

Finite Element Analysis of Dynamic Characteristics and Bending Stiffness for Cross Laminated Timber Floor Panels with and without Openings

Analiza dinamičkih obilježja i krutosti pri savijanju podnih ploča od križno lameliranog drva provedena metodom konačnih elemenata

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ABSTRACT • The aim of this paper is to present numerical investigations of dynamic characteristics and bending stiffness for cross laminated timber floor panels with and without service openings. Five-layer panels with the outer layers oriented in the longitudinal direction of the panel have been analyzed. In order to explore the full potential of this floor system using a limited number of measurements and structural tests, models based on the finite element method have been proposed, validated against experimental results and then used to investigate the effect of opening position in the floor on main structural performance parameters. The results showed that, when the need for additional service opening appears, a slight decrease of the main structural characteristics of the cross laminated timber floor panels is achievable with an adequate geometrical position of the opening in the floor.

Keywords: cross laminated timber floors; bending stiffness; floors with openings; finite element analysis

SAŽETAK • Cilj ovog rada jest prikaz numeričkog modela dinamičkih obilježja i krutosti pri savijanju podnih ploča od križno lameliranog drva (CLT) sa servisnim otvorom i bez njega. Analizirane su peteroslojne ploče s vanjskim slojevima orijentiranim u uzdužnom smjeru ploče. Kako bi se uz pomoć ograničenog broja mjerenja i mehaničkih ispitivanja istražio puni potencijal takvoga podnog sustava, predloženi su modeli utemeljeni na metodi konačnih elemenata koji su validirani u usporedbi s eksperimentalnim rezultatima te primijenjeni za istraživanje utjecaja položaja otvora u podu na glavne parametre ponašanja konstrukcije. Rezultati su pokazali da se odgovarajućim pozicioniranjem naknadnog otvora u podu može postići vrlo malo smanjenje glavnih mehaničkih svojstava podnih ploča od CLT-a.

Ključne riječi: podne ploče od CLT-a; krutost pri savijanju; podovi s otvorima; analiza metodom konačnih elemenata

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1 INTRODUCTION

1. UVOD

Cross laminated timber (CLT) is a sophisticated modern product that has greatly improved the load-bearing capacity of traditional wood as building material. CLT was first developed and used in Germany and Austria in the early 1990s and has been gaining popularity ever since (Blass and Fellmosser, 2004; Laguarda-Mallo and Espinoza, 2014; Espinoza *et al.*, 2016). It is increasingly used in construction applications such as floors, walls, beams and has the potential to replace concrete, masonry, and steel in some applications (Pei *et al.*, 2016; Wei *et al.*, 2020). CLT now has a global reach, with many large buildings erected using this material (Cvetkovic *et al.*, 2015; Popovski and Gavric, 2016).

CLT elements are mainly used for walls and floor structures. If used as shear walls in buildings, in-plane stiffness is an important consideration. In-plane loading for CLT has been extensively studied in the literature (Shahnewaz *et al.*, 2017; Wang *et al.*, 2018; Danielsson and Serrano, 2018; Song *et al.*, 2019). Considering the fact that the out-of-plane stiffness is important for floors, many researchers conducted out-of-plane loading tests and proposed new design procedures (Park *et al.*, 2003; Minjuan *et al.*, 2018; Okabe *et al.*, 2018; Song and Hong, 2018; Pang and Jeong, 2019; Crovella *et al.*, 2019). Its dynamic behavior is another characteristic, important for the serviceability of these structures, extensively studied in the literature (Damme *et al.*, 2017; Ussher *et al.*, 2017; Casagrande *et al.*, 2018; Kozaric *et al.*, 2019; Huang *et al.*, 2020).

The bending stiffness and bending strength of CLT floor panels are important properties because they determine the design of CLT elements. In order to obtain the most rational construction, designers are often guided by the highest possible utilization of stresses, but meeting the structural safety, that is determined by serviceability limit state. However, during the exploitation of the structure, the need for additional opening can appear. Openings in the floors are needed for architectural purposes such as passing service ducts or passing shear walls or continuous structural elements. Adding such openings in the floors, when they were not taken in the account during the design, affects the efficiency of the panel in carrying the assigned loads.

Investigation of the effect of openings in the floor on bending stiffness was not much represented in the existing literature. One of the papers dealing with this problem is the paper by Popovski *et al.* (2016). They conducted experimental investigation of the structural and

dynamic characteristics of CLT floor system with and without openings. The results showed the deflection of the CLT panel when the opening is more than 10 % larger than the deflection of the same panel without opening. This is in direct correlation with the stiffness, which is decreased with the presence of an opening. The above study shows the importance of investigating bending stiffness of CLT panels with openings in order to obtain results that can lead to safe and reliable structures.

This paper presents the analysis of bending stiffness of CLT floor panels with and without openings. Modelling was performed using the ABAQUS software package, using the 2D and 3D elements. 3D model was used to investigate the influence of the gaps between boards in non-edge-glued floor panels on the mechanical and dynamical behavior of the panels. The gaps between boards have been shown to influence the shear and torsional stiffness in the panels (Franzoni *et al.*, 2016; Franzoni *et al.*, 2017). The aim of this paper is to investigate the change of bending stiffness due to the presence of an opening and to make recommendations on the position of the opening so as to cause the least possible reduction of stiffness.

2 MATERIALS AND METHODS

2. MATERIJALI I METODE

Two types of CLT floor panels from 3 different manufacturers, with and without openings, were analyzed. They are defined as P1-P3 and PO1-PO3, respectively. All CLT panels had 5 layers with the outer layers oriented in the longitudinal direction of the panel with dimensions identical to the point-supported CLT floor system experimentally analyzed by Popovski *et al.* (2016) (Table 1). Geometry of the panels is shown in Figure 1.

A two-point loading method was used for the non-destructive tests. This method considers applying loads at two points that are located in the middle of each span of the floor (Figure 2). Each CLT floor panel was loaded up to its service design load level and the deflection was measured. The estimated service design load for the panels without openings was 148 kN and for the panels with service openings 108 kN. In this research, all panels were loaded with load of 54 kN per span in order to obtain comparable results.

Once the experimental tests were completed, Popovski *et al.* (2016) determined the average density and moisture content of CLT panels. The results showed that the average density of the CLT panels from manufacturer 1 was 473 kg/m³, while it was 443

Table 1 Thickness of layers in CLT panels and total floor thickness (Popovski *et al.*, 2016)

Tablica 1. Debljina slojeva ploča od CLT-a i ukupna debljina poda (Popovski *et al.*, 2016.)

Manufacturer <i>Proizvođač</i>	Thickness of layers and CLT panels / <i>Debljina slojeva ploča i CLT-a, mm</i>					
	Layer / <i>Sloj</i>					Total <i>Ukupno</i>
	1	2	3	4	5	
1	40	30	30	30	40	170
2	34	34	34	34	34	170
3	32	35	35	35	32	169

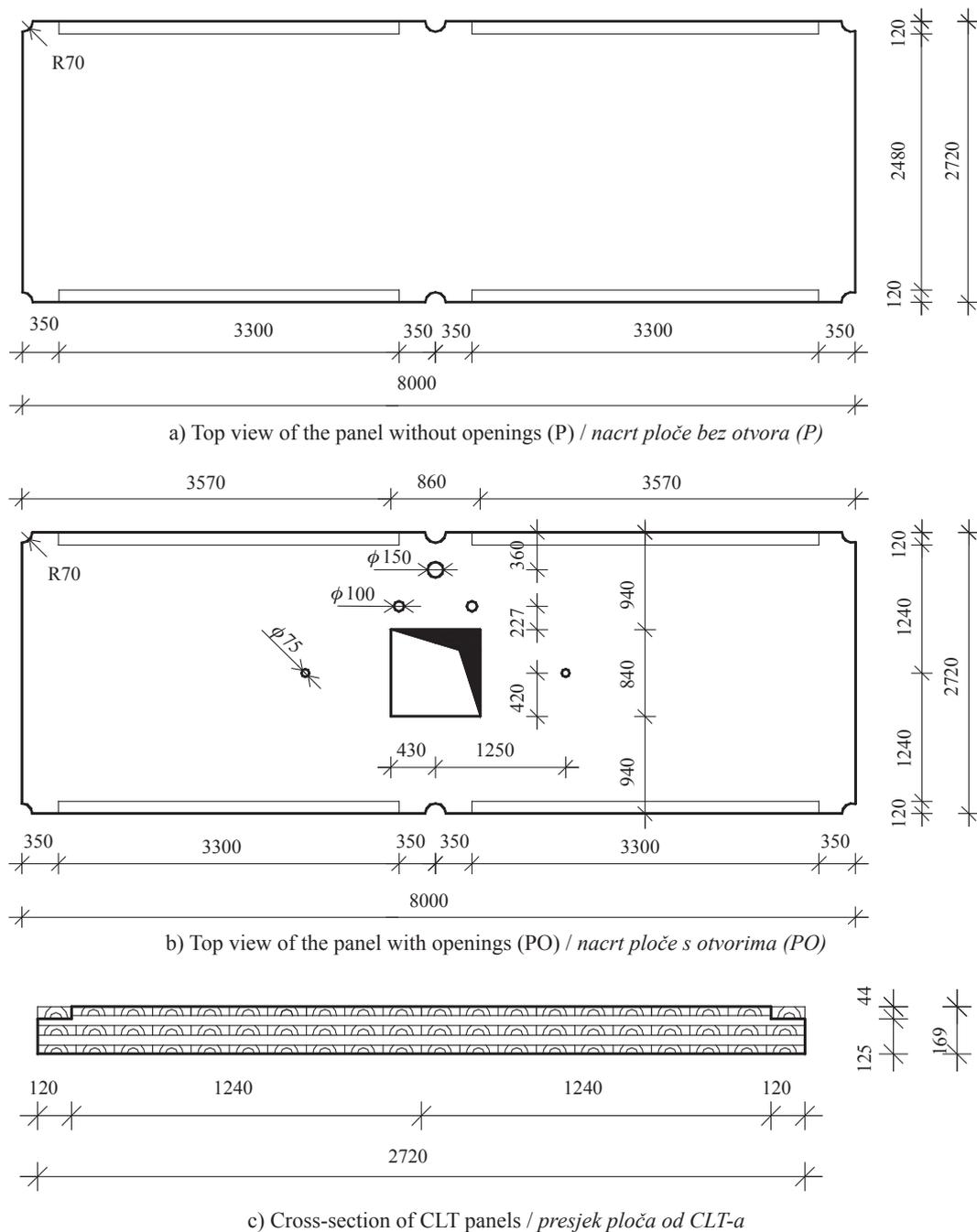


Figure 1 Geometrical characteristics of CLT floor panels (Popovski *et al.*, 2016)

Slika 1. Geometrijska obilježja ploča od CLT-a (Popovski *et al.*, 2016.)

kg/m³ and 452 kg/m³ for the panels from manufacturers 2 and 3, respectively. The moisture content of the CLT panels from manufacturer 1 and 2 was similar (about 8.9 %), while the CLT panels from manufacturer 3 had higher moisture content of 13.3 %.

Finite element method (FEM) was applied by using the Abaqus 6.13-1 software package. In order to calibrate the applied modelling method, the numerically determined behavior of the panels was compared with the experimentally obtained values (Popovski *et al.*, 2016). Three different simulation models were used: one 2D model and two 3D models (one for edge-glued and one non-edge-glued panel). The 2D model

was only used for simulation of edge-glued panels because non-glued edges cannot be modelled under 2D. The adopted mesh was determined by an iterative procedure, until the results of two successive steps differed by less than 1 %.

The 2D model was created using Abaqus internal Composite Layup Manager. The material, thickness, rotation angle, and number of integration points per layer were specified for the lay-up. The model was meshed with S8R elements, an eight-node doubly curved thick shell element with reduced integration (Figure 3).

The 3D models were built up in 5 layers using individual boards assembled to a panel (Figure 4). A

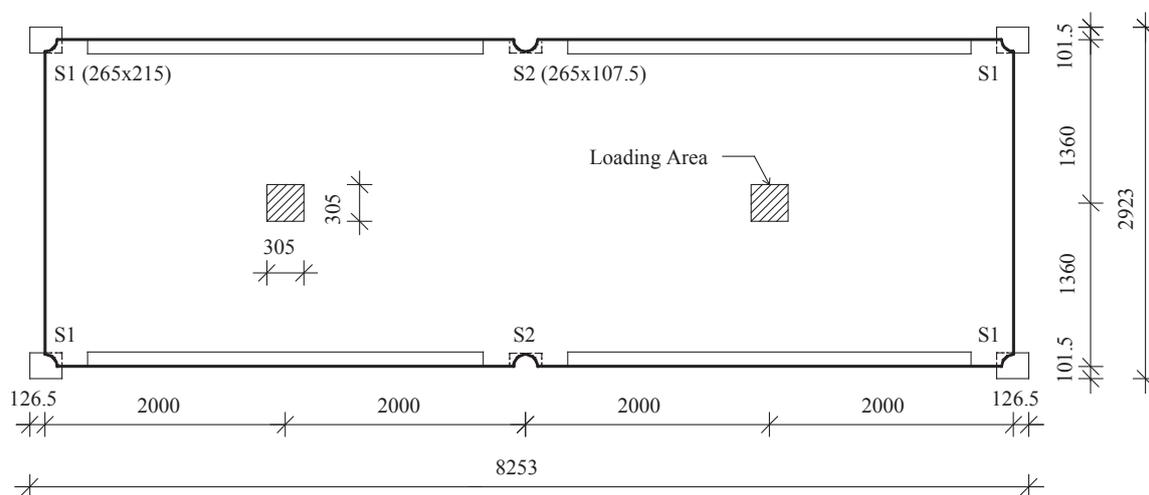


Figure 2 Location of loading points and supports (Popovski *et al.*, 2016)

Slika 2. Položaj mjesta opterećenja i oslonaca (Popovski *et al.*, 2016.)

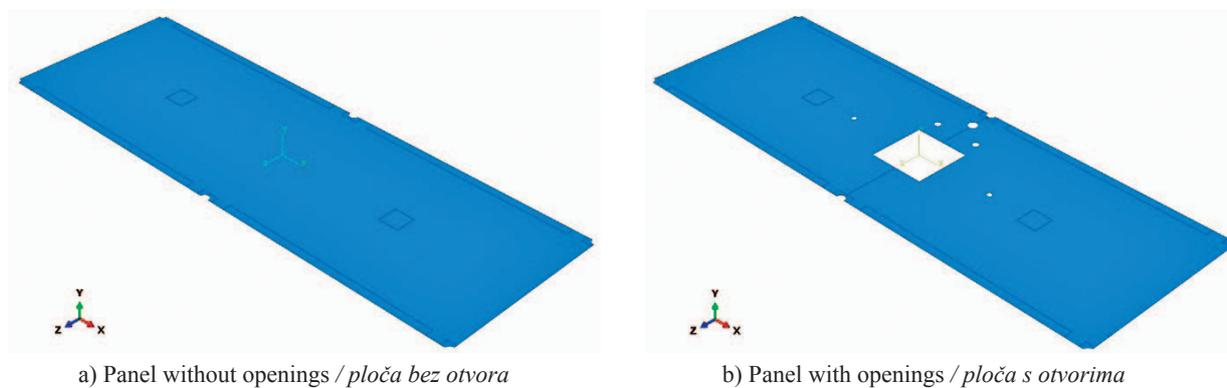


Figure 3 2D model of CLT floor panels

Slika 3. 2D model ploča od CLT-a

Cartesian coordinate system was used to specify the material directions. Glued contact surfaces between the layers were simulated with rigid contact conditions, which did not allow any movement between contact areas. To model the non-glued contact surfaces between the side edges of the boards, flexible contact condition was applied allowing tangential sliding without friction. The model was meshed with the element C3D20R, which is a 20-node quadratic hexahedral element with reduced integration (Figure 5).

Once the FE-model is verified against experiments, the influence of different opening position on the bending stiffness of the CLT floor system was simulated towards the improvement of the design of the



Figure 4 3D model of assembled boards

Slika 4. 3D model sastavljenih ploča

CLT floor panels with openings using a limited number of measurements and structural tests. Another 4 different type panels with one single opening in different positions were analyzed (Figure 6). They are defined as PO11-PO14. The service opening for all analyzed panels had the same dimensions and shape, square with sides of 860 mm × 840 mm.

3 RESULTS

3. REZULTATI

The fundamental frequency and the maximum deflection of the CLT floor panels with and without openings are shown in Table 2. The results obtained by numerical analysis in Abaqus (6.13-1) were compared with the experimentally determined data. Deformed shape and deflection values for the CLT floor panels from manufacturer 1 under the two point loads are illustrated in Figure 7. Comparison of the obtained results from 3D non-edge-glued model with variation of opening position in the panel is provided in Table 3.

4 DISCUSSION

4. RASPRAVA

The numerically obtained results for the proposed model, shown in Tab. 2, correspond to the results obtained experimentally. The non-edge-glued 3D mod-

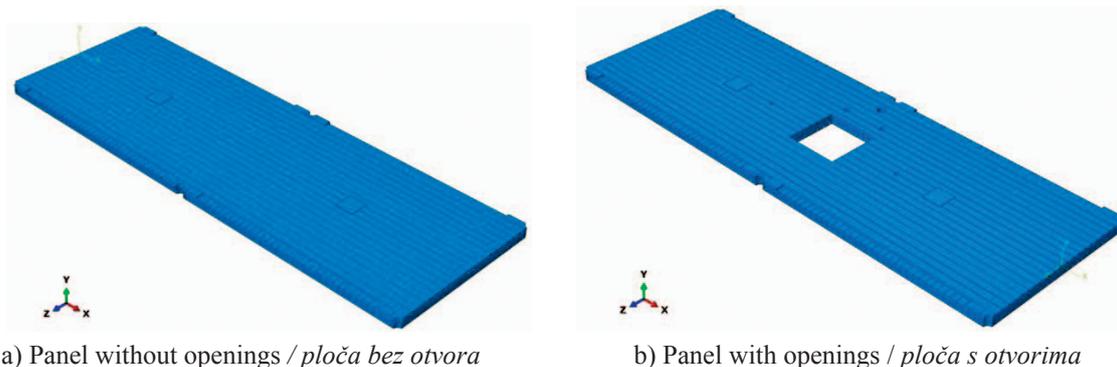


Figure 5 3D model of CLT floor panels
Slika 5. 3D model ploča od CLT-a

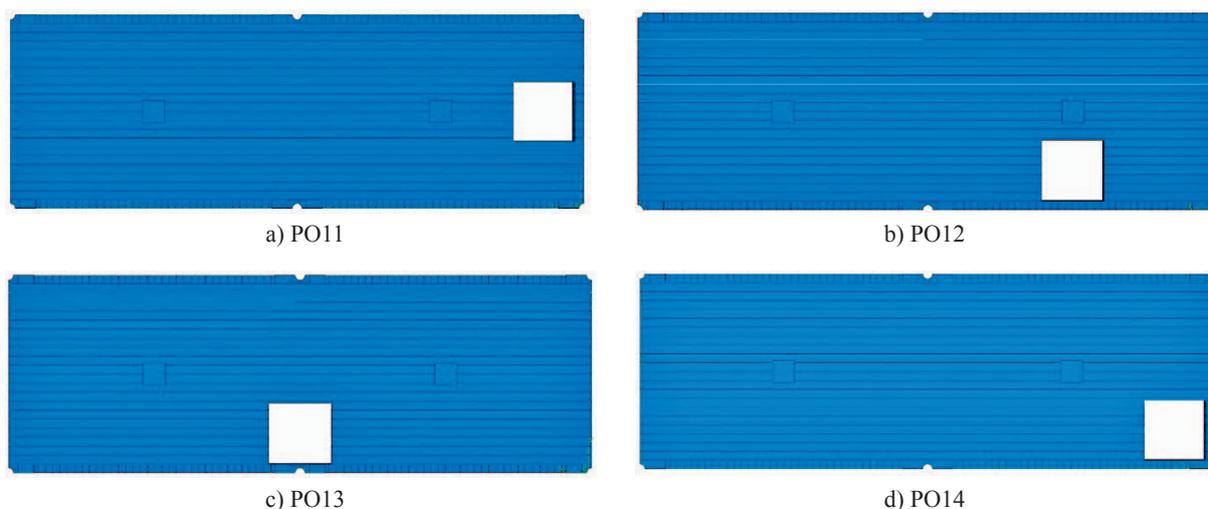


Figure 6 Positions of opening in analyzed panels
Slika 6. Položaji otvora u analiziranim pločama

Table 2 Fundamental frequency and maximum deflection of CLT floor panels
Tablica 2. Osnovna frekvencija i najveći pomak podnih ploča od CLT-a

Model P1		No openings <i>Bez otvora</i>			With openings <i>S otvorima</i>		
		P2	P3	PO1	PO2	PO3	
Frequency, Hz <i>Frekvencija, Hz</i>	Experimental results (Popovski <i>et al.</i> , 2016) <i>eksperimentalni rezultati (Popovski et al., 2016.)</i>	16.8	17.5	16.8	15.9	16.0	15.5
	2D	17.1	18.0	17.4	16.5	17.8	17.2
	Difference / <i>razlika</i> , %	1.8	2.9	3.6	3.8	11.2	11.0
	3D edge-glued / <i>3D lijepljeni rub</i>	17.9	19.4	18.6	17.4	18.7	18.2
	Difference / <i>razlika</i> , %	6.5	10.9	10.7	9.4	16.9	17.4
	3D edge-glued / <i>3D bez lijepljenog ruba</i>	16.6	17.5	17.1	15.7	16.6	15.3
Difference / <i>razlika</i> , %	-1.2	0.0	1.8	-1.3	3.7	-1.3	
Deflection, mm <i>Pomak, mm</i>	Experimental results, average Popovski <i>et al.</i> (2016) <i>eksperimentalni rezultati, srednje vrijednosti (Popovski et al., 2016.)</i>	11.3			12.9		
	2D	12.0	10.6	11.0	13.3	11.8	12.3
	Average / <i>srednja vrijednost</i>	11.2			12.5		
	Difference / <i>razlika</i> , %	-0.9			-3.1		
	3D edge-glued / <i>3D lijepljeni rub</i>	11.2	10.2	10.6	12.5	11.3	11.7
	Average / <i>srednja vrijednost</i>	10.7			11.8		
	Difference / <i>razlika</i> , %	-5.3			-8.5		
	3D edge-glued / <i>3D bez lijepljenog ruba</i>	12.5	10.8	11.3	15.4	13.0	13.7
	Average / <i>srednja vrijednost</i>	11.5			14.0		
Difference / <i>razlika</i> , %	1.8			8.5			

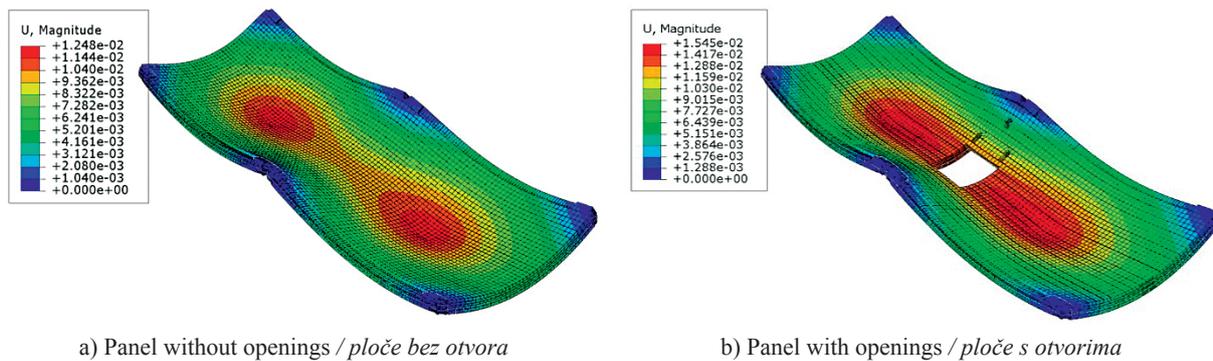


Figure 7 Deformed shape and deflection values of CLT panels from manufacturer 1
Slika 7. Deformacija i vrijednosti pomaka ploča od CLT-a proizvođača 1

el proved to be the most appropriate model for accurate simulation of CLT panel behavior.

The 2D model is the simplest and fastest to model, but gives slightly higher values of the fundamental frequency than the experimental results, 1.8-3.6 % for panels without openings, while for panels with openings these deviations are much larger (3.8-11 %) and depend on panel manufacturers. The maximum deflection of the CLT floor panels is 0.9 % lower for panels without openings, and for panels with openings this deviation is slightly larger and amounts to 3.1 %. With this model, the gaps between the boards for the non-edge-glued panels cannot be modelled. In 3D modelling, it is possible to account for this feature in calculations when constructing a floor.

The largest deviations from the experimental results appear in using the 3D edge-glued model. In edge-glued CLT panels, the side edges of the boards in each layer are glued together, which yields a fully solid plate without gaps, indicating greater stiffness, and therefore their fundamental frequency is much higher than the experimental results. For panels without openings, 6.5-10.7 % higher value is obtained, for panels with openings the difference goes up to 17.4 %. The difference between the numerical results and the experimental results is slightly smaller for the maximum deflection of the CLT floor panels, being 5.3 % for panels without openings and 8.5 % for panels with openings. The 3D non-edge-glued model simulates the most similar behavior of CLT panels. The largest difference in panels with an opening is 3.7 % for the fundamental frequency and 8.5 % for the maximum deflection.

3D non-edge-glued model, that has been shown to best represent the actual behavior of CLT panels in a

parametric study of the influence of the opening position on the dynamic characteristics and bending strength of the CLT floor panels, was investigated. Based on the results presented in Table 3, it can be concluded that, although the presence of openings in the floor reduces the fundamental frequency and bending stiffness of the panels, choosing the favorable position of that opening can minimize the influence. This can be achieved by placing an opening in the middle of the panel or along the axis of the shorter edge of the panel.

4 CONCLUSIONS 4. ZAKLJUČAK

In this study, the main structural performance parameters of the CLT floor panels with and without openings were investigated and numerical models based on the finite element method were proposed. The model parameters were calibrated based on the previously published experimental results in the literature. The high correlation between the numerical and experimental data produces the opportunity to investigate and predict the structural behavior of these floor systems through various numerical parametric studies, since the experimental investigation is generally costly and requires a significant amount of time.

In the parametric study, the influence of the opening position on dynamic characteristics and bending strength of the CLT floor panels was investigated. During the exploitation of the structure, the need for additional service openings can appear. Adding such openings in the floors, when they were not taken into account during the design, affects the efficiency of the panel in carrying the assigned loads. The results of the

Table 3 CLT floor panels with different positions of opening
Tablica 3. Podne ploče od CLