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BENDING BEHAVIOUR OF CROSS LAMINATED TIMBER PANELS MADE FROM LOCALLY SOURCED SPRUCE WOOD

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ABSTRACT

Cross laminated timber (CLT) is relatively new engineering wood product made by gluing cross-wise layers of solid timber boards to form large-scale panels. Due to excellent in-plane and out-of-plane resistance, CLT panels have become very common as wall and floor structural elements. CLT is validated as an excellent alternative to more traditional construction materials like reinforced concrete and steel for use in single- and multi-storey buildings.

This paper presents an experimental study conducted on five-layer CLT panels manufactured using spruce boards. The panels were tested in four-point bending configuration, loaded in the out-of-plane direction. Bending behaviour of CLT panels in the major axis orientation was evaluated through failure modes, load-deflection relationship, ultimate moment capacity, stiffness and strain distribution profile. The obtained experimental results indicated brittle failure modes and linear load-deflection relationship up to failure. In addition, strain distributions of panels were quite linear during the entire loading, confirming the assumption that plane sections remain plane after bending.

Bending response of CLT panels was also investigated using finite element modelling. The stress and deflection analysis was executed in the RFEM software using the RF-LAMINATE module. The calculation was carried out according to the laminate theory, taking into account shear coupling of layers. A good agreement between the results of numerical model and experimental investigation was found.

Keywords: CLT, panel, bending test, FEM

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1. INTRODUCTION

Cross laminated timber (CLT) represents a massive engineering wood product made of multiple layers of alternating boards stacked together to form large-scale panels (Fig. 1). Each layer is usually oriented perpendicularly to the adjacent layer, with the exterior ones following the main bearing direction. Since timber is an anisotropic material, gluing laminations perpendicularly allows the panel to have better strength and stiffness properties in both directions compared to traditional timber. Number of laminations and thickness can be varied depending on the architectural requirements of specific building. However, CLT products are usually fabricated with an odd number of layers. Due to their excellent in-plane and out-of-plane resistance, CLT panels have become very common for walls and floors (Fig. 2), allowing for larger buildings to be built in timber. Advantages of CLT include: structural flexibility as it can be used for walls or floors of different spans; prefabrication which allows easy construction on site; sustainability as it is an eco-friendly material; low specific weight allowing easy manipulation and overall lighter structures; good insulation properties inherited from wood. Main disadvantages of CLT are lack of design standards and production cost which is still high compared to other materials.

Fig. 1. CLT panel

Fig. 2. CLT panels as wall and floor elements

With many mentioned advantages over traditional building materials, especially related to lower CO_2-emissions, CLT is becoming increasingly popular in the construction industry. Therefore, many authors have investigated mechanical properties of CLT panels in order to accurately comprehend their behaviour in mid- and high-rise timber buildings. Compressive strength was evaluated by Oh et al. [1] using a lamina-property-based model verified by CLT short column tests with a conclusion that compressive strength increases with the increase in the number of laminations. Effects of thickness of CLT panels made from Irish Sitka spruce on mechanical performance in bending and shear were investigated by Sikora et al. [2], who found that both bending strength and rolling shear decrease as panel thickness increases. Ido et al. [3] analysed effects of CLT width and lay-up on its tensile strength and concluded that the estimated tensile strength calculated using the Young's modulus of the lamination of each layer was found to be in good agreement with the measured tensile strength of CLT. Li [4] evaluated CLT rolling shear strength properties and found that lamination thickness significantly affects the rolling shear strength of CLT. He et al. [5] investigated bending and compressive properties of CLT panels made from Canadian hemlock and developed numerical models to predict bending stiffness and ultimate load carrying capacity of CLT panels calibrated using the experimental results. Ukyo et al. [6] tested rolling shear properties of CLT panels made from Japanese cedar, and concluded that rolling shear strength was highly correlated with the shear modulus. Bending and shear performance of Australian Radiata pine CLT was experimentally and numerically examined by Navaratnam et al. [7], who highlighted that shear strength decreases as thickness of the CLT panel increases. He et al. [8] experimentally and numerically evaluated bending, shear and compressive properties of CLT made of black spruce. They have shown that increasing the CLT thickness whilst maintaining identical span-to-thickness ratios can slightly reduce the bending strength, but can also slightly enhance the shear strength.

