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A NUMERICAL MODEL FOR ANALYZING CROSS LAMINATED TIMBER UNDER OUT OF PLANE LOADING

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ABSTRACT

This paper targets the validity of a novel numerical model for analyzing CLT under out of plane loading. This numerical model was initially developed for determining the shear lag effect that appears in laminated thin walled composite beams. A parametric study was conducted in order to determine the influence of orientation of layers in CLT panels on bending strength and deflection. For confirming the accuracy of the proposed model, the results from the numerical model are compared with the external results of the computer software Ansys. The differences in bending stress vary from 0.27% to 1.69% depending on the orientation of layers and for deflection the differences are ranged from 2.25% to 7.42%. A numerical study was conducted and obtained data corresponds to results obtained from experimental study. It was concluded that the proposed numerical method can enough precisely predict the behavior of CLT under out of plane loading.

KEYWORDS: Timber engineering; finite element analysis; cross laminated timber; out of plane bending.

INTRODUCTION

Timber as a material is increasingly used in construction, mostly due to the ecological aspect and the fact that it is a natural material. Given that it has limited mechanical properties, in recent times there is an increasing use of CLT (Sandoli et al. 2021, Schenk et al. 2022, Velebil et al. 2020). It is an engineering product which is created by joining a certain number of layers of timber that are glued together. This product improves the mechanical and physical properties of solid wood (Brandner et al. 2016, Mestek et al. 2008). The stability of such constructions is improved; therefore, they can be used as structural elements without the need for reinforcing them with concrete or steel. Since its use is increasing, a European standard that refers this area has been published (EN 16351: 2015). In CLT, layers that are positioned in transversal direction are called cross layers. The specific of those layers is appearance of the rolling shear. The reason for that lies in the fact that the cross layers have lower shear modulus than the layers in other planes. Therefore, a shear deformation of CLT due to out of plane loads is higher comparing to other products made of wood, like glulam.

Various analytical methods are applied in order to determine the load capacity of CLT. These are the Shear analogy, k-method, Timoshenko and modified Gamma method (Kozarić et al. 2015, 2016). All of them are used for calculation of performances of CLT due out of plane loads. In CLT constructions whose ratio of span in relation to depth is larger than 30 (Li et al. 2020), K-method can be used, because this method does not take into account shear deformation, therefore it is suitable in case when shear deformation is small. The modified Gamma method is a method that partially takes shear deformations into account. The rigid connection of cross layer between two longitudinal layers is assumed in this method (Bajzecerová 2017). A slip factor is used to determine the shear deformation which appears in cross layers (Porteous et al. 2012). Shear analogy and Gamma method were used to investigate influences of low rolling shear modulus. It was concluded that due to shear deformation, modified Gamma method estimates lower deflection when compared against shear analogy method (Sandoli and Calderoni 2020). Shear analogy and Timoshenko methods are the most commonly used methods for determining the deflection in CLT (Christovasilis et al. 2016). In the Shear analogy method, CLT are considered as two beams that are joined with a rigid web, and the stiffness is calculated as the sum of the stiffness of every layer, taking into account their distance from the neutral axis (Jeleč et al. 2018). The Timoshenko beam theory represents a theory which takes into account the shear deformation of thick beams contrary to Bernoulli–Euler beam. The extension of the Timoshenko beam theory was presented by Thiel and Schickhofer (2010). They investigated out of plane behavior.

The CLT construction implies that the laminates are placed perpendicular to each other, which means that the layers are placed alternately in longitudinal and transverse order (Gagnon and Karacabeyli 2019). All the analytical methods mentioned above imply this type of CLT construction. However, since wood is an anisotropic material, it is possible to distribute the forces more favorably if the orientation of the fibers were varied. Buck et al. (2016b) performed a series of experimental compression and bending tests on CLT products with 45 alternating layers. Analysis of the results found that there was an increase in strength and stiffness in such panels compared to layers with 90 alternating layers.

In this study, finite element modeling (FEM) and experimental results conducted by Buck et al. (2016a) were used to investigate the accuracy of the proposed numerical method. The aim was to conduct the parametric analysis in order to define the deflection of CLT panels constructed of materials with different mechanical properties and layer orientation. The technique that had been used was confirmed throughout existing bending tests conducted on CLT panels.

MATERIALS AND METHODS

Finite element modeling

Effective stiffness, stresses and strains of three types simply supported floor CLT panels with 4.2 m span were analyzed. The height of the panel is 14 cm, and the thickness of every layer in panel is 34/19/34/19/34 mm (P1), then 30/25/30/25/30 mm (P2) and 28/28/28/28/28 mm (P3) (Fig. 1). In the analysis the angle of layers in minor direction varies from 0° to 90°, with the angle of 0° corresponding to the classical glued laminated wood, while the angle of 90° corresponds to conventional CLT.

