyde (MUF) adhesive Cascomin 1247 alongside hardener 2526, manufactured by Casco Adhesives AB (AkzoNobel, Amsterdam Netherlands). Glue type 1 was used according to CEN/EN 301 (2012). An industrial separate ribbon spreader, 6230 from Casco Adhesives AB, applied glue on all flat board surfaces during production, with no edge bonding. The adhesive hardener ratio was established at 29.2% and 320 g/m² glue was applied.

Pressing the boards into panels was performed in one step in a high-frequency press (HF Press) SM 6013 HFS from Stenlund Maskiner AB, which applied 185 bar of vertical pressure and 29 bar of horizontal pressure transversely to the CLT. Time spent in the HF press was 290 s and the final panel temperature was 78 °C. After curing, the CLT panel dimensions were 95 mm thickness × 1200 mm width × 4136 mm length. Six elements were produced with five-layers consisting of alternating 90° and ± 45° transverse layers: three elements with transverse board layers arranged in a 90° direction (0°, 90°, 0°, 90°, 0°), and another three elements with boards at a ± 45° orientation (0°, 45°, 0°, − 45°, 0°).

During production, the CLT panels were constructed with every second panel being a modified CLT containing 45° layers, followed by a conventional CLT, and so forth. Overlapping simultaneous production resulted in equally matched materials and environment, which allowed more comparable results. All manufacturing parameters were within the ranges required by CLT standards, and production line procedures were confirmed by the manufacturer.

Each panel was sawn into four specimens using computer numerical control (CNC). The CLT specimen count for this investigation was 10 samples of 90° alternating in the transverse direction and 10 samples of 45° alternating layers. Thus, a combined total of 20 samples was examined by four point bending.

The measurement of sample dimensions fulfills the standard requirement of CEN/EN 325 (2012). The average dimension was based on 10 measurements of each sample. Thickness was measured in six positions, width was measured three times, and length was measured once. The final average dimension of the specimens for the four point bending test was 95 mm (S.D. 0.2) thickness × 590 mm (S.D. 0.3) width × 2000 mm (S.D. 0.1) length.

Fig. 3. Industrial production of conventional CLT (90°) and modified CLT ± 45° panels: (A) Arrangement of 45° layers; (B) HF press; and (C) CNC sizing

The bending properties of each specimen were tested according to the European standard CEN/EN 408 (2012) (Fig. 4). This standard was suggested for determining strength and stiffness properties of CLT according to the standard CEN/EN 16351 (2015). The corresponding tests were carried out at SP Technical Research Institute of Sweden in Skellefteå (Fig. 5). The mechanical properties measured in this paper were applied load with corresponding global and local displacement. The samples were tested in the major direction, as arranged in a flatwise layup. The global bending span was 1710 mm, with 570 mm between the two inner load points and support widths were 50 mm, with a 5 mm edge radius.

Testing was conducted in an accredited laboratory, and all measuring devices and equipment were calibrated according to SP standard operating procedures. During testing, measurements were recorded 100 times per second. The measuring accuracy of the electronic calipers used for measuring sample dimensions was ± 0.04–0.05 mm. The acceptance accuracy of the two 25-mm-long micro-measurement linear displacement sensors, which measured local displacement, was ± 0.02 mm. The accuracy of the two 50-mm-long displacement sensors, which measured global displacement, was ± 0.04 mm. The load cell was at ± 0.20% maximum output.

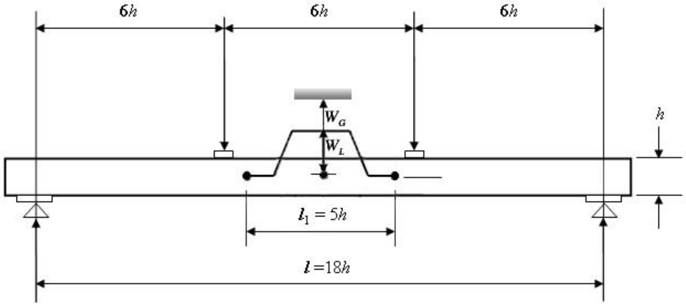

Fig. 4. Test arrangement for measuring strength and respective global and local stiffness in four point bending according to CEN/EN 408 (2012)

The methods for determining CLT properties, including MOR, global MOE, and local MOE in the four point bending tests are defined by the standard CEN/EN 408 (2012). The global MOE was resolved with displacement measurements from the neutral axis W_G over the full panel span 18 h between the two outer supports, including the effects of shear in bending. Local MOE was determined by local displacement W_L, which was determined as span length $l_1 = 5$ h as measured from the center from the neutral axis (Fig. 4). Calculations were based on 10% and 40% of the respective ultimate load with corresponding local and global displacement.

