Production and In-Plane Compression Mechanics of Alternatively Angled Layered Cross-Laminated Timber

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Increasing awareness of sustainable building materials has led to interest in enhancing the structural performance of engineered wood products. This paper reports mechanical properties of cross-laminated timber (CLT) panels constructed with layers angled in an alternative configuration on a modified industrial CLT production line. Timber lamellae were adhesively bonded together in a single-step press procedure to form CLT panels. Transverse layers were laid at an angle of 45°, instead of the conventional 90° angle with respect to the longitudinal layers' 0° angle. Tests were carried out on 20 five-layered CLT panels divided into two matched groups with either a 45° or a 90° configuration; an in-plane uniaxial compressive loading was applied in the principal orientation of the panels. These tests showed that the 45°-configured panels had a 30% higher compression stiffness and a 15% higher compression strength than the 90° configuration. The results also revealed that the 45°-configured CLT can be industrially produced without using more material than is required for conventional CLT 90° panels. In addition, the design possibility that the 45°-configured CLT can carry a given load while using less material also suggests that it is possible to use CLT in a wider range of structural applications.

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INTRODUCTION

Driven by consumer demand, builders and architects are becoming increasingly interested in the use of ecologically friendly renewable materials and are shifting toward the use of timber products in the construction of larger spans and high-rise buildings. Enhancing the competitiveness and reliability of structural engineered wood products (EWPs) will ensure their future use as sustainable, low-carbon-footprint materials, and as a major contributor to affordable structures (Asdrubali *et al.* 2016).

Developments in timber engineering resulting from changed industrial conditions have awakened interest in the use of wood as a building material. EWPs, such as cross-laminated timber (CLT), are increasingly used for timber construction and targeted toward a global market. CLT has been gaining acceptance in residential and non-residential applications (Brandner *et al.* 2016).

CLT is a prefabricated panel of solid wood, conventionally composed of an uneven number of layers placed orthogonally, with adhesively bonded lamellae placed in a side-by-side manner (Fig. 1). CLT panels can be formed as solid straight or curved panel elements. These panels benefit from the homogenized mechanics that result from the interaction of the various layers and lamellae. This layered matrix construction reduces

impacts from cracks, grooves, cuts, knots, grain deviations, annual ring width variations, and related heterogeneous features. The cross-layered arrangement forms a product with the advantage of having a more predictive dimensional stability and a greater load-bearing capacity than traditional structural timber (Steiger *et al*. 2012; Brandner *et al*. 2016).
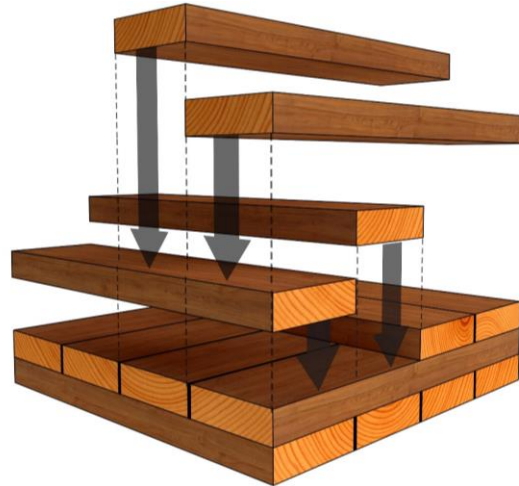

Fig. 1. Conventional alternating 0°/90° cross-laminated timber (CLT) panel

Hyperbolic paraboloid shell-shaped timber-roof constructions, with a double-curved hyperbolic shape, appeared in Europe in 1957. The panel used was formed from adhesive-bonded 0°/90° cross-layered timber lamellae as a CLT. Later, this construction material was superseded by the changed availability of industrial steel combined with trends in architectural design (Booth 1997). As a result of advances in industrial automation technology, the concept for CLT as it is known today was motivated in the early 1990s by the need of the Central European sawmill industry to increase the value-yield for sideboards. A further increase in the volume of CLT produced is expected as technology advances and more industrial automation is introduced. Such an increase will attempt to recapture the sizeable market share held by non-renewable mineral-based construction materials, such as steel and concrete, as well as that of traditional wood-based products (Brandner *et al.* 2016).

Research focusing on the structural performance of buildings made of EWPs has grown and has contributed to an expanded use of wood as a construction material. As reported by Foster *et al.*, as of 2016 the wider use of EWPs for a 300-m-tall building concept was in the exploratory stage. This indicates the potential of EWPs as a future structural material; however, fundamental challenges remain to be addressed with respect to the structural design, due to the increasing impact of lateral and dynamic loads at such heights (Foster and Ramage 2016). A 24-story building in Vienna called "HoHo", constructed as a structural hybrid based on CLT, glulam, and reinforced concrete, is expected to be completed in 2018. The lateral resistance to wind load in this building is primarily provided by a central vertical concrete core (Xiong *et al*. 2016).

In 2016, the world's tallest wooden apartment block was an 18-story, 53-m-tall building in Vancouver, Canada. The structure was constructed mainly of glulam and five-layered CLT, with a concrete elevator shaft that takes the lateral loads from wind (Poirier *et al.* 2016). This raises the question of whether the structural stabilization for wind load provided by the concrete elevator shaft can, in future similar applications, instead be

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provided by a timber-panel solution. In one exemplification, glulam beams with orientations of ± 45° have been used to provide wind load support (Fig. 2). The principle demonstrated by these beams, that glulam in a ± 45° orientation offers increased wind load resistance, will presumably also apply to CLT panels. The applications of such panels then include replacing ± 45° oriented glulam beams, ± 45° oriented steel rods, or the central vertical concrete core used for wind load stabilization. A CLT panel-based approach in similar cases could involve ± 45° layers acting as a shear wall element. This may provide an alternative design approach that distributes the load more uniformly instead of acting through individual beams.

Fig. 2. A combined glulam and CLT structure. Glulam beams oriented at ± 45° provide structural wind load resistance (Photo used with permission from Alexander Schreyer/UMass)

Compressive stiffness and strength are the principal of concerns when the demand on load-bearing structural applications of CLT is increased. In turn, compression stress as a result of bending in walls can be considerably introduced by wind loads. Increased floor spans contribute to the compression loads on walls due to the weight of the material distributed across a larger area. Design features such as windows and doors increase the concentration of compressive loads on walls. Building elements, such as the upper part of structural subfloors or at the bottom side of overhanging parts can experience compressive loads. The preceding examples illustrate the critical role that compressive resistance plays when CLT is considered in structural design (Dujic *et al.* 2008; Oh *et al.* 2015; Schmid *et al.* 2015; Christovasilis *et al.* 2016).

Wood is an orthotropic material, having different mechanical properties depending on the load orientation. Conventional CLT is therefore fabricated as a 0°/90° laminate, with layers alternating in the longitudinal and transverse directions. Thus, layers oriented transverse to the load orientation are stressed perpendicularly to the grain orientation under in-plane compression. The modulus of elasticity and the shear modulus of Norway spruce in the grain orientation are approximately 25 higher times greater than the values perpendicular to the grain in clear wood (Dinwoodie 2000). Hence, in a conservative design, the contribution of the cross-layers to the global compressive stiffness and strength in 90° layers is generally neglected because of the ratio of mechanical properties of the longitudinal to those of transverse layers (Brandner *et al.* 2015). If the lamellae are aligned at angles less than 90°, such as 45°, there is a potential to distribute the stresses more suitably along the fiber orientation.

Based on tests of panels containing one 45° layer in the center exposed to a principal in-plane shear proportion, Jakobs (1999) concluded that a CLT with a 45°-layer structure can offer twice the stiffness of conventional CLT. Such an increase in stiffness raises the question of whether CLT can become increasingly relevant if different layers and angle arrangements are combined as industrial automation develops. If so, it would offer a greater freedom in design when using a panel approach, further supporting the re-ascension of CLT in the structural applications market. In response to this, the performance of CLT, including under uniaxial compression, is of interest for CLT with layers at alternative angles.

Erwin Thomas has designed, and his company, Thoma, manufactures Holz100, an industrial product featuring alternating lamellae alignments (ETA 2013). Their product is manufactured using ± 45° transverse layers with the lamellae held together by wooden dowels instead of adhesive (Fig. 3). This approach can partly retain the reinforcing effect in both the major and minor orientations *via* the ± 45° transverse layers. However, to achieve the desired mechanical performance, adhesive was used in this research to achieve stiffer panels. Gluing load-bearing timber components results in a substantially stiffer panel than the use of purely mechanical connections such as wooden dowels or nails. The stiffer assembly is the result of areal connection bonding, as opposed to multiple pointwise connections with nails or dowels. Bonding between the adhesive and the wood is based on both chemical and mechanical adhesion (Blaß *et al.* 1995).
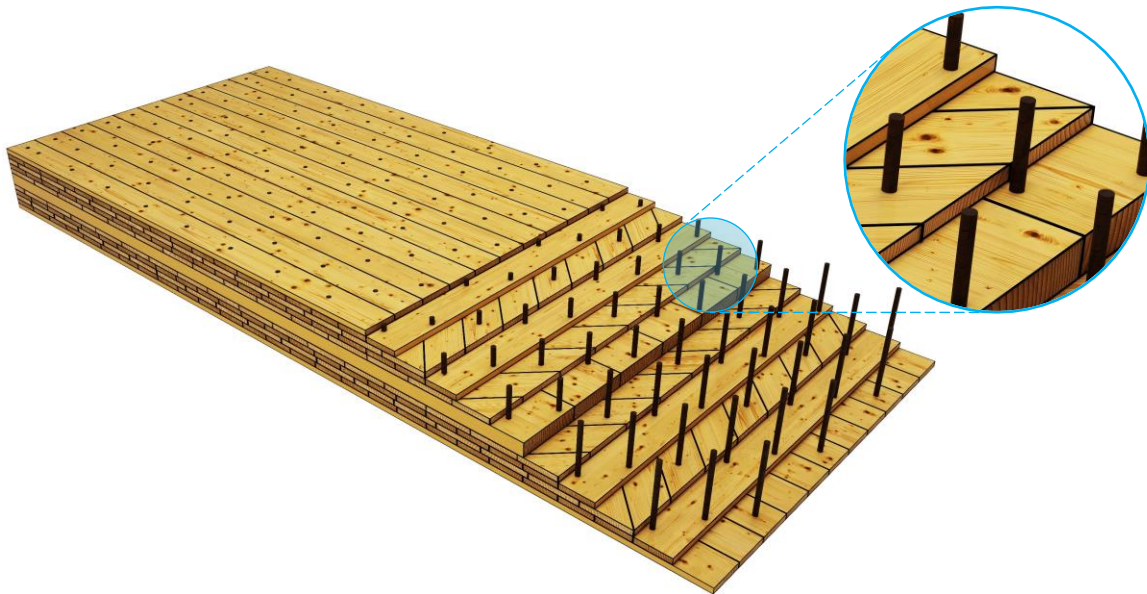

Fig. 3. Thoma's Holz100 is an engineered wood product with lamellae assembled in a ± 45° orientation and connected with wooden dowels

Objective

There were two main objectives of this work. The first was to develop a guideline for industrial production of alternatively angled CLT. The second was to determine the extent to which the load-bearing capacity of such panels can be enhanced. Specifically, to determine the extent to which transverse layers arranged at ± 45° angles can influence the load-bearing capacity of CLT (Fig. 4). This was of particular interest with regard to the in-plane uniaxial compression properties in the principal load-bearing orientation of the panels. The material properties in question are the stiffness, strength, indicated

characteristics and the related failure modes. This research strived to create an enhanced CLT product that offers the performance necessary to meet the increase in demand for timber-based building construction materials

Fig. 4. Schematic of the configuration of a five-layered CLT panel with 0° longitudinal and ± 45° transverse layers

EXPERIMENTAL

The experimental data refer firstly to the evaluation of CLT production under industrial conditions and secondly to laboratory testing of CLT panels. Two groups of different types of CLT, configured 0° / 90° and 0° / ± 45°, were the basis for the evaluation of material properties.

Materials

Norway spruce [*Picea abies* (L.) Karst.] was used to produce CLT panels with transverse layers alternating at either 90° or ± 45°. The panels were produced on Martinsons CLT production line in Bygdsiljum, Sweden using a specially designed process (Fig. 5). The lamellae of the CLT panels were machine-stress-graded by a Dynagrade in accordance with the operating procedure described by the Dynalyze AB patent (Larsson *et al.* 1998). The timber selected corresponded to C24 grade CEN/EN 338 (2009). The average density of lamellae was 462 kg/m^3 at an average moisture content of 8%, in accordance with ISO 3131 (1975) and CEN/EN 13183 (2003) respectively. The surfaces of lamellae were planed along the narrow and wide flat sides through a jointer. The resulting dimensions of a single lamella were a thickness of 19 mm and a width of 94 mm. No finger joints were used in the production of lamellae. The production line cross-cut saw was adjustable, enabling it to cut single full-length lamellae of differing lengths at an angle of 45° for the transverse layers before they were assembled into panels.

A Melamine–Urea–Formaldehyde (MUF) adhesive was used to bond lamellae. Adhesive resin with 29.2% hardener was used and a total of 320 g/m² adhesive was applied. The resin, Cascomin 1247, and hardener 2526, was made by Casco Adhesives AB (AkzoNobel, Amsterdam, Netherlands). This adhesive type and combination corresponds to CEN/EN 301 (2012) adhesive type 1. An industrial separate ribbon spreader 6230, also made by Casco Adhesives AB, was used to apply the adhesive on the wide sides of lamellae during panel fabrication. There was no narrow face bonding of the sides of lamellae.

A high-frequency press SM 6013 HFS from the former Stenlund Maskiner AB, Ursviken, Sweden was used in a single-step procedure to press the lamellae into CLT panels. Vertical and horizontal pressures, respectively 0.37 MPa at 185 bar cylinder pressure and 0.32 MPa at 29 bar cylinder pressure, were applied transversely to the CLT.

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The duration of the press stage was 290 s and the production temperature of the panels was 78 °C.

After curing in the press, the average dimensions of the CLT panels were 1200 mm in width × 95 mm in thickness × 4136 mm in length. A total of six CLT panels were manufactured, including alternating 90° and ± 45° transverse layers: three panels with alternating layers arranged transversely at 90° (0°, 90°, 0°, 90°, 0°), and three panels with alternating layers arranged at ± 45° (0°, 45°, 0°, - 45°, 0°). During manufacture, every second panel passing through the production line was modified CLT ± 45° followed by conventional CLT 90°, and so forth. Production was performed in an overlapping and simultaneous fashion, resulting in enhanced matching of materials and environmental conditions to ensure panel comparability. All relevant production line procedures and manufacturing parameters were within the nominal range used by CLT company Martinsons when producing conventional CLT.

CLT panels were sawn using computer numerical control (CNC) in systematic sampling to represent the natural material diversity, for a total of 40 samples, consisting of either 90°-configured or ± 45°-configured CLT. Half of these samples were tested in destructive four-point bending (Buck *et al.* 2016), and the other 20 were examined under in-plane uniaxial compression in this paper. The sample dimensions were measured in accordance with the recommendations of CEN/EN 325 (2012). The final average dimensions of the samples for the compression test were 95 mm in thickness × 180 mm in width × 570 mm in length; all were five-layered.

Fig. 5. Industrial modified production of CLT ± 45° panels

Methods

Technical case study

The proposed method for CLT production is the result of an exploratory technical case study performed at an industrial CLT production line, where real events were investigated in their natural environment (David and Sutton 2016). Case study research can be a linear but iterative process, dealing with the technically distinctive situation in which the data points are fewer than the number of variables for the result in question (Yin 2009). This approach can be characterized by analyzing a single case in a variety of aspects

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involving a close, in-depth evaluation (Eriksson and Wiedersheim-Paul 2014), such as the modified production line described here.

Fundamental requirements were determined before the case study was performed. The manufacture of the modified CLT product should require that: (1) no more material than needed for conventional CLT production should be used, (2) all adhesive should be industrially applied, (3) the study should result in a product within the nominal requirements of the conventional production method currently in use on the CLT production line.

This case study focused on identifying suitable process modifications to the CLT production line. Decisions were based on input from multiple sources, including the manufacturing team's process expertise. Brainstorming processes with risk analysis were combined with decision trees in preparation for production and adapted to necessary technical realities prior to the definitive production.

Experimental Mechanics

Quasi-static compression testing to determine the properties of each sample followed the European standard CEN/EN 408 (2012). This standard is suggested for determining the stiffness and strength characteristics of CLT by the CLT standard CEN/EN 16351 (2015). The tests were performed at the RISE Research Institutes of Sweden (Fig. 6).
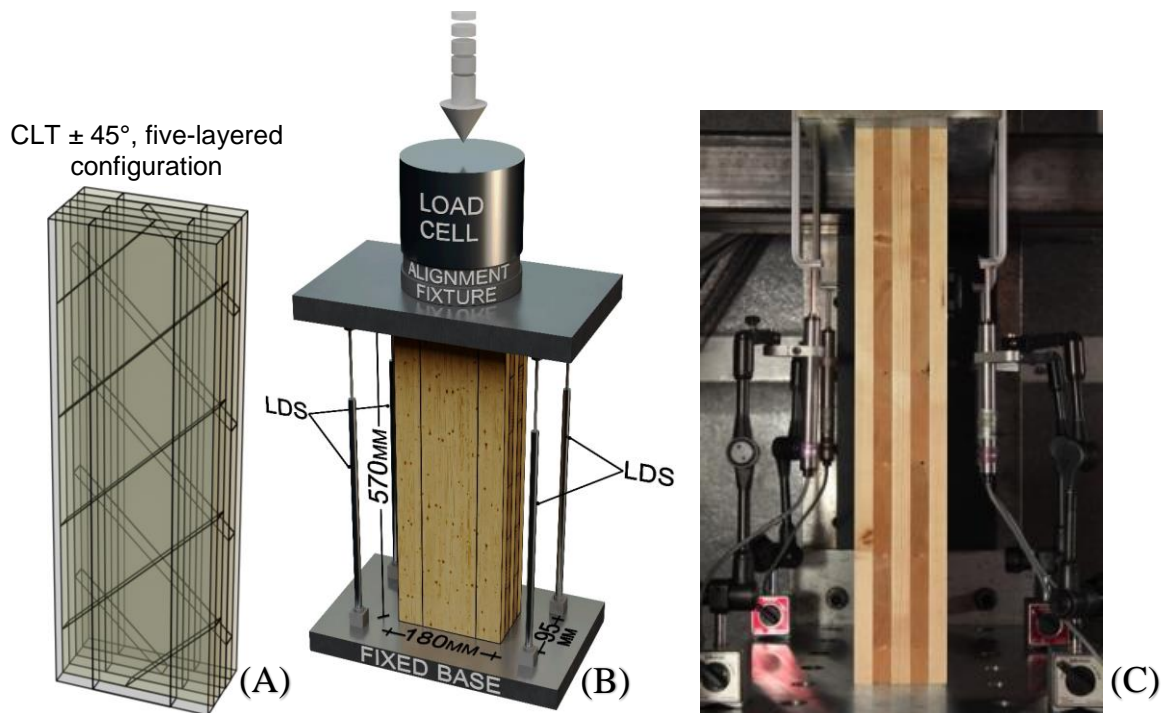

Fig. 6. (A) Layer arrangement of CLT ± 45, (B) uniaxial compression setup with four linear displacement sensors (LDS), and (C) an example of the equipment used for testing CLT 90°

All testing was performed in an accredited laboratory, and all devices were calibrated in conformity with the CEN/EN ISO/IEC 17025 (2005) standard. During the tests, the measurements were logged 100 times every second. The accuracy of the four 50-mm-long displacement sensors, which measured global displacement, was ± 0.04 mm. The

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displacement-controlled rate of the loading-head was 1 mm/min. The accuracy of the load cell LCHD was ± 0.20% with a 667 kN safe overload. According to Omega Engineering, Norwalk, CT, USA, the prescribed ultimate overload is twice this limit.

Samples were exposed to in-plane uniaxial compression parallel to the major panel orientation loaded along the length axis of the sample. The samples were placed between two rigid steel plates, one of which was locked spherically to the seated loading-head to counteract the compressive load and thereby avoid introducing bending.

