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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF CLT PANELS WITH DIFFERENT ORIENTATIONS OF TRANSVERSE LAYERS

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ABSTRACT

This paper presents an experimental and numerical investigation of two configurations of panels made of locally produced cross-laminated timber (CLT) with different orientations of laminations (boards) within transverse layers - conventional and modified orientation. Modified orientation refers to laminations of transverse layers positioned at an angle of ±45° in relation to longitudinal layers. The expected advantages of modified CLT are improved mechanical performance, more efficient use of resources considering material properties, reduction in variability of characteristics within the panels and increase in shear resistance. In addition to experimental testing, numerical analysis based on finite element method was performed and successfully validated in order to serve as a more efficient tool for CLT panel investigation and optimization.

KEYWORDS: CLT, conventional and modified layup, experimental test, FE model.

INTRODUCTION

Cross-laminated timber (CLT) is an innovative wood-based product which utilises advantages of wood as a building material such as light weight and sustainability, while overcoming its main disadvantages in terms of mechanical properties' variability and dimensional instability. CLT is produced in form of large-scale panels which contain multiple layers usually oriented perpendicularly which enables load-bearing in two directions. These panels are primarily used as floors and walls in mid- and high-raise buildings.

As CLT is becoming widely popular building material its optimization became focus of many scientific experimental and numerical investigations (He et al. 2018, Berg et al. 2019, Li et al. 2020, Ma et al. 2021, Shen et al. 2023). Optimization of CLT includes varying layup (Buck et al. 2016a, Ido et al. 2016), number of layers (Franzon et al. 2016, He et al. 2020), thickness of laminations (Pang and Jeong 2019, Kong et al. 2024) and reinforcement possibilities (Song et al. 2019, Li et al. 2023). One of the possible methods of optimization is positioning laminations of transverse layers at different angles in relation to laminations of longitudinal layers. The advantages of CLT panels modified in this manner are improved mechanical performance in the load-carrying direction (direction of fibres of longitudinal layers) and more efficient use of resources considering material properties. In addition, advantages associated with modified layup of CLT are reduction in variability of characteristics within the panels and increase in rolling shear resistance. Buck et al. (2016b) performed bending tests on CLT panels with two different configurations: modified - transverse layers at ±45° and conventional - transverse layers at 90°. The results indicated that bending strength increased for elements assembled with 45° layers in comparison with 90° layers, concluding that improved mechanical load-carrying properties could lead to a larger span length with less material. Arnold et al. (2022) investigated diagonal laminated timber with layers arranged at angles of ±45° and ±30° (±60°). The authors argued that the adjusted layup increases stiffness properties and provides ideal product properties for plates under biaxial bending. The results proved a considerable increase in torsional stiffness of diagonal laminated timber compared to conventional CLT, making the modified CLT an interesting option for floor systems which are governed by serviceability limit states such as deflections or vibrations.

In this paper, experimental research was conducted in order to determine stress-strain state of 5-ply CLT panels subjected to out-of-plane bending and to evaluate the effects of different orientations of laminations (boards) within transverse layers of the panels. This research is a part of larger investigation analysing different aspects of CLT panels, such as optimisation and reinforcement possibilities with the aim of improving vibration serviceability (Milojević et al. 2023, Simović et al. 2023, Todorović et al. 2023). All tested panels were produced from locally sourced spruce timber. Behaviour of CLT panels under serviceability and ultimate loads is described through load-deflection relationship, failure modes, load-carrying capacity, stiffness and strain distribution. Additionally, numerical modelling was performed to develop an efficient tool for analysing different CLT configurations.