Flexural rigidity (EI) is a measure of stiffness and is defined as the resistance offered by a structure. E is the Young's modulus, and I is the second moment of gross cross-section area.

Minitab 17 Statistical software (Minitab Inc., Pennsylvania, USA) was used to analyze the data. Mechanical property variations are presented to statistically quantify the results using standard deviation (S.D.), coefficient of variation (COV), and a confidence interval (CI) at the 95% confidence level (CL). A normal probability test showed the data are approximately normally distributed. The differences in means and ± margin of error between the groups were calculated in Minitab with two-sample CIs, taking into account different S.D. at 95% CL.

The lower one-side 75% CL for the 5th percentile value, which is known as 5-percentile or 5%-quantile, was calculated. The 5th percentile establishes the value for which 5% of the test values are lower and within the suggested CL according to timber structure standard CEN/EN 14358 (2006).

Specimen number 20 was excluded from all calculations due to measurements being stopped before the ultimate load was reached. The presented values are based on the average ultimate load to indicate their behavior in Table 2.

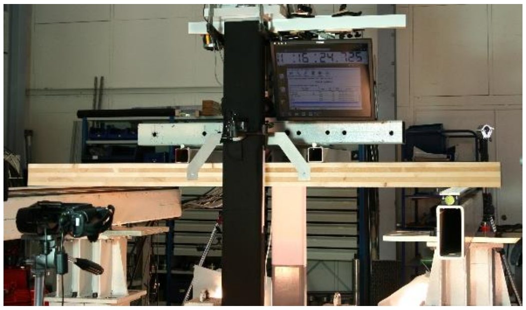

Fig. 5. Four point bending test of CLT panels with an alternating layer configuration

RESULTS AND DISCUSSION

Tables 1 and 2 summarize the mechanical properties of the tested CLT specimens consisting of transverse layers alternating at 90° or ± 45°. Results include the four point ultimate bending load, global and local modulus of elasticity (MOE), modulus of rupture (MOR), flexural rigidity (EI), and failure mode for both the 90° and 45° alternating CLT layers. The 5th percentile values were calculated as an indication of design values for these two types of CLT as load-bearing building materials.

Table 1. Results from Four Point Bending for Conventional CLT with 90° Layers

Specimen CLT 90°	Ultimate Load (kN)	MOE Global (MPa)	MOE Local (MPa)	MOR (MPa)	EI Global (10^9·Nm^2)	Failure Mode
1	114.0	7664.6	8814.2	36.6	323.1	Tensile & Rolling Shear
2	91.3	8526.4	10034.2	29.3	359.4	Rolling Shear
3	90.7	8545.3	9962.8	29.1	360.2	Rolling Shear
4	119.1	8127.8	9669.9	38.3	342.6	Rolling Shear
5	116.6	7601.5	8464.4	37.4	320.4	Tensile & Rolling Shear
6	119.5	8597.7	9081.6	38.4	362.4	Tensile & Rolling Shear
7	107.8	8102.9	9621.7	34.6	341.6	Tensile & Rolling Shear
8	116.6	7903.3	9144.4	37.4	333.2	Rolling Shear
9	108.8	8970.5	9817.2	34.9	378.1	Tensile & Rolling Shear
10	112.5	8390.3	8925.9	36.1	353.7	Tensile & Rolling Shear
Ave.	109.7	8243.0	9353.6	35.2	347.5	
Max.	119.5	8970.5	10034.2	38.4	378.1	
Min.	90.7	7601.5	8464.4	29.1	320.4	
S.D.	10.6	440.1	537.9	3.4	18.6	
COV (%)	9.7	5.3	5.8	9.7	5.3	
5th percentile	88.1	7357.2	8269.6	28.3	310.1	

Table 2. Results from Four Point Bending for CLT with ± 45° Alternating Layers

Specimen CLT ± 45°	Ultimate Load (kN)	MOE Global (MPa)	MOE Local (MPa)	MOR (MPa)	EI Global (10^9·Nm^2)	Failure Mode
11	143.6	9584.1	10738.8	46.1	404.0	Longitudinal & 45° Shear
12	157.7	9309.3	10217.8	50.6	392.4	Tensile & 45° Shear
13	162.8	9704.3	10607.3	52.3	409.1	Tensile, Longitudinal & 45° Shear
14	137.2	9845.8	10309.4	44.0	415.0	Tensile & 45° Shear
15	147.8	9568.2	10654.9	47.5	403.3	Longitudinal Shear
16	139.5	9140.4	10146.3	44.8	385.3	Tensile, Longitudinal & 45° Shear
17	139.9	9511.2	10745.3	44.9	400.9	Tensile, Longitudinal & 45° Shear
18	148.4	9562.4	10748.7	47.7	403.1	Tensile
19	155.5	9428.9	10943.8	49.9	397.5	Tensile, Longitudinal & 45° Shear
20	148.0	9392.7	10654.8	47.5	395.9	Tensile, Longitudinal & 45° Shear
Ave.	148.0	9517.2	10568.0	47.5	401.2	
Max.	162.8	9845.8	10943.8	52.3	415.0	
Min.	137.2	9140.4	10146.3	44.0	385.3	
S.D.	9.0	207.7	276.3	2.9	8.8	
COV (%)	6.1	2.2	2.6	6.1	2.2	
5th percentile	130.3	9087.4	9997.3	41.8	383.1	

Global and Local Modulus of Elasticity (MOE)

As demonstrated in Table 1, the average global MOE of the 90° alternating CLT layers was 8243.0 MPa, COV 5.3%, and the 5th percentile design value was 7357.2 MPa. However, for the 45° alternating CLT (Table 2), the average global MOE was 9517.2 MPa, COV 2.2%, and the 5th percentile design value was 9087.4 MPa.

When comparing the 45° with the 90° alternating CLT, the average value for the global MOE increased by 15.5%. The COV decreased by 59.1% and the 5th percentile design value increased by 23.5%.

For the local MOE, the average value for the 90° alternating CLT (Table 1) was 9353.6 MPa. The COV was 5.8% and the 5th percentile design value was 8269.6 MPa. For the 45° alternating CLT (Table 2), the average local MOE was 10568.0 MPa, COV 2.6%, and the 5th percentile design value was 9997.3 MPa.

The average value for the local MOE was increased by 13.0%, COV was decreased by 54.5%, and the 5th percentile design value was increased by 20.9% for 45° compared with the 90° alternating CLT.

Modulus of Rupture (MOR)

Table 1 shows that the average MOR for 90° alternating CLT layers was 35.2 MPa, COV 9.7%, and the 5th percentile design value was 28.3 MPa. Table 2 demonstrates that with the 45° alternating CLT, the average MOR was 47.5 MPa, COV 6.1%, and the 5th percentile design value was 41.8 MPa.

Comparing the 45° with 90° alternating CLT, the average value for the MOR increased by 35.0%. The COV decreased by 37.3% and the 5th percentile design value increased by 47.8%.

Average values and their standard deviations (S.D.) of MOE global, MOE local, and MOR for both 45° and 90° alternating CLT are displayed in Fig. 6. Comparisons are visually more clear and show that the 45° alternating CLT strength and stiffness increased compared with 90° alternating CLT values MOE global, MOE local, and even more MOR. Moreover, the S.D. were smaller for 45° than 90°.

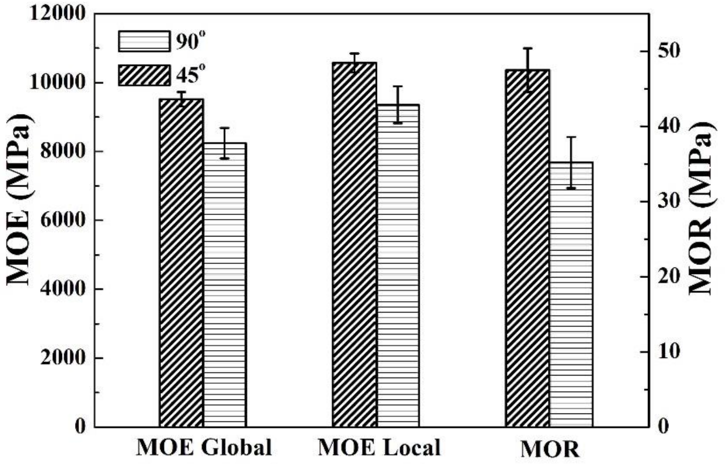

Fig. 6. Comparison of the average values and their standard deviations (S.D.) of MOE global, MOE local, and MOR for both 45° and 90° alternating CLT

The relationship between load and global displacement behavior of investigated samples at 90° and 45° alternating CLT are also illustrated in Fig. 7.

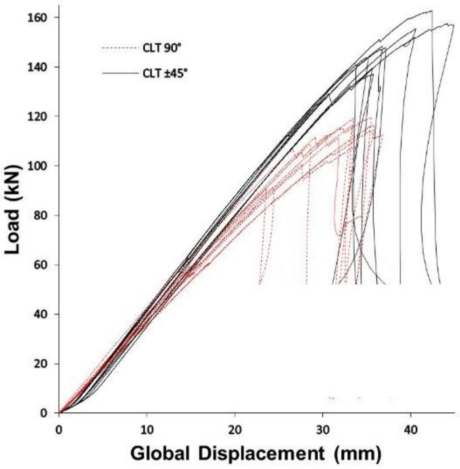

Fig. 7. Four point bending behavior of investigated samples: load/displacement for 90° and ± 45° CLT

Flexural Rigidity (EI)

For flexural rigidity (EI), 347.5 × 10^9 Nm^2 was the average value for 90° alternating CLT layers (Table 1). The COV was 5.3% and the 5th percentile design value was 310.1 × 10^9 Nm^2. For the 45° alternating CLT (Table 2), 401.2 × 10^9 Nm^2 was the average flexural rigidity, COV 2.2%, and the 5th percentile design value was 383.1 × 10^9 Nm^2.

Comparing the 45° with the 90° alternating CLT, the flexural rigidity increased by 15.5%, COV decreased by 59.1%, and the 5th percentile design value increased by 23.5 times, and more for the 45° than the 90° alternating CLT.

Statistical Analysis

Statistical analysis of the two CLT groups showed a significant improvement in mechanical properties when comparing 45° with 90° alternating CLT. A two-sample 95% CIs test showed the following difference in means ± margin of error: load 38 ± 10 kN; global MOE 1274 ± 336 MPa; local MOE 1215 ± 418; MOR 12 ± 3 MPa; and flexural rigidity $54 \pm 14 \times 10^9$ Nm^2.

Failure Modes

The types of failure differed among CLT specimens. There were three main failure modes observed, which could appear in combination in tested specimens: (1) bending failure caused by tension in the lowest outer layer, which appeared in both types of CLT (Fig. 8); (2) failure due to initial rolling shear close to the bondlines, which appeared as shear stress transverse to the grain and occurred more in 90° layers (Fig. 9); and (3) failure due to longitudinal shear, which occurred as shear stress parallel to grain and appeared in 45° CLT (Fig. 10).

Fig. 8. Bending failure due to tension in the lowest outer layer

Fig. 9. Failure due to initial rolling shear near to bondlines appeared as shear stress transverse to the grain

Fig. 10. Failure due to longitudinal shear occurred as shear stress parallel to the grain

Failures also appeared in combination with longitudinal shear and initial rolling shear close to bondlines as shown in Fig. 11. In Table 2, 45° shear is a combination of longitudinal and rolling shear in the 45° transverse layers, not in the longitudinal layers. The appearance from the sample side is similar to Fig. 9, except that the boards are orientated in 45° instead of 90°.

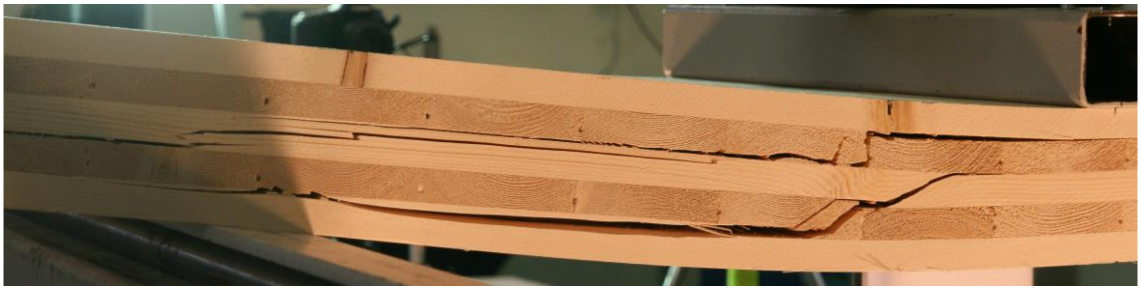

Fig. 11. Failure due to a combination of longitudinal shear and initial rolling shear near to the bondlines