This paper presents an experimental and numerical study conducted on five-layer CLT panels. Experimental behaviour of CLT panels in the main direction was evaluated through failure modes, load-deflection relationship, ultimate moment capacity, stiffness and strain distribution profile. Bending response of CLT panels was also investigated using finite element modelling. The stress and deflection analysis were executed in the RFEM software using the RF-LAMINATE module.

2. EXPERIMENTAL PROGRAM

The experimental program included investigation of five CLT panels (specimens A1-A5). All panels were manufactured by the "Kolarević" Company from Pojate, Serbia. Panels were made of softwood (locally sourced spruce from area of Mt. Romanija) classified in the strength class C24 according to EN 338 [9]. Dimensions of tested CLT panels were 15 × 48 × 400 cm. The panels consisted of five layers made of laminations (boards) with approximate width of 12 cm and thickness of 3 cm. Longitudinal laminations were formed by joining the boards with finger joints. Transverse laminations did not contain joints. Melamine-urea-formaldehyde adhesive was used for finger joints and connecting longitudinal and transverse layers. Adjacent laminations within the layers had no edge bonding.

The experimental investigation was carried out at the Laboratory of Structures, Faculty of Civil Engineering, University of Belgrade. All panels were tested in bending as simply supported beams with a span of 380 cm (approximately 25 times the panel thickness) symmetrically loaded with two concentrated forces at a distance of 90 cm (6 times the panel thickness), in accordance with EN 16351 [10]. With this arrangement of forces, a constant bending moment was obtained in the middle part of the panels, without transverse force. Bending test configuration is given in Fig. 3. Testing of CLT panels was performed in a closed steel frame (Fig. 4). Load was applied using a hydraulic jack at a controlled rate of 12 kN/min in order to achieve panel failure in about 5 min. Load application was measured using a loading cell (HBM). The load was transformed from one concentrated force to two forces distributed along the panels' width using a steel box section with welded steel sheets at the points of force input. Steel roller bearings were used at the supports and at the load application points to ensure that the load acts vertically. Steel plates were placed under the roller bearings to minimize local indentations. Mid-span deflection was measured on both sides using two LVDTs (HBM W100TK, ±100 mm), positioned near the neutral axis, while deflection at the supports was measured on both sides using four LVDTs (HBM W20TK, ±20 mm). Strains were measured around the mid-span cross-section using strain gauges (TML PL-60-11, 60 mm long). Strain, deflection and corresponding load data were collected using the acquisition system (HBM MGC). Data acquisition was carried out with a frequency of 2 Hz.

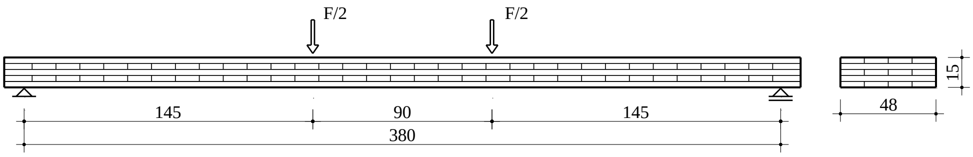

Fig. 3. Bending test configuration

Fig. 4. Test set-up

During testing, humidity and air temperature were measured. Humidity was between 50 and 60% and temperature was about 25 °C. The moisture content of timber was measured using a digital hygrometer at various points on the panel. Recorded moisture content in all specimens ranged from 9.8 to 11.2%.

3. EXPERIMENTAL TEST RESULTS

3.1. Load-deflection curves and failure modes

Load-deflection curves for all tested CLT panels are presented in Fig. 5. Displayed deflection values of each specimen represent the mean values of measurements of two LVDTs placed in the mid-span on both sides of the panels. CLT panels showed linear-elastic behaviour until failure. All experimentally tested specimens experienced failures due to excessive tensile stresses of the outer longitudinal layer.

Failure in tension zone is accompanied by pronounced shear cracks that extend along the glued line between outer longitudinal layer and adjacent transverse layer and/or through transverse layer. In addition, a combination of fibre tearing and rolling shear failure was also observed. Typical failure mode of CLT panels is shown in Fig. 6. Tension failure was initiated at wood defects (knots) or finger joints of longitudinal laminations in maximum bending moment area, between load application points. At the moment of failure, simultaneous fracturing of several laminations of longitudinal layers was observed in all specimens. None of the panels showed signs of plastification in form of timber fibres buckling in compression zone.

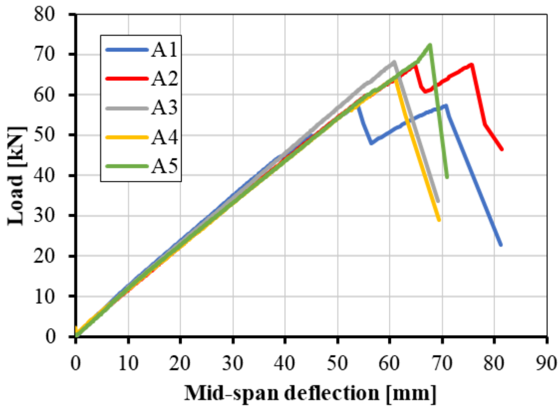

Fig. 5. Load-deflection curves of CLT panels

Fig. 6. Typical failure mode of CLT panels

3.2. Ultimate moment capacity, deformability and bending stiffness

For tested panels, the experimental results in terms of maximum load and ultimate moment capacity, as well as mid-span deflection at maximum load and at failure are given in Table 1. Based on ultimate load, the ultimate moment capacity M_u was calculated according to Eq. (1):

$$M_u = \frac{0.5 \cdot F_{max} \cdot a}{b} \tag{1}$$

where: F_{max} - maximum load; a - distance of the applied force from the nearest support; b - panel width. The mean ultimate bending moment for tested CLT panels was 99.7 kNm/m, with coefficient of variation of 8.3%. The difference between the minimum and maximum value (87.2-109.4 kNm/m) indicates a significant variability in strength of timber, which is expected since timber is a natural material. However, the recorded coefficient of variation for cross laminated timber is significantly lower than the coefficient of variation for glued laminated and solid timber (for bending strength it is 15-25%). This can be explained by the fact that wood defects are more evenly distributed and that the influence of each individual defect on strength of timber is significantly smaller (the so-called laminating effect). The mean mid-span deflection at failure was 67.3 mm. As expected, a higher variation of results was recorded for deflection at failure than for the ultimate moment capacity.

Experimental results of the out-of-plane bending stiffness for tested CLT panels are also given in Table 1. It was determined based on measurement of "global" deflection of the panels. "Global" deflection reflects mechanism of both bending and shear deformation of CLT panels. Due to high span-to-depth ratio ($l/h \approx 25$) of tested panels, which ensures the dominance of bending deformations, the influence of shear deformations in bending stiffness can be neglected. Bending stiffness was calculated based on the load-deflection curves' slope, for the linear-elastic region of behaviour between $0.1F_{max}$ and $0.4F_{max}$ according to the following Eq. (2):

$$EI_{global} = \frac{3 \cdot a \cdot l^2 - 4 \cdot a^3}{48 \cdot \left(\frac{w_2 - w_1}{F_2 - F_1} \right)} \tag{2}$$

where: EI_{gobal} - "global" bending stiffness; F_1 - load corresponding to 10% of the maximum load ($0.1F_{max}$); F_2 - load corresponding to 40% of the maximum load ($0.4F_{max}$); w_1 - mid-span deflection corresponding to the load F_1; w_2 - mid-span deflection corresponding to the load F_2; l - spacing of specimen supports (span); a - distance of the applied force from the nearest support.

The mean bending stiffness was 11.67 × 10^8 kNmm^2, with coefficient of variation of 3.5%. Low coefficient of variation indicates uniform quality of timber used for the production of the CLT panels.

Table 1. Experimental test results

Specimen	Maximum load F_{max} (kN)	Ultimate bending moment M_u (kNm/m)	Deflection at maximum load w_{corr} (mm)	Deflection at failure w_{max} (mm)	Bending stiffness EI_{global} (kNmm^2)
A1	57.8	87.2	53.8	71.4	12.26 × 10^8
A2	67.5	102.0	75.6	75.6	11.49 × 10^8
A3	68.1	102.9	60.9	60.9	11.92 × 10^8
A4	64.2	96.9	60.8	60.8	11.24 × 10^8
A5	72.4	109.4	67.7	67.7	11.44 × 10^8
Average	66.0	99.7	63.8	67.3	11.67 × 10^8
STDEV	5.5	8.3	8.2	6.5	0.41× 10^8
CV (%)	8.3	8.3	12.9	9.7	3.5

STDEV = standard deviation; CV = coefficient of variation

3.3. Strain distribution profile

Strains in the mid-span were measured for each specimen continuously. Due to wood damages, some strain gauges were not in operation after a certain load level, therefore those values were not considered in the analysis. Typical load-strain diagrams are given in Fig. 7. Since these are plate elements composed of longitudinal and transverse layers with no edge bonding of adjacent laminations, a certain discrepancy in strain values measured on both sides of the panels was recorded. Strain distribution was determined based on the values read from the load-strain diagrams and the position of strain gauges. Example of typical strain distribution at different load levels is also given in Fig. 7. The profile shows compressive and tensile strains on x-axis as negative and positive values, respectively, and the position of strain gauges along the panels' height on y-axis, measured from the lower edge of the cross-section. The given strain values represent the mean values of corresponding measurements on both sides of the panel.

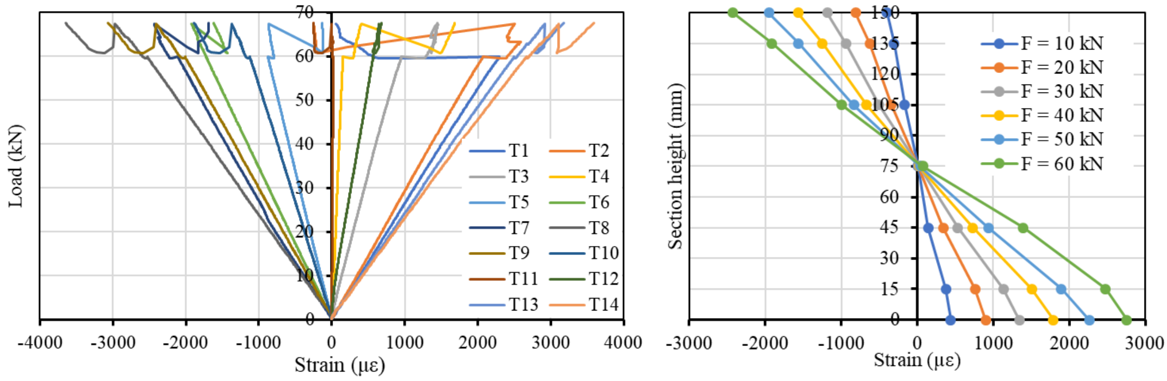

Fig. 7. Typical strain distribution of CLT panels (specimen A2)

Strain distribution is quite linear, confirming the assumption of bending theory that plane sections remain plane during deformation. Measured strains on longitudinal and transverse layers of CLT panels indicate that there is no sliding between the layers. Certain deviations that exist in strain values on transverse layers can be explained by the influence of end-grain area roughness to which strain gauge was glued. Although minor variations are noticeable immediately before reaching load-carrying capacity, when load is redistributed, it can be stated that strain values in tension and compression were approximately the same at all load levels. With load increase, no displacement of neutral axis position was recorded, confirming that wood plastification did not occur on the compression side.

4. FINITE ELEMENT MODELLING

In order to verify experimental results and better describe behaviour of tested CLT panels, numerical analysis was conducted using finite element modelling. There are several design-oriented programs that include layered materials such as CLT. In this study, commercial program RFEM (Dlubal Software GmbH) was selected for the analysis as it is often used for design of CLT structures in everyday practice. RFEM is a 3D finite element analysis software for structural analysis and design of members, surfaces, and solids. One of the biggest advantages of RFEM is its modular concept with add-ons that are integrated directly into the program. The add-on module RF-LAMINATE can be used to analyse the stresses and deformations of laminate surfaces [11].

4.1. Stiffness matrix of CLT panels

When modelling CLT in FE program, parameters required for the analysis can be given in various ways. The most commonly used method is to define the stiffness matrix for each element directly. Timber is an anisotropic material with three principal axes (longitudinal, tangential, radial), but it is usually considered as an orthotropic material in FE modelling. Due to the composition of CLT with several crosswise layers, it can be defined as orthotropic material with different properties parallel and perpendicular to the main direction of the panel. Hence, properties of each layer are used as an input for defining an orthotropic material and generating the stiffness matrix of CLT panel. Depending on whether CLT panel is used as wall or floor panel, it is dominantly loaded in its plane or out of its plane. Therefore, CLT wall panel behaves as a membrane (plane) element in which internal membrane forces (n_x, n_y, n_{xy}) occur as shown in Fig. 8, and CLT floor panel behaves as a plate element in which bending (m_x, m_y, m_{xy}) and shear (v_x, v_y) internal forces occur as shown in Fig. 9. The transverse layers of the panels have relatively low strength and stiffness properties, which affect the strength and stiffness of the overall cross-section. For CLT applications, the Mindlin-Reissner theory of thick orthotropic plates [12] is more relevant than the Kirchhoff theory of thin plates, since the transverse shear deformation cannot be ignored.

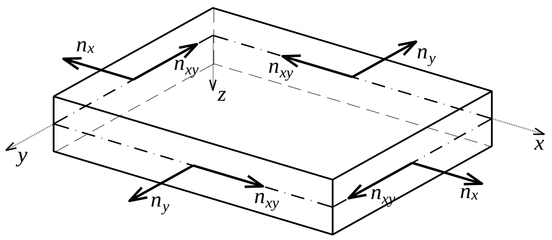

Fig. 8. Membrane internal forces

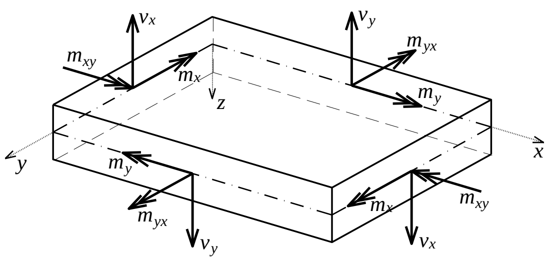

Fig. 9. Plate internal forces

CLT panel in real structures is loaded both in-plane and out-of-plane, thus combined behaviour should be considered through shell element, which is a combination of plate and membrane element. CLT panels as shell elements are applicable for the floors of a building which not only carry out-of-plane loads, but also act as diaphragms. Furthermore, the shell consideration is used in external walls that carry vertical loads and/or shear (in-plane loads) as well as horizontal wind loads (out-of-plane loads).

The relation between internal forces and strains for shell elements is presented in Eq. (3):

$$\begin{Bmatrix} m_x \\ m_y \\ m_{xy} \\ v_x \\ v_y \\ n_x \\ n_y \\ n_{xy} \end{Bmatrix} = \begin{bmatrix} D_{11} & D_{12} & D_{13} & 0 & 0 & D_{16} & D_{17} & D_{18} \\ & D_{22} & D_{23} & 0 & 0 & \text{sym.} & D_{27} & D_{28} \\ & & D_{33} & 0 & 0 & \text{sym.} & \text{sym.} & D_{38} \\ & & & D_{44} & D_{45} & 0 & 0 & 0 \\ & & & & D_{55} & 0 & 0 & 0 \\ & & \text{sym.} & & & D_{66} & D_{67} & D_{68} \\ & & & & & & D_{77} & D_{78} \\ & & & & & & & D_{88} \end{bmatrix} \cdot \begin{Bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \\ \gamma_{xz} \\ \gamma_{yz} \\ \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \tag{3}$$

The stiffness of a shell element is described by a [8×8] matrix. In this matrix four different sections are presented: bending and torsion stiffness (elements D_{11}, D_{12}, D_{13}, D_{22}, D_{23} and D_{33}) and shear stiffness (elements D_{44}, D_{45} and D_{55}) due to the plate action, membrane stiffness (elements D_{66}, D_{67}, D_{68}, D_{77}, D_{78} and D_{88}) due to the plane action, as well as the eccentricity effects (elements D_{16}, D_{17}, D_{18}, D_{27}, D_{28} and D_{38}). Main input parameters for calculation of these stiffness matrix elements are modulus of elasticity E_x and E_y, shear modulus G_{xy}, G_{xz} and G_{yz} and Poisson's ratios ν_{xy} and ν_{yx}. Common properties of CLT elements are that the board layers are arranged only orthogonally to each other and that the cross sections are symmetrical. These assumptions give the simplified form of stiffness matrix. The shear stiffness elements D_{44} and D_{55} can be treated with or without consideration of shear coupling of the layers in the CLT element. The effects of whether shear coupling is considered or not can be seen in Fig. 10.

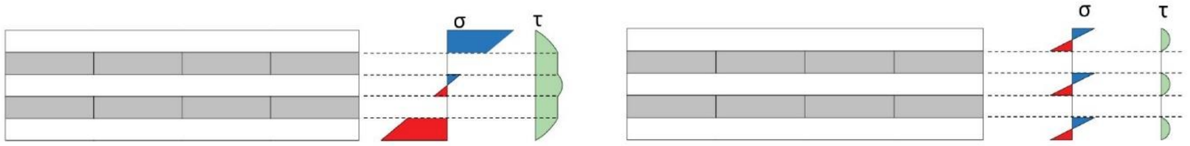

Fig. 10. Distribution of stresses including shear coupling (left) and excluding shear coupling (right) [13]

4.2. Numerical modelling of CLT panel in RFEM

As mentioned, numerical model of CLT panel was created in RFEM 5 software in combination with RF-LAMINATE add-on module. In the initial step, before incorporating RF-LAMINATE module, only general input parameters of the model need to be defined. CLT panel was modelled as a 2D surface without its composition and material properties. Geometry of the surface and support conditions were entered in accordance with experimental test set-up.

Since the service load of structures is considered to be 20-30% of the ultimate load, in numerical analysis the panel was loaded up to a force of 15 kN. This value is around 22.7% of experimentally obtained maximum load (average value). The load was distributed over two lines across the panel's width, with the resulting value of 15.625 kN/m. FE model of CLT panel in RFEM is presented in Fig. 11.

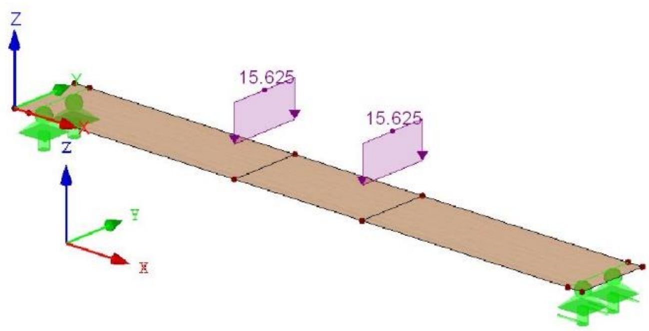

Fig. 11. CLT numerical model in RFEM

The RF-LAMINATE module can be run for the model defined up to this level. The calculation is carried out using the orthotropic material model according to the Mindlin-Reissner plate bending theory. At this point, load combinations for ULS (ultimate limit state) and SLS (serviceability limit state) are selected. The calculation is performed only for the implemented load, with partial factor for the variable action included in stress analysis.

After defining general data for calculation, composition and material properties should be assigned to the CLT panel. It is possible to define separately each layer's properties, such as thickness, orientation, modulus of elasticity, shear modulus, Poisson's ratios, material strengths etc. Also, there is an option to import layers from the library (database) of existing CLT manufacturers with all incorporated properties. When designing CLT elements, the material properties of the constituent boards are sometimes used. However, CLT elements are likely to have a slightly higher strength and stiffness as it is not just one, but several boards that are being bent or pulled at the same time (system effect) [14]. No strength classes have yet been developed for CLT, so calculations can be based on CLT's properties as set out in the

Technical Assessments of manufacturers. Input material properties of CLT used in numerical modelling are shown in Table 2.

Table 2. Composition and material properties of panel integrated in RF-LAMINATE module (KLH producer)

Layer	Thickness t (mm)	Direction β (°)	E_x (MPa)	E_y (MPa)	G_{xz} (MPa)	G_{yz} (MPa)	G_{xy} (MPa)	ν_{xy} (-)	ν_{yx} (-)
1	30	0	12000	0	690	50	500	0	0
2	30	90	12000	0	690	50	500	0	0
3	30	0	12000	0	690	50	500	0	0
4	30	90	12000	0	690	50	500	0	0
5	30	0	12000	0	690	50	500	0	0

Important options that still need to be considered when defining the material model are whether there is edge bonding of adjacent laminations and whether shear coupling of layers is taken into account. If there is no edge bonding, the modulus of elasticity perpendicular to grain can be neglected (E_y = 0). In addition, the transverse expansion of CLT is minimum and neglectable (ν_{xy} = ν_{yx} = 0) due to the reinforcing effect of the transverse layers [15]. Shear coupling should be included since it affects the behaviour of CLT and stress distribution across layers in the cross-section.

Using input data, RF-LAMINATE module creates the global stiffness matrix of CLT panel, according to the Eq. (2), by combining the stiffness matrices of each layer. Back in RFEM base module, this global stiffness matrix is used for calculating the internal forces which are then used in RF-LAMINATE module to calculate the stress distribution. Stress and deflection analysis is carried out in accordance with the selected standard (in this case Eurocode), thus providing stress and deflection design ratios of the panel.

4.3. Results of numerical modelling

To compare numerical with experimental results, load-deflection curve was determined for the implemented load with a step of 1 kN. Good agreement can be seen between the numerical and experimental results (Fig. 12). Given that the behaviour of the panel in numerical model is linear, the global bending stiffness of the panel is calculated as the slope of the curve. This leads to a global bending stiffness value of 11.14 × 10^8 kNmm^2, which is 4.54% less than the average value of the experimental results (11.67 × 10^8 kNmm^2). The variability of stiffness properties of timber layers was the reason for deviation between numerical and test results.

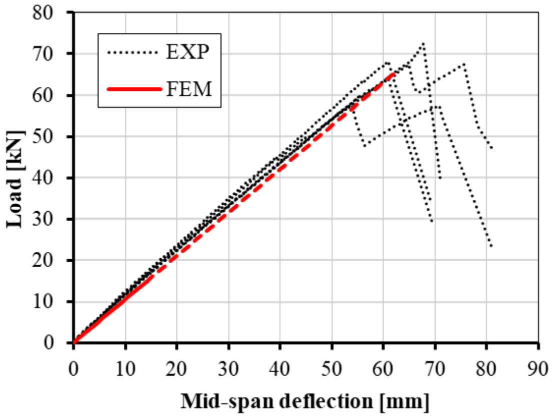

Fig. 12. Experimental (EXP) and numerical (FEM) load-deflection curves

By running the calculation in RF-LAMINATE module, the stress analysis is performed for every surface and material composition. Results can be read for each FE mesh or grid point and for each layer in the composition. For the load of 15 kN and relevant ULS load combination, distributions of normal and shear stresses are shown in Figs. 13-16. Rolling shear stress is one of the key design parameters affecting the performance of a CLT element. It is obtained that the maximum stress design ratio is 90%, which leads to the conclusion that CLT panel satisfies ULS requirements.

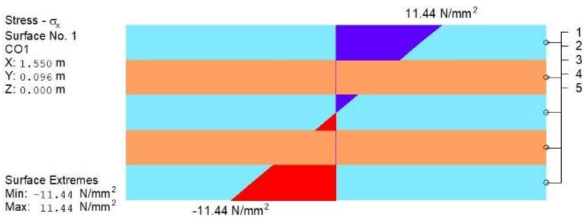

Fig. 13. Normal stress σ_x (for m_x = 33.98 kNm/m)

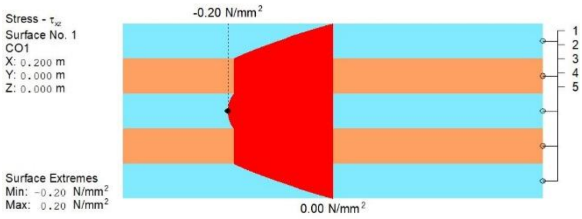

Fig. 14. Shear stress τ_{xz} (for v_x = 23.45 kN/m)

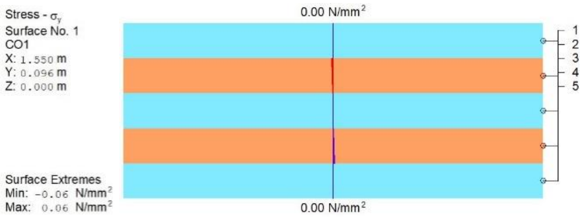

Fig. 15. Normal stress σ_y (for m_y = 0 kNm/m)

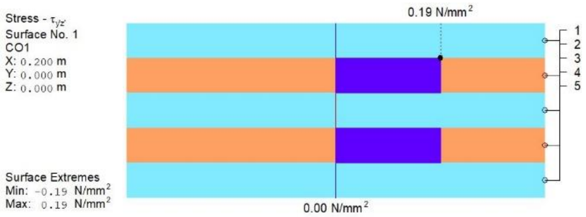

Fig. 16. Rolling shear stress $\tau_{y'z'}$ (for v_x = 23.45 kN/m)

Deformation analysis shows that a maximum value of mid-span deflection is 14.2 mm (Fig. 17). If the limit deflection value is taken as standardized *l*/300 (SLS criteria), it is equal to 12.7 mm. Limit value of mid-span deflection is then exceeded by 12%. Comparing with the average value of the experimental results (12.7 mm), finite element model gives larger deflection which can be explained by the design assumptions made during modelling. Calculated value of deflection is therefore on the safe side.

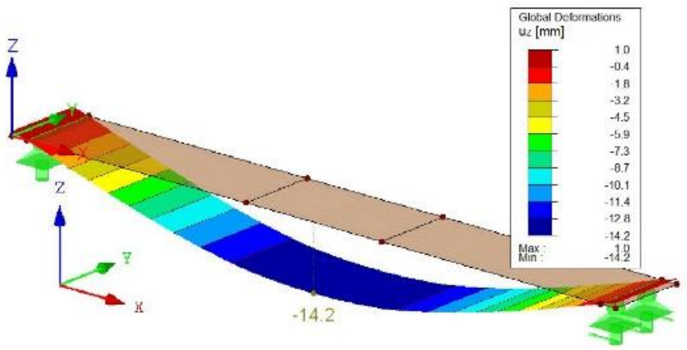

Fig.17. Deflection of the CLT panel corresponding to the load of 15 kN

5. CONCLUSIONS

In this paper, bending behaviour of five-layer CLT panels made from locally sourced spruce was investigated. Both experimental and numerical analysis were performed. Obtained results are valuable from both scientific and practical point of view, since the design of CLT structures has not yet been included in standards.

In the experimental study, five CLT panels were tested in four-point bending configuration. The panels exhibited quite linear load-deflection behaviour until the point of failure. The failure mechanism of these panels was characterized by tension failure initiated at weak points such as wood defects or finger joints in the outer longitudinal layer. Failure in tension zone was accompanied by pronounced shear cracks that extend along the glued line between outer longitudinal layer and adjacent transverse layer and/or through transverse layer. Experimental investigation has shown that the strain distribution was almost entirely linear up to failure, which confirms that plane sections remain plane during deformation. Also, this indicates that there was no sliding between the layers.

RFEM software and its add-on module RF-LAMINATE was used for FE modelling. CLT was modelled as an orthotropic material where each layer has its own material properties. Numerical calculation of panels was performed according to Mindlin-Reissner plate bending theory with considered shear coupling. Based on defined material composition, the global stiffness matrix of the panel is created in the RFEM software. It is possible to directly analyse stresses and deformations of multilayer panels. Instead of ultimate load, FE model of the panel was loaded with the assumed service load. Good agreement between experimental and numerical results was found. A slight discrepancy in the slope of load-deflection curve of numerical model was observed when compared to experimental results. This can be justified by the fact that mechanical performance of CLT panels depend on the combination of many factors. On the basis of the performed analyses, it can be concluded that RFEM software with RF-LAMINATE add-on module is successful in modelling CLT structural elements if accurate material properties are defined.

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