MATERIAL AND METHODS

The experimental program included investigation of two configurations of 5-ply CLT panels with different orientation of laminations (boards) within transverse layers. A total of 10 panel specimens were tested – 5 specimens with conventional layup with orientation of laminations of transverse layers at an angle of 90° in relation to laminations of longitudinal layers (Series A) and 5 panels with modified layup with orientation of laminations of transverse layers at an angle of ±45° in relation to laminations of longitudinal layers (Series B). Fig. 1 and 2 show conventional and modified CLT layup considered in this paper. Series A testing procedure and results have been described in paper by Todorović et al. (2023). As in the case of conventional panels, modified panels were made of locally sourced softwood (spruce) classified in the strength class C24 according to EN 338 (2009). Dimensions of tested 5-ply CLT panels were 48 cm width × 400 cm length × 15 cm thickness. The cross-section of laminations (boards) was 12 cm width x 3 cm thickness.

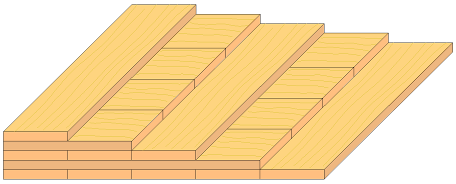

Fig. 1: *Conventional layup.*

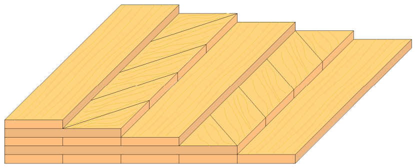

Fig. 2: Modified layup.

All production parameters were within the limits required by EN 16351 (2015). An industrial CLT production line was used to manufacture the panels, with process and production procedure being adapted in the case of panels with modified transverse layers.

The panels were tested in four point bending test in accordance with the requirements of EN 16351 (2015). The testing layout is given in Fig. 3.

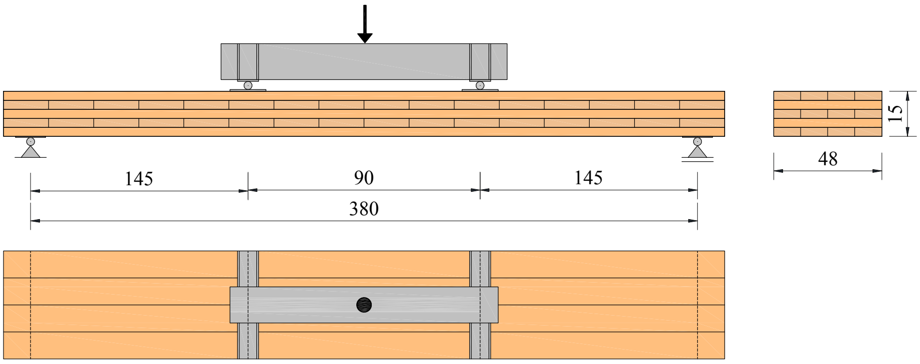

Fig. 3: Panel testing layout (dimensions in cm).

Same testing equipment was used for both series, including steel frame, hydraulic jack for load application, steel SHS for force transformation, steel roller bearings and plates for both supports and load application points. Steel roller bearings and plates provided that the load is transmitted and the panel is supported continuously in the transverse direction (across the entire width of the panel). Typical testing set-up is shown in Fig. 4.

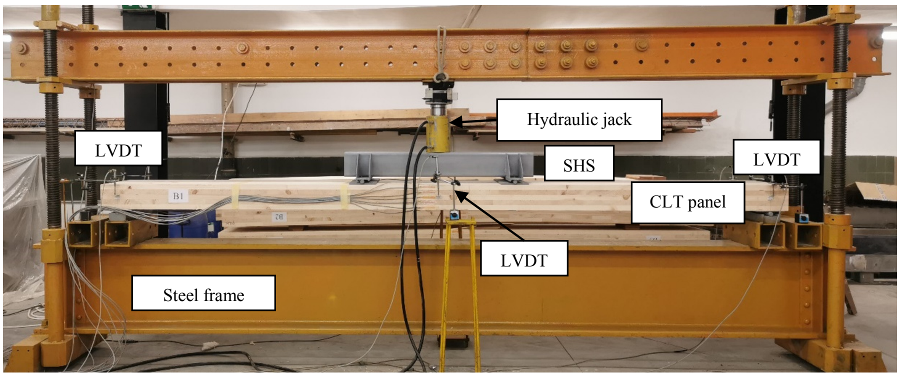

Fig. 4: Panel testing set-up (SHS – square hollow section, LVDT – linear variable differential transformer).