CONCLUSIONS

1. Bending tests were conducted with cross laminated timber (CLT) products, which consisted of 45° or 90° alternating transverse layers. The CLT with 45° alternating layers showed improved mechanical properties compared with conventional 90° alternating layers.
2. Comparing the 45° with the 90° alternating CLT layers, the four point bending strength MOR increased by 35.0%, whereas global bending stiffness MOE and corresponding flexural rigidity (EI) were raised by 15.5%. Specifically, the 5th percentile value for MOR improved by 47.8%.
3. A statistical significant increase in the investigated mechanical properties was observed, and the S.D. was smaller when comparing 45° with 90° alternating CLT using two-sample 95% CIs difference in means ± margin of error, which is positive from a design perspective.
4. Three main types of bending failure modes could be observed: tensile failure of the outer layer; rolling shear failure appeared more in 90° specimens and longitudinal shear failure occurred in 45° specimens.
5. The 45° CLT is beneficial in regard to structural engineering and its design values. These findings could lead to further CLT developments in the field as load-bearing building construction materials to the construction of larger spans with less material.

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REFERENCES CITED

Ceccotti, A., Sandhaas, C., Okabe, M., Yasumura, M., Minowa, C., and Kawai, N. (2013). "SOFIE Project - 3D shaking table test on a seven-story full-scale cross-laminated timber building," *Earthquake Engineering & Structural Dynamics* 42(13), 2003-2021.

CEN/EN 301:2013. (2012). "Adhesives, phenolic and aminoplastic, for load-bearing timber structures – Classification and performance requirements," European Committee for Standardization, Brussels, Belgium.

CEN/EN 325:2012. (2012). "Wood-based panels – Determination of dimensions of test pieces," European Committee for Standardization, Brussels, Belgium.

CEN/EN 338:2009. (2009). "Structural timber – Strength classes," European Committee for Standardization, Brussels, Belgium.

CEN/EN 408:2010+A1:2012. (2012). "Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties," European Committee for Standardization, Brussels, Belgium.

CEN/EN 13183-1:2002. (2003). "Moisture content of a piece of sawn timber – Part 1: Determination by oven dry method," European Committee for Standardization, Brussels, Belgium.

CEN/EN 14081-1:2005+A1:2011. (2011). "Timber structures – Strength graded structural timber with rectangular cross section – Part 1: General requirements," European Committee for Standardization, Brussels, Belgium.

CEN/EN 14358:2006. (2006). "Timber structures – Calculation of characteristic 5-percentile values and acceptance criteria for a sample," European Committee for Standardization, Brussels, Belgium.

CEN/EN 16351:2015. (2015). "Timber structures – Cross laminated timber – Requirements," European Committee for Standardization, Brussels, Belgium.

Dinwoodie, J. M. (2000). "Timber: its nature and behavior," CRC Press, Boca Raton, FL, USA.

ETA-13/0785 (2013). "European Technical Approval ETA-13/0785 (Thoma Holz 100)," DIBt, Germany.

Fredriksson, Y. (2003). "Samverkan mellan träkomponenttillverkare och stora byggföretag: En studie av massivträbyggande," ["Collaboration between the wood component manufacturers and large construction companies: A study of solid wood construction,"] *Licentiate thesis*. Luleå University of Technology, Sweden.

Gagnon, S., and Pirvu, C. (eds.). (2011). *CLT Handbook: Cross-Laminated Timber*, FPInnovations, Pointe-Claire, Canada.

ISO 3131. (1975). "Wood – Determination of density for physical and mechanical tests," International Organization for Standardization, Geneva, Switzerland.

Larsson, D., Ohlsson, S., and Perstorper, M. (1998). Method and arrangement for nondestructive classification. World patent WO98/01737.

Li, M., Lam, F., and Li, Y. (2014)."Evaluating rolling shear strength properties of cross laminated timber by torsional shear tests and bending tests," *WCTE*, Quebec City Canada.

Schickhofer, G., Bogensperger, T., and Moosbrugger, T. (2009). *BSP Handbook - Wood Massive Construction in Laminated Timber, The Evidence on the Basis of the New European Standard Concept*, Institute for Timber Engineering and Wood Technology, Graz, Austria.

Skidmore, Owings, and Merrill, LLP (SOM). (2013). “Timber tower research project,” (http://www.som.com/ideas/research/timber_tower_research_project). Accessed 16 January 2015

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