Compression stiffness is presented here as the modulus of elasticity $E_{c,0,90}$ and $E_{c,0,\pm 45}$, while compression strength as $f_{c,0,90}$ and $f_{c,0,\pm 45}$. The evaluation followed the recommendations for conventional structural timber in the CEN/EN 408 (2012) standard. Compression stiffness was determined from displacement measurements taken along the full panel sample length of 570 mm. The length of each sample corresponded to six times its thickness of 95 mm; the dimensional relationship (Fig. 6) was according to the standard. The stiffness calculations were based on 10% and 40% of the ultimate load. The displacement was measured at the four axial sample corner edges and used as a weighted value for considering the parallelism, which can also be seen as an average. All stiffness and strength calculations were based on a combination of longitudinal and transverse layers as an average of the samples' cross-sectional area of 95 mm × 180 mm in accordance with CEN/EN 408 (2012).

An analysis of adhesive bondlines and adjacent wooden layers was conducted with a scanning electron microscope (SEM). The surfaces of CLT ± 45° were first examined in the center of the panel with a Nikon smz-1 optical stereozoom microscope at magnifications of 7–30× with 10× eyepieces (Nikon, Japan). Five samples from bondline sections with dimensions of 5 mm × 8 mm × 10 mm were further investigated by SEM. After coating with a layer of gold using a Denton Vacuum DESK II Cold Sputter/Etch unit (Denton Vacuum, USA), a JSM-5200 electron microscope (JEOL, Japan) was used for the analysis. The representative image shown in the Results section was taken at an accelerating voltage of 20 kV with 75× magnification. A SemAfore passive image digitizer (Insinööritoimisto Rimppi Oy, Finland) was used to acquire digital images from the SEM.

To further analyze the data, the Minitab statistical software package (Minitab Inc., Version 17, State College, PA, USA) was used. Mechanical property variations were presented to statistically quantify the results using standard deviation (SD), coefficient of variation (COV), and a confidence interval (CI) at the 95% confidence level. A normal probability test was performed utilizing the experimental data. The differences in the means and ± margins of error between the groups were calculated with two-sample CIs, which took into account different SDs at the 95% confidence level. A two-tailed t-test was applied to assess the significance of the difference between the groups.

To evaluate the results for values below 5% of the test results, the 5th lower one-sided percentile was used. This measurement value was regarded as an approximation of the characteristics of the samples and was based on the logarithmic sample mean value. Its value had an estimated probability within the prescribed 75% confidence level, in conformity with the established standard for the verification and calculation of characteristic timber structure values, CEN/EN 14358 (2006).

RESULTS AND DISCUSSION

The in-plane uniaxial compression properties of the two different types of layered panel groups CLT 90° and CLT ± 45° are summarized in Table 1. The evaluation metrics included compression stiffness $E_{c,0,90}$ and $E_{c,0,\pm 45}$ and the compression strength $f_{c,0,90}$ and $f_{c,0,\pm 45}$. As an approximation of the overall characteristics of both CLT types, the 5th percentile value is indicated to characterize their load-bearing capacities as construction materials.

Table 1. In-plane Uniaxial Compression Stiffness and Strength for 20 Five-layered CLT panels with Three 0° Longitudinal Layers and Two Alternating Transverse Layers at ±45° or 90°

Structural Compression Properties	Samples CLT 90°		Samples CLT ± 45°	
	Stiffness $(E_{c,0,90})$ (MPa)	Strength $(f_{c,0,90})$ (MPa)	Stiffness $(E_{c,0,\pm 45})$ (MPa)	Strength $(f_{c,0,\pm 45})$ (MPa)
Average	5533.0	26.3	7167.2	30.2
Standard Deviation (SD)	584.7	2.5	474.5	0.8
Coefficient of Variation (COV), %	10.6	9.5	6.6	2.6
Confidence Interval (CI)	440.9	1.9	357.8	0.6
5th percentile	4393.2	21.4	6230.4	28.5

In general, the modified CLT ± 45° offered increased higher stiffness and strength under compression compared to conventional CLT 90°. The average compression stiffness $E_{c,0,\pm 45}$ for CLT ± 45° was 30% higher and its COV decreased 37%; the 5th percentile value was 42% higher for CLT ± 45° compared to the conventional CLT 90°. The average compression strength $f_{c,0,\pm 45}$ for CLT ± 45° was 15% higher, and a 72% decrease in the COV was observed; thus, the 5th percentile value was 33% higher for the CLT ± 45° panels than for conventional CLT 90°.

In all cases, the SDs for CLT ± 45° were smaller than those for CLT 90°; the difference was especially sizeable relative to strength. These differences confirm that the expected increase in the homogenized mechanics of CLT ± 45°, from increased interaction between the 0° layers connected by the ± 45° layers, did occur. This is also indicated by the failure modes it exhibited. These interactions result from the added contribution from the ± 45° transverse layers, which act together to distribute the impact of inhomogeneous features.

Statistical Analysis

A statistical analysis of the two CLT groups revealed a statistically significant difference in the mechanical properties of CLT ± 45° and CLT 90°. The data were approximately normally distributed, allowing a two-sample 95% confidence interval (CI) test and t-test to be applied to indicate the magnitude of difference between the groups. The two-sample CIs are presented as difference in mean ± marginal error: The mean difference in stiffness was 1634.5 MPa ± 502.5 MPa ($t_{(17)}$ = 6.86; $P < 0.0005$), while the strength value was 3.9 MPa ± 1.8 MPa ($t_{(10)}$ = 4.73; $P = 0.001$).

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Failure Modes

The two CLT configurations displayed different dominant failure modes. The failure modes were more consistent for CLT ± 45°, but the different modes had a more combined appearance for CLT 90°. Three main failure modes were observed: (1) failure caused by crushing and axial splitting between layers near bondlines (Fig. 7); (2) crushing failure (Fig. 8A), which appeared in CLT 90°, and (3) shear failure, observed in CLT ± 45° as a 45° shear band in the 0° layers (Fig. 8B).

Shear bands like the one shown in Fig. 8B occurred in some cases as multiple shear bands across a ± 45° angle, creating a kink-band running across the width of the samples. A kink-band is an asymmetric, linear zone of deformation characterized by short folded limbs and hinge zones, occurring in some cases as conjugate sets (André *et al.* 2013). In clear Norway spruce wood, a characteristic kink-band formation developed at an angle of 23° (Poulsen 1998). In this case, the kink-band angle was at an angle of 45° in the 0° longitudinal layers because of the presence of the 45° layers; as a result, kink-band formation occurred in conjugate sets in the three 0° layers of CLT ± 45°.

In conjunction with the kink-band formation in the 0° layers, some extent of shear was observed along the grain in the ± 45° layers. The performed compression test in regard to the ± 45° angled layers introduced in-plane shear partly in the panel. This method has some similarities to a proposed compression test method for determining the in-plane shear of conventional CLT 90° panels, which were placed at an angle of 45° relative to the orientation of the load (Brandner *et al.* 2015).

Side view   Front view

Fig. 7. Uniaxial compression test sample: side and front views of crushing and axial splitting failure in the same CLT 90° sample
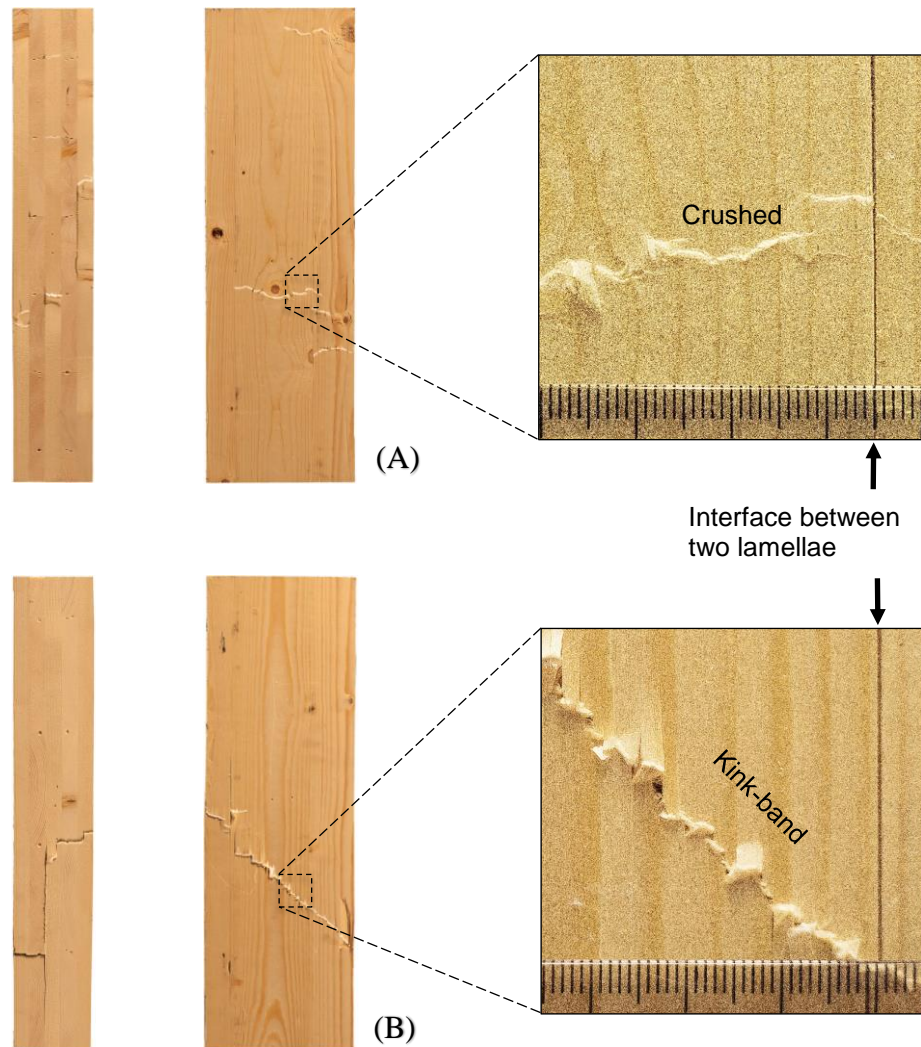
Fig. 8. (A) Compression test sample failure due to crushing in CLT 90°, with a millimeter scale. (B) CLT ± 45° sample exhibiting shear band failure known as "kink-band formation"

In general, no adhesive failure was observed in the bondlines, but failure zones were in some cases closely aligned along the bondlines, though not in the adhesive itself. Failure that propagated perpendicularly between different layers, directed by non-homogenous features, was only seen in cases where failure crossed the adhesive. If failure closely followed the bondline in the transverse layer, it could be related to orthotropic material dependency. However, since it also occurred in the longitudinal layer closely aligned to the bondline, further causes were considered. It was of interest to examine whether the jointer-transport-rollers for surface planing had any impact on the bonding quality (Jacobs and Lück 1989). No damage to the surface of lamellae from the jointer press rollers was detected by scanning electron microscopy; a representative bondline in CLT ± 45° is shown in Fig. 9. Another reason could be that the adhesive was too stiff and caused higher stress concentrations in the wood close to the bondline. It has been shown that an increased load-bearing capacity can be achieved in glulam with a more flexible bondline that allows active distribution of the load through the entire bonded area, reducing the stress concentrations (Gustafsson 2008).
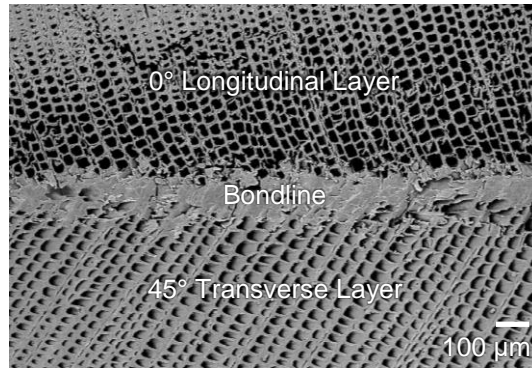
Fig. 9. Scanning electron micrograph of CLT ± 45° showing a 0° longitudinal layer bonded to a 45° transverse layer, with an intermediate bondline

Proposed Alternatively Angled Layered CLT Production Process

Based on the results from a temporarily modified industrial CLT production line, it is stated that CLT ± 45° can be produced in industry using the same material volume required to produce the same amount of conventional CLT 90°. A vital factor in this work was the ability to adjust the production-line cross-cut saw to cut the required lengths of lamellae at 45° for the transverse layers before assembling them into panels. Finger-jointing lamellae into a continuous, long lamella would contribute to simplicity in the process flow and such finger-jointing could be used for untrimmed lengthwise lamellae having different falling lengths from the sawmill (Fig. 10A). Thereafter, surface preparation would be completed by planing the longitudinal sides through a jointer (Fig. 10B). To use the same amount of material in the 45°-configuration as in the conventional 90°-configuration, the lamellae were continuously cross-cut at 45° (Fig. 10C) before they were assembled into a rectangular panel (Fig. 10E). Cutting the lamellae continuously at an angle other than 45° at the line was possible and would have resulted in use of the same amount of material. Performing the steps in the correct order from a material perspective is essential; there are a variety of possibilities depending on existing conditions. The order used in the production of adhesive-based CLT ± 45° differs from that used for the established dowel system (Fig. 3). To highlight a major difference, in the dowelled system the ends of the 45° transverse layer lamellae are cut by a CNC in the final step of assembly, leading to higher material usage.

Knowledge gained from this case study has suggested refinements in the production specifications. Bonding the narrow sides, as suggested in Fig. 10D, offers an alternative solution to the handling of the 45° lamellae, cross-cutting the layer length at 90° with the 45°-angled lamellae placed side-by-side (Fig. 10F). This step is based on the same idea as for the continuous 45° cross-cutting of individual lamellae going into the line (Fig. 7C). The procedure as it was performed required that the individual, shorter, 45° lamellae received support from a frame on the transporting conveyer-rubber-belt. In general, bonding of the narrow sides should lead to a more airtight and rigid CLT panel product. Subsequently, the narrow sides can be bonded by passing through on-line curing (Fig. 10E). When the full panel length has passed the 90° cross-cutting saw (Fig. 10F), the 45° panel can be rolled, depending on the final – or + 45° orientation (Fig. 10G). Adhesive can be applied on the flat wide surfaces (Fig. 10H) to build the panel layer-by-layer. Thereafter, the layers can be pressed together by pressure applied to all sides (Fig. 10I), followed by CNC sizing.

In summary, the proposed production procedure shown in Fig. 10 is as follows:

(A)   Finger-jointing for untrimmed lengthwise lamellae having different falling lengths from the sawmill
(B)   Planing of longitudinal sides in a jointer
(C)   Cross-cutting of lamella at 45°
(D)   Bonding the narrow sides
(E)   On-line curing, lamellae 45° placed side-by-side
(F)   Cross-cutting the 45° layer at 90°
(G)   Rolling of + 45° panel if in - 45° orientation
(H)   Application of adhesive on the flat surfaces to build the panel layer-by-layer
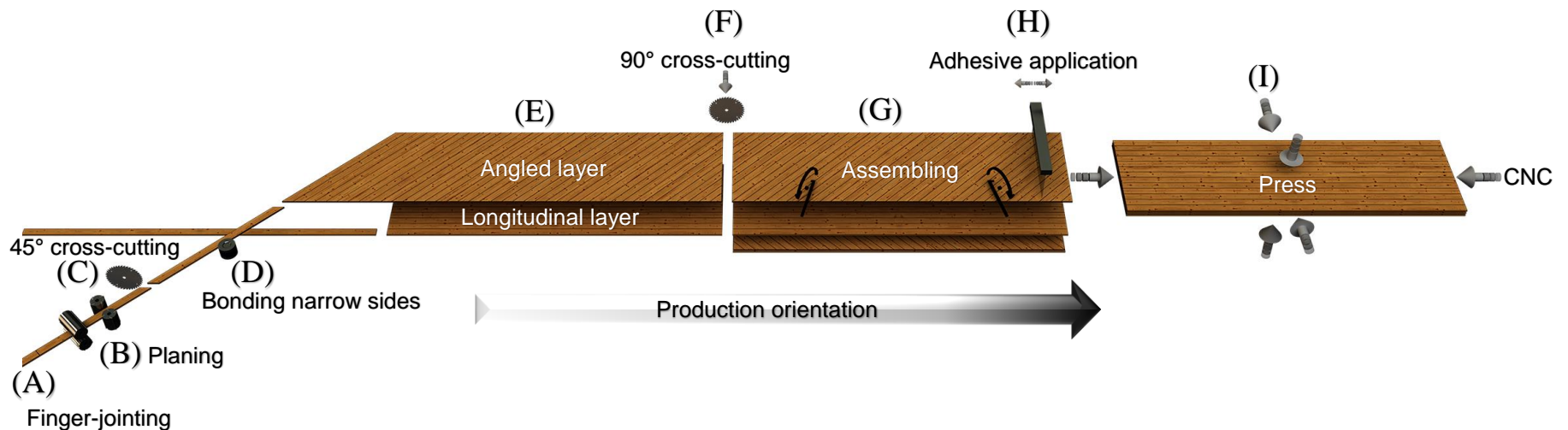(I)   Pressing by applying pressure in all transverse orientations

Fig. 10. Concise summary of modified CLT production: lamellae surface preparation, lamellae cross-cut sawn at 45°, adhesive assembly, pressing into panels, and finally, CNC-sizing of panels. This order resulted in use of the same amount of material required for conventional CLT 90° production. For a refined continuous process, (A) finger-jointing, (D) bonding the narrow sides of lamellae, and (F) cross-cutting the 45° layer at an angle of 90° are proposed

Implications

The greater stiffness and strength of CLT ± 45° panels with the same material volume offers the potential for increasing the load-carrying capacity exhibited by CLT 90°. Alternatively, the properties of CLT ± 45° panels make it possible to carry the same load using less material, creating the potential for CLT to be used in larger structures. The increased freedom in architectural design made possible by widened panel performance could help CLT capture market share from other structural design materials. CLT ± 45° is particularly suggested for use in areas that require increased shear resistance, for example, in the construction of shear walls to take lateral wind loads, as mentioned as a structural alternative for the load case described in the Introduction (*cf*. Fig. 2).

Timber construction contributes to the sustainability of the building sector (Asdrubali *et al.* 2016). Future structural design may choose CLT ± 45° because of its sustainability benefits and for its 5th percentile values that indicate its load-bearing capacity as a construction material. The findings of the current work should lead to the further development of CLT technology and increase its use in a broader approach based on timber panel construction. CLT ± 45° has potential as an alternative load-bearing building material, facilitating the construction of larger spans with less material and making it possible for a timber product to support larger loads.

The advantages inherent in CLT ± 45°, such as reduced inter-panel variability and increased shear resistance, will support the creation of more open structures, appropriate for both residential and commercial use. Implementing the proposed changes in the production method for CLT with ± 45° transverse layers will be a step towards providing this performance while using less material.

CONCLUSIONS

1. The performance of cross-laminated timber (CLT) panels consisting of either ± 45° or 90° transverse layers combined with 0° longitudinal layers (CLT ± 45° and CLT 90°), was evaluated for in-plane uniaxial quasi-static compression testing. Results from testing 20 five-layered CLT panels showed that the modified CLT ± 45° exhibits advantageous mechanical characteristics compared to conventional CLT 90°.

2. CLT ± 45° panels show a 30% increase in average in-plane uniaxial compression stiffness and a 15% increase in strength over conventional CLT. This increase in their load-bearing capacities was statistically significant; specifically, the 5th percentile values, indicating the load-bearing capacities as construction materials, were 42% higher for stiffness and 33% higher for strength, an advantage for CLT ± 45° over CLT 90°. In addition, CLT ± 45° had a smaller standard deviation, indicating it offers more predictable performance, an advantage for its use in constructions.

3. Three dominating failure modes were identified after ultimate load was reached: shearing, crushing, and a combination of crushing and axial splitting. Failure resulting from axial splitting and crushing of the internal layers was observed more frequently in CLT 90°. The main failure mode for CLT ± 45° was shearing, which occurred as a combination of kink-band formation in the 0° layers and in-plane shear along the grain in the 45° layers.

4. Based on results from a temporarily modified industrial CLT production line, it is evident that CLT ± 45° can be produced using the same volume of material required to produce the same amount of conventional CLT 90°. From the manufacturing process viewpoint, it was essential that the production line saw could be changed to cut at an angle of 45° instead of the regular 90° cutting angle before assembling. During production, the CLT ± 45° and CLT 90° panels were produced in an overlapping process that ensured material-matching conditions.

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