To ensure a valid comparison of the results, speed of load application was the same for both conventional and modified panels at 12 kN/min. All panels failed in approximately 5 min.

Loading cell, LVDTs and strain gauges were used to record applied load, deflections and strains. Acquisition system was used to collect these data. Arrangement of strain gauges of tested panels is given in Fig. 5. Parameters of the environment were controlled during testing (humidity 50 - 60% and temperature about 25°C). Timber moisture content in CLT panels ranged from 9.8 to 11.2 %.

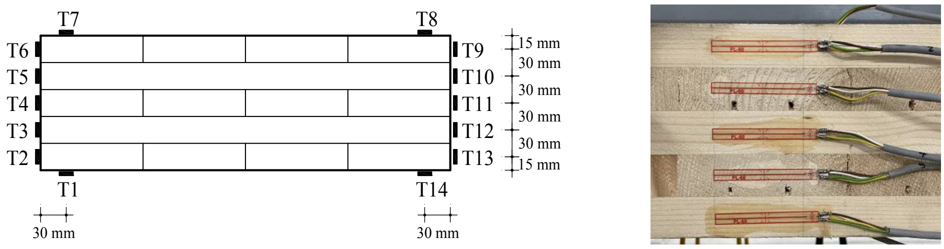

Fig. 5: Arrangement of strain gauges on panel's cross section.

In order to better understand stress-strain behaviour a simple numerical model of tested CLT panels was developed using finite element software Abaqus. Geometry of the panels, loading and boundary conditions were modelled so as to correspond to the experimental set-up. The CLT panels were modelled using S4R finite elements (4-node shell finite elements with reduced integration), with size of 30 mm. Composite layup was selected in section assignment to describe different longitudinal and transverse layers. Execution of the model involved a static small displacement analysis consisting of a series of vertical displacement-controlled increments applied at the loading points. Boundary conditions, position of the loading point and mesh of the FE model are shown in Fig. 6.

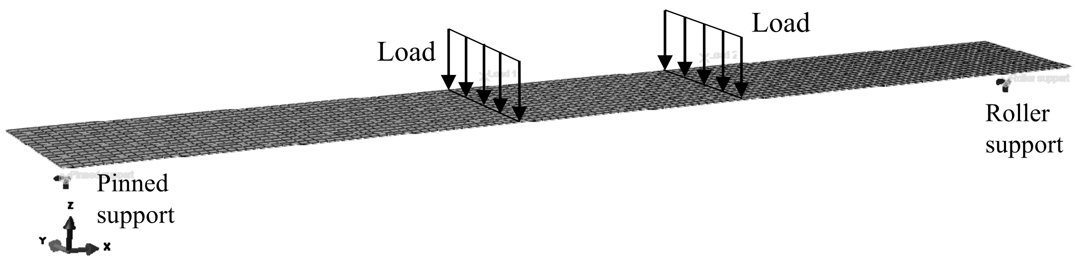

Fig. 6: FE model.

Timber was modelled as an orthotropic linear-elastic material. The material parameters (moduli of elasticity, shear moduli and Poisson's ratios) that describe the wood behaviour were taken for strength class CL24h given by Brandner et al. (2016) and based on values for softwood given by Bodig and Jayne (1982), shown in Tab. 1. Material orientation was defined to describe different behaviour depending on direction of wood grain.

Tab. 1: Wood material parameters for FE modelling

E_L* (N/mm^2)	**E_R* (N/mm^2)**	**E_T* (N/mm^2)**	**G_{LR}* (N/mm^2)**	**G_{LT}* (N/mm^2)**	**G_{RT}* (N/mm^2)**	**ν_{LR}** (-)**	**ν_{LT}** (-)**	**ν_{LT}** (-)**	**ρ* (kg/m^3)**
11 600	300	300	650	650	65	0.37	0.42	0.35	420

*Brandner et al. (2016); ** Bodig and Jayne (1982).

RESULTS AND DISCUSSION

Mechanical behaviour of tested conventional and modified 5-ply CLT panels was compared through load-deflection curves, failure modes, load-carrying capacity and deformability, bending stiffness values and strain distribution. Load-deflection curves are given in Fig. 7. Deflection values are the mean measurements of two LVDTs placed in the mid-span on both sides of the panels. As part of the experiment, deflections on the supports were also measured in order to monitor local deformations. Given that extremely small values (approximately equal to zero) were recorded, these deformations were excluded from further analysis.

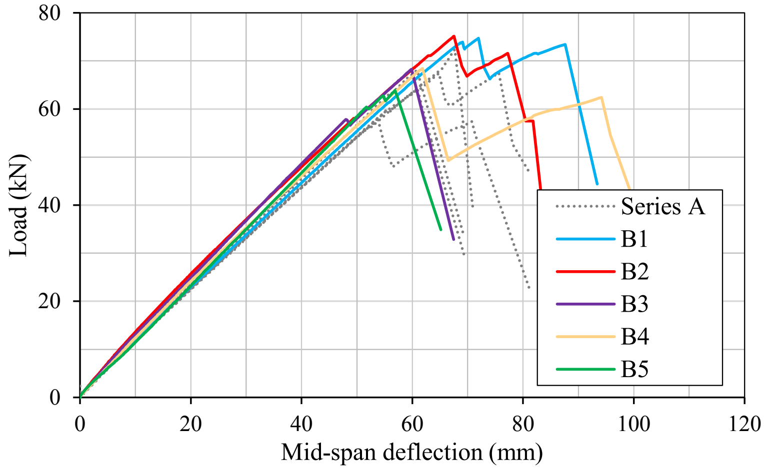

Fig. 7: Comparison of load-deflection curves for Series A and B.

Load-deflection behaviour of conventional CLT panels (Series A) is generally linear-elastic until sudden failure which occurred due to tensile failure of the bottom longitudinal layer. Detail description of Series A panels behaviour and failure mechanism is given in paper by Todorović et al. (2023). Typical failure mode of Series A panels is shown in Fig. 8. It can be seen that failure was initiated at knots or finger joints.

Fig. 8: Typical failure mode of Series A panels (specimen A2).

The out-of-plane bending behaviour of modified CLT panels (Series B) is essentially linear-elastic, with some ductility just before final failure. As in the case of conventional CLT panels, all specimens showed a somewhat similar failure mechanism, which is determined by the tensile strength of timber. Typical failure mode of Series B panels is shown in Fig. 9.

Fig. 9: Typical failure mode of Series B panels (specimen B1).

The initial fracture was caused by the presence of timber defects and finger joints within the outer longitudinal layer. This initial fracture in some panels did not mean immediate failure, but the panels continued to carry the load for a certain period of time until the ultimate failure. This phenomenon is observed in the load-deflection curves as a sudden drop and then a gradual increase in force. The ultimate failure was announced, which was not the case in Series A panels. Load-carrying capacity, as well as ductility, in the phase after the initial fracture, depends on shear crack path. Laminations of transverse layers at 45° acted as a bridge over local defects and thus enabled redistribution of load to the adjacent longitudinal laminations. This effect is not sufficiently pronounced due to concentration of knots in the adjacent laminations of the outer longitudinal layer, as well as due to no edge bonding of laminations. Signs of plastification in compression zone were not recorded in any of the tested specimens, as was the case in Series A.

The experimental and numerical results of maximum load, mid-span deflection at maximum load and at ultimate failure for tested panels are given in Tab. 2.

Tab. 2: Comparison of experimental and numerical results for Series A and B.

Specimen	Maximum load F_{max} (kN)	Deflection at max load w (mm)	Deflection at failure w_{max} (mm)	Bending stiffness EI_{global} (kN/mm^2)	Initial failure mode
A1	57.8	53.8	71.4	12.26×10^8	tension
A2	67.5	75.6	75.6	11.49×10^8	tension
A3	68.1	60.9	60.9	11.92×10^8	tension
A4	64.2	60.8	60.8	11.24×10^8	tension
A5	72.4	67.7	67.7	11.44×10^8	tension
Average EXP A	66.0 (CV = 8.3%)	63.8 (CV = 12.9%)	67.3 (CV = 9.7%)	11.67×10^8 (CV = 3.5%)	/
FEM A	61.9	58.0	/	11.27×10^8	/
FEM/EXP	0.94	0.91	/	0.97	/
B1	74.7	71.9	87.6	11.56×10^8	tension
B2	75.2	67.5	77.2	12.83×10^8	tension
B3	68.3	59.9	59.9	12.48×10^8	tension
B4	68.5	61.8	94.2	12.46×10^8	tension
B5	63.9	56.9	56.9	12.26×10^8	tension
Average EXP B	70.1 (CV = 6.8%)	63.6 (CV = 9.5%)	75.2 (CV = 21.9%)	12.32×10^8 (CV = 3.8%)	/
FEM B	66.2	58.1	/	12.01×10^8	/
FEM/EXP	0.94	0.91	/	0.97	/

Difference EXP B/A	**1.06**	**0.99**	**1.12**	**1.06**	/

CV – coefficient of variation.

Corresponding values for loads and deflections were read from experimentally obtained curves (Fig. 7). Experimental results of bending stiffness (Tab. 2) represent the out-of-plane bending stiffness calculated from global deflection of the panels, which reflects mechanism of both bending and shear deformations of CLT panels. Considering the applied experimental test set-up within this research (span-to-depth ratio) and load configuration that prevents rolling shear failure, the contribution of shear deformation is negligibly small (Li et al. 2023). Stiffness values determined only using measurements of "local" deformations show greater scatter than those calculated from "global" deformations due to local variability within CLT panels (Ridley-Ellis et al. 2009). Out-of-plane bending stiffness was calculated based on the slope of load-deflection curves for the linear-elastic region between 10% and 40% of the maximum load, in accordance with EN 408 (2012).

The mean ultimate load for conventional CLT panels (Series A) was 66.0 kN, with coefficient of variation of 8.3%. Test carried out on modified CLT panels (Series B) showed the mean ultimate load of 70.1 kN, with coefficient of variation of 6.8%. When comparing load-carrying capacity of the considered panel configurations, failure of modified CLT panels occurred at a higher load compared to the conventional CLT panels. If laminations of transverse layers are placed at angles less than 90°, such as 45°, there is a potential for better distribution of stresses along laminations of longitudinal layers, as well as for reducing variability of their characteristics. However, the recorded increase did not live up to the expectations, as it amounted to only 6.2%. At the same time, it is interesting to note that three specimens of Series B (B3, B4, B5) had lower ultimate load compared to the "strongest" specimen of Series A (A5). Certainly, this is not a reliable indicator of the effectiveness of the applied modification, because failure of CLT panels is largely conditioned by presence of wood defects and discontinuities.

In general, the modified CLT panels had higher deformations at ultimate failure than the conventional CLT panels. The increase in the mean mid-span deflection at failure was 12%. However, a large variation in deflection at failure for Series B (21.9%) is noticeable, which can explain premature failure and therefore absence of ductile behaviour of specimens B3 and B5.

The mean bending stiffness of Series A was 11.67×10^8 kN/mm^2, with coefficient of variation of 3.5%. Test carried out on modified CLT panels (Series B) showed the mean bending stiffness of 12.32×10^8 kN/mm^2, with coefficient of variation of 3.8%. The low coefficient of variation of the results recorded for both series indicates uniform quality of timber boards used for CLT panels. Placing laminations of transverse layers at an angle of 45° instead of 90° in relation to laminations of longitudinal layers led to an increase in bending stiffness of the panels by 5.6%. Since in timber modulus of elasticity perpendicular to the grain is significantly lower compared to modulus of elasticity parallel to the grain ($E_{90,mean} \approx 1/30\cdot E_{0,mean}$), it can be stated that the recorded increase is a result of greater contribution of transverse layers to bending stiffness. However, this effect is not significantly pronounced due to the position of transverse layers within the cross section of the panels (the centre of gravity of transverse layers is relatively close to the neutral axis of the section). In addition, no edge bonding of adjacent laminations of transverse layers has a certain influence.

As a comparison, Buck et al. (2016b) found that the ultimate load and global bending stiffness of CLT panels with 45° alternating transverse layers was increased by 35.0% and 15.5% in relation to 90° alternating transverse layers, respectively. This significant increase can be attributed to the fact that a better timber quality class was used and that the boards in panels contained no finger joints.

Comparison of strain distributions for tested CLT panels are given in Fig. 10. Compressive strains are negative and tensile strains are positive values on x-axis and they are mean values of the corresponding measurements on both sides of the panel. Position of strain gauges along the height is given on y-axis, measured from the lower edge of the cross-section. Strain distribution, both in conventional CLT panels (Series A) and in modified CLT panels (Series B), is quite linear up to failure, thus confirming the assumption of bending theory that plane sections remain plane during deformation. Strain profiles prove that there was no sliding between the layers. The modified panels showed insignificant improvement in strain values compared to conventional panels. Tensile and compressive strains are approximately the same at all load levels in both series.

Numerical simulations closely followed linear parts of the curves obtained experimentally, as presented in Fig. 11.

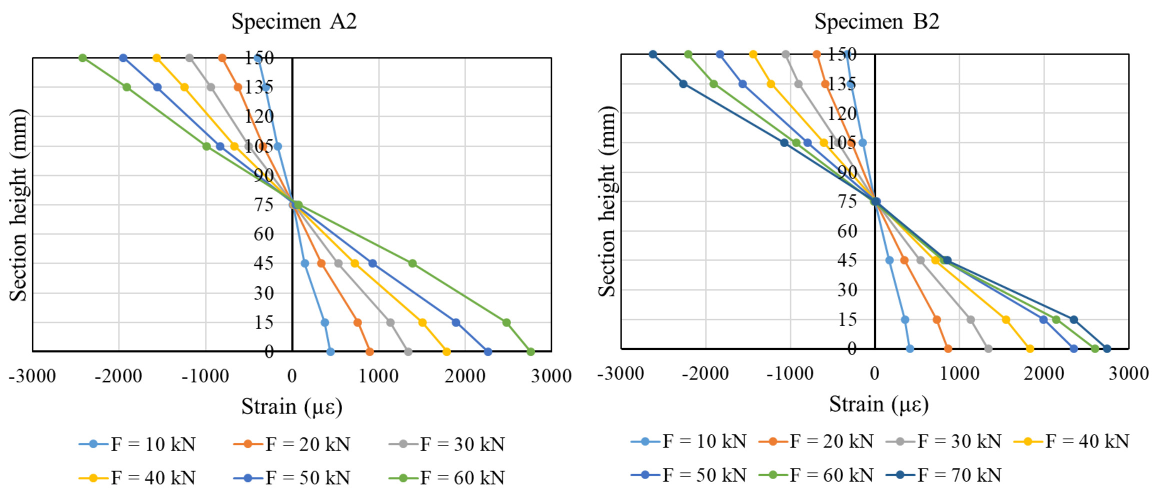

Fig. 10: Comparison of strain profiles for Series A and B.

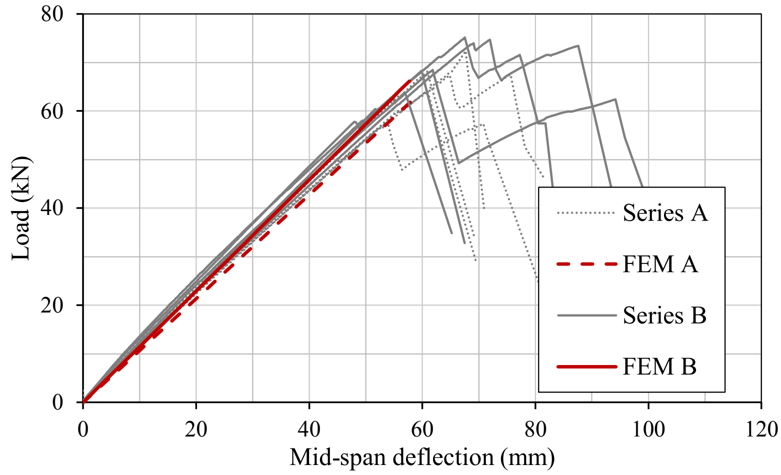

Fig. 11: Comparison of FEM and experimental load-deflection curves for Series A and B.

As all experimental panels primarily failed due to excessive tensile stress of bottom laminations, in the FE model failure was defined at the moment when computed stresses reached tensile strength of timber. Due to stress distribution effect in timber flexural members, tensile stress at failure is greater in bending than in axial tension. Hence, ultimate tensile stress was assumed to be equal to bending strength $f_{m,mean} = 31\ N/mm^2$ obtained after transformations from characteristic value for strength class CL24h (coefficient of variation for glulam of 15% and lognormal distribution according to JCSS Probabilistic Model Code (2006)).

Figs. 12 and 13 show contours of normal stresses in panels at ultimate load for both series. Distribution of normal stress σ_{11} at failure is presented in Fig. 14. It is obvious from the diagram that there is better utilisation of transverse layers in the case of modified series.

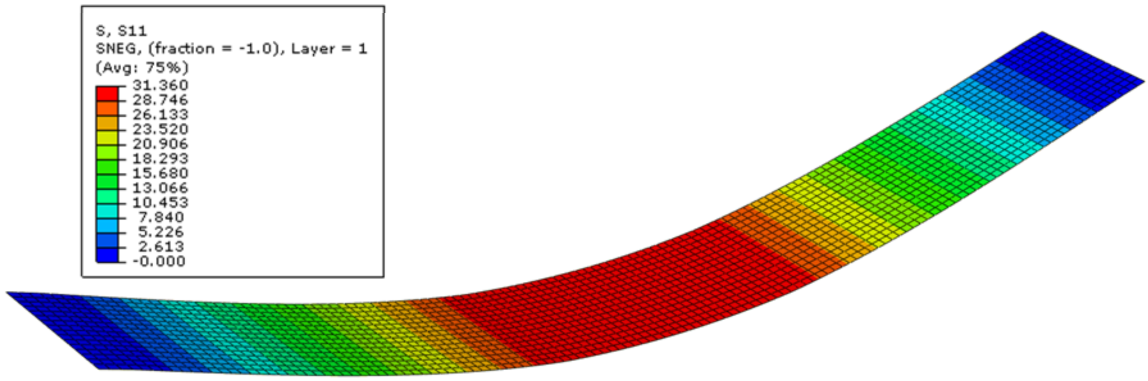

Fig. 12: Normal stress σ_{11} [MPa] at ultimate load for Series A.

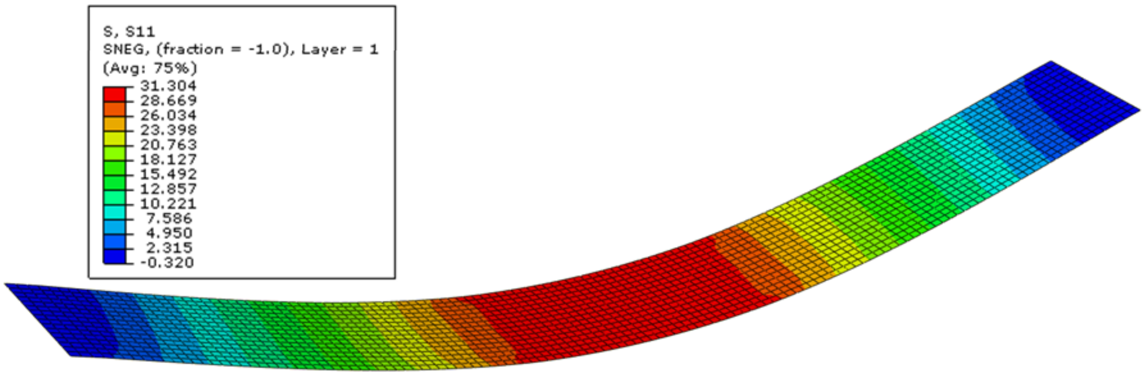

Fig. 13: Normal stress σ_{11} [MPa] at ultimate load for Series B.

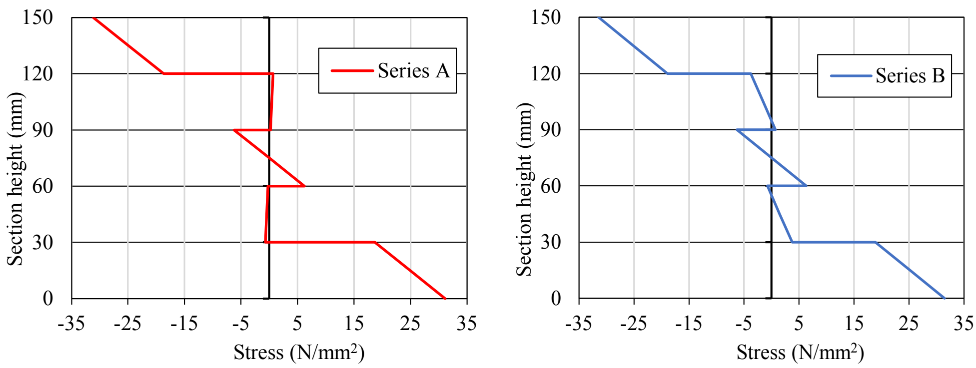

Fig. 14: FEM stress distribution at failure.

Results of the FE analysis showed good agreement in the case of both tested series, especially in terms of stiffness (differences 3 %). In the case of maximum load this discrepancy is a bit higher (around 6 % difference). This can be explained by the system strength being higher than strength of individual boards. This is especially pronounced for bending and tensile effect of CLT. However, as this is a very simple FE model, it can be useful for the preliminary analysis in further experimental testing of CLT panels with different loading arrangements, lamination layups and other modifications.

CONCLUSIONS

Based on the experimental tests on 5-ply CLT panels with different orientations of transverse layers subjected to out-of-plane bending following conclusions can be drawn: *1)* Behaviour of CLT panels is generally linear-elastic until failure. A certain degree of ductility immediately before the ultimate failure is possible in panels with modified layup. *2)* Failure of CLT panels, regardless of orientation of transverse layers, occurs due to fracture in tension zone. The fracture was initiated at wood defects (knots) or at finger joints of longitudinal laminations in the area of maximum bending moment. *3)* Placing laminations of transverse layers at an angle of 45° instead of 90° in relation to laminations of longitudinal layers leads to improvement in load-carrying capacity and bending stiffness of panels. The recorded increase in ultimate load of 6.2% and stiffness of 5.6% did not live up to the expectations. Whether this increase in properties is sufficient to justify modifications in production is left for further discussion. *4)* Contribution of transverse layers to stiffness of modified panels would be greater if larger number of layers were used (seven or nine instead of five). Increased stiffness of the modified CLT panels make it an interesting option for floor systems which are governed by serviceability limit states such as deflections or vibrations. *5)* Linear strain distribution of conventional and modified CLT panels was observed for different load levels until failure. Cross-sections remain plane even after deformation. There is no sliding between longitudinal and transverse layers of CLT panels. *6)* Simple linear finite element shell model was developed and successfully validated through comparison with the experimental results. This model can be a useful tool for analysing CLT panels with different loading arrangements, lamination layups and other modifications before performing experimental research which can be expensive and time-consuming.

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