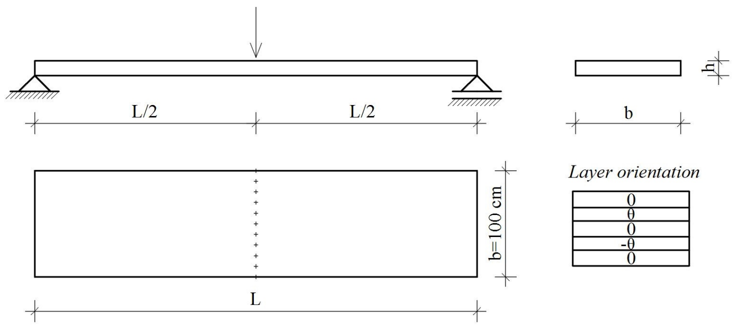

Fig. 1: Layer orientation, geometric characteristics of the CLT panels P1, P2 and P3 and scheme of loading.

Mechanical properties of the major and minor layers of floor panels are presented in Tab. 1. Shearing deformation is not taken into account because the relation of span/depth of the CLT panel is 30. The density of wood is 462 kg/m^3. Panels are loaded with imposed loads of 2 kN/m^{-2} and 55 kN/m^{-1} in midspan. Self weight of panels is included in calculation.

Tab. 1: Mechanical properties of the layers (EN 338: 2009).

Layers	Strength classes	f_m (MPa)	E_0 (MPa)	E_{90} (MPa)	G_0 (MPa)	G_R (MPa)
Major direction	C24	24	11000	370	690	69
Minor direction	C18	18	9000	300	560	56

f_m - bending strength, E_0 - modulus of elasticity parallel to the grain, E_{90} - modulus of elasticity perpendicular to the grain, G_0 - shear modulus parallel to the grain, G_R - rolling shear modulus.

A tensor of elasticity for anisotropic materials contains 21 independent material constants, but for CLT as an orthotropic material with three planes of elastic symmetry, the number of independent material constants is reduced to 9. The dilatation in the direction normal to the beam was ignored. Then, the following equation represents the relation between strain and stress (Jones 1999) in which elements in matrix can be defined if it is known Poisson`s coefficient, Yang's modulus of elasticity and orientation of fibers:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} \sigma_z \\ \sigma_s \\ \tau_{se} \\ \tau_{ez} \\ \tau_{zs} \end{bmatrix} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & 0 & 0 & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & 0 & 0 & \bar{Q}_{26} \\ 0 & 0 & \bar{Q}_{44} & \bar{Q}_{45} & 0 \\ 0 & 0 & \bar{Q}_{45} & \bar{Q}_{55} & 0 \\ \bar{Q}_{16} & \bar{Q}_{26} & 0 & 0 & \bar{Q}_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_z \\ \varepsilon_s \\ \gamma_{se} \\ \gamma_{ez} \\ \gamma_{zs} \end{bmatrix} \quad (1)$$

A computer program that has been developed based on the finite element method (FEM) and the lamination theory was used to calculate the relations in CLT panels. The program was previously used to determine shear lag effects in thin walled composite beams (Vojnić et al. 2019). The Fig. 2 shows a flow chart of developed computer program based on the FEM and stresses are determined through calculated unknown displacements.

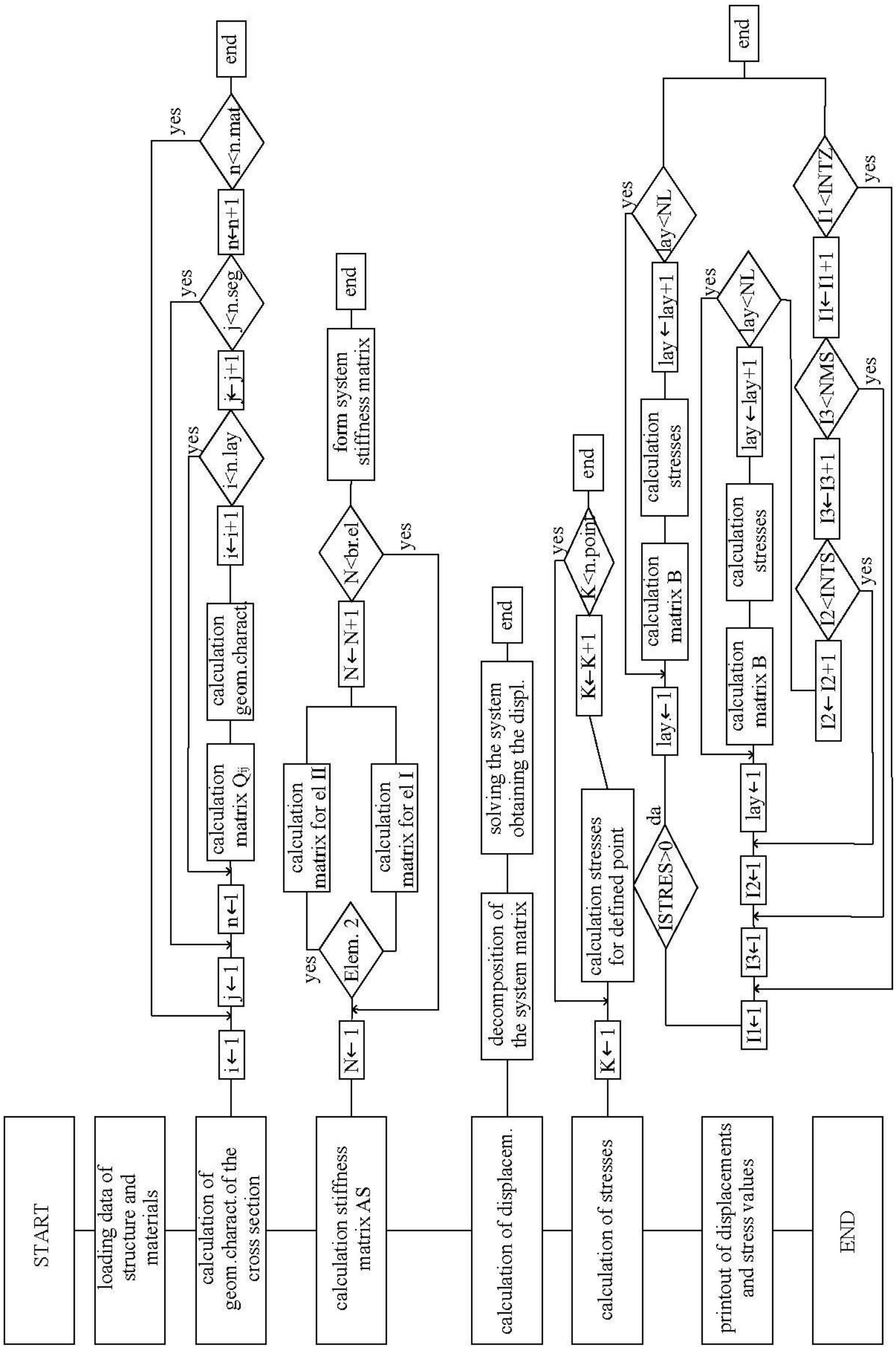

Fig. 2: Flow chart.

The software Ansys 18.0 was used for validation of results. The floor structure is modelled as a 2D laminated model with the thickness of layers as their third dimension. Structure modelling was performed using 4 node two dimensional SHELL 181 element from the Ansys library within stacking sequence, thickness and orientation of layers defined. The SHELL 181 element has four nodes and in every node there is a six degrees of freedom, three translations and three rotations. Modulus of elasticity, Poason's coefficient and density of wood represent the basic input data. The size of final element is 0.125 x 0.10 m (Fig. 3). The density of the mesh was determined by the iterative procedure by passing through the moment until the results of the two successive steps did not differ less than 1%.

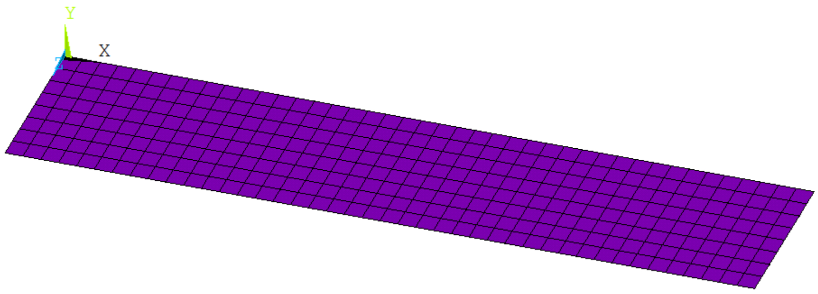

Fig. 3: Nodes and finite elements arrangement for the CLT panel P1 in ANSYS R18.0.

The experimental bending and compression tests

The experimental bending and compression tests on CLT panels were conducted by Buck et al. (2016a). The test was performed on 20 samples. Ten samples with orientation of layers for 90° in the transverse direction and ten samples with orientation of layers for 45°. European Norway spruce was used for experimental study. Mechanical characteristics of the structural timber are: strength class LS15, quality class Q61 in accordance with EN 14081: 2011 and corresponding to C24-grade (EN 338: 2009). The samples used in experimental investigation had average moisture content of 8%. It is determined by the oven dry method according to EN 13183: 2003. The average density was 462 kg/m^3 according to ISO 3131: 1975. The dimensions of the specimens were 95×590×2000 mm.

RESULTS AND DISCUSSION

The effective stiffness of conventional CLT panels with 0/90/0/90/0 layer orientation was calculated using the Gamma method (EN 1995-1-1: 2016), K method, Kreuzinger's analogy and exposed analytical method (Tab. 2). For the other layer orientations only proposed numerical method is applicable.

Tab. 2: Effective bending stiffness of the CLT panels with 0/90/0/90/0 layers orientation (kNm^2).

Type of panel	γ-method	K-metod	Kreuzinger	Numerical model
P1	2087	2218	2218	2217,57
P2	2069	2082,88	2082,88	2082,88
P3	1990,60	2006,41	2006,41	2006,41

Maximum stress and mid-span deflection for all types of CLT floor panels and layer orientation was calculated using the Eq. 1 and the moment-area method respectively. All calculated values were compared with results obtained in Ansys (Tab. 3).

Fig. 4 shows the Ansys calculation results for stresses in the CLT panel P1 with 0/75/0/75/0 layer orientation. Tab. 3 shows the comparative analysis of the results obtained by parametric study of proposed numerical model and Ansys computer software.

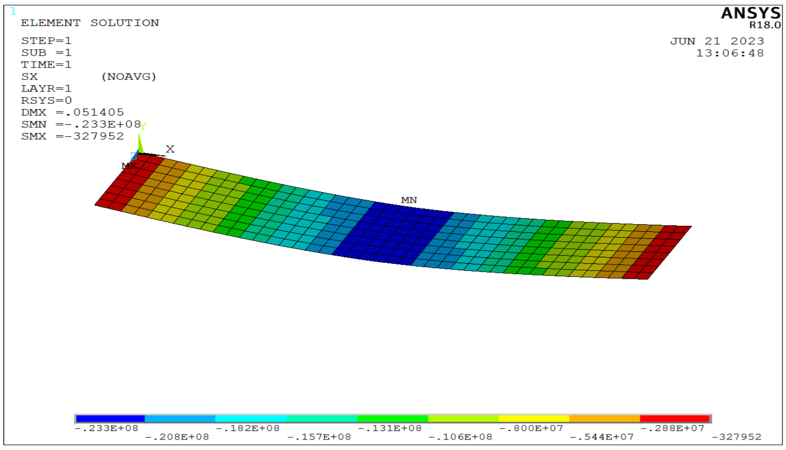

Fig. 4: Stress of the CLT panel P1 with 0/75/0/-75/0 layer orientation.

Tab. 3: The maximum stress and deflection of the CLT panels.

θ (deg)	Calculation method	P1		P2		P3	
		σ_m (MPa)	f (mm)	σ_m (MPa)	f (mm)	σ_m (MPa)	f (mm)
0	Numerical model	21.25	4.21	21.56	4.27	21.71	4.30
	Ansys	21.04	4.31	21.14	4.36	21.39	4.39
	Differences (%)	**1.01**	**2.32**	**1.99**	**2.06**	**1.51**	**2.05**
15	Numerical model	21.90	4.34	22.12	4.38	22.33	4.42
	Ansys	21.50	4.44	22.05	4.57	22.39	4.65
	Differences (%)	**1.86**	**2.25**	**0.33**	**4.16**	**0.27**	**4.95**
30	Numerical model	22.83	4.52	23.55	4.67	24.26	4.81
	Ansys	22.32	4.68	23.36	4.92	24.01	5.08
	Differences (%)	**2.28**	**3.42**	**0.80**	**5.08**	**1.03**	**5.31**
45	Numerical model	23.46	4.65	24.66	4.89	25.24	5.00
	Ansys	22.93	4.87	24.25	5.19	25.08	5.39
	Differences (%)	**2.31**	**4.51**	**1.67**	**5.78**	**0.67**	**7.23**
60	Numerical model	23.54	4.67	24.95	4.94	26.02	5.16
	Ansys	23.24	5.01	24.69	5.37	25.59	5.58
	Differences (%)	**1.27**	**6.79**	**1.07**	**8.01**	**1.69**	**7.53**
75	Numerical model	23.82	4.72	25.18	4.99	26.12	5.18
	Ansys	23.33	5.09	24.83	5.47	25.76	5.70
	Differences (%)	**2.11**	**7.27**	**1.44**	**8.78**	**1.41**	**9.12**
90	Numerical model	23.87	4.74	25.27	5.01	26.18	5.19
	Ansys	23.34	5.12	24.84	5.51	25.78	5.74
	Differences (%)	**2.22**	**7.42**	**1.72**	**9.07**	**1.53**	**9.58**

θ - angle of layers, σ_m - maximum bending stress, f - midspan deflection.

The results of bending stress and deflection differ up to 10% for all types of CLT panels and layer orientation. More precisely the results for maximum stress vary up to 2.31% and the results for deflection up to 9.58%. The result difference varies depending on whether the maximum bending stress or midspan deflection is analyzed. If the analysis of the results excludes the case when all layers are oriented in the same direction, in CLT panels of type P1, P2 and P3, the smallest error in the calculation of the maximum bending stress is at 0/60/0/-60/0, 0/15/0 /-15/0 and 0/15/0/-15/0 layer orientation, respectively. When calculating the midspan deflection, the smallest error for all panel types is at the 0/15/0/-15/0 layer orientation, where the proposed numerical model in all cases gives lower midspan deflection values compared to the results obtained by Ansys computer software, which in in the case of maximum bending stress calculations, this is not the case.

Fig. 5 shows load in relation to global displacement of experimentally tested specimens and also results obtained by proposed numerical method. Observing the results shown in Fig. 5, the conclusion is that proposed numerical method gives high accuracy results in relation to the result obtained by experimental tests.

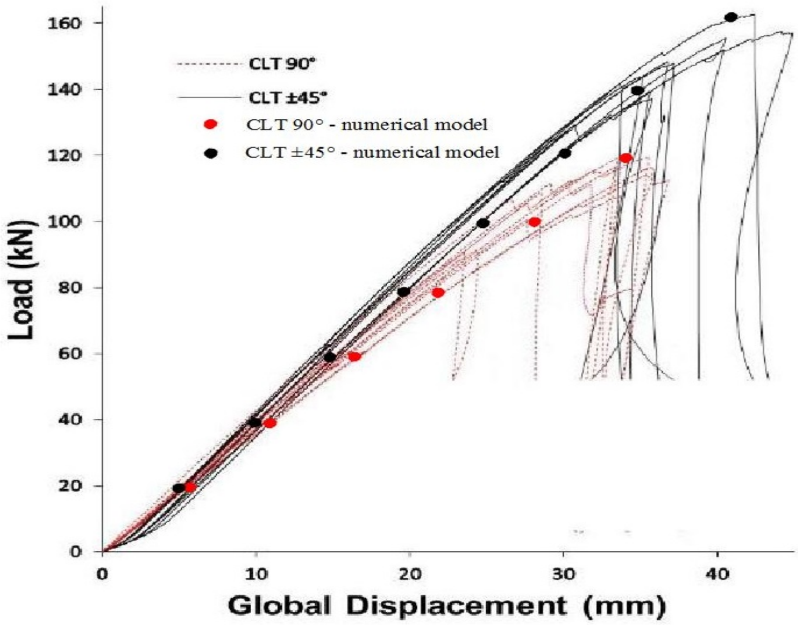

Fig. 5: Comparison of four point bending behavior of investigated samples (Buck et al. 2016b) and numerical model results.

CONCLUSIONS

The numerical model for calculation of deflection and stresses under out-of-plane bending has been proposed. A parametric study was conducted in order to determine the influence of orientation of layers in CLT panels on bending strength and deflection. The results obtained from numerical model are compared with the external results of the computer software Ansys in order to confirm the accuracy of the proposed model. Observing the results that show maximum stress, it can be concluded that the smallest difference in results is for the panel which has the same thickness of every layer. The differences in stress vary from 0.27% to 1.69% depending on the orientation of layers. The situation is different when observing deflection. In that case, the smallest difference in results is for the panel with major layers much thicker than the layers in minor direction, and it varies from 2.25% to 7.42%. Another confirmation of the accuracy of the proposed model is a comparison of the results obtained by the proposed model with the results obtained through previously published experimental results. The total displacement in relation to the magnitude of the force was compared for two types of panels with different layer orientations. The results obtained by proposed numerical model and experimental data are very highly correlated. The proposed model is suitable to predict the behavior of CLT floor systems through presented numerical parametric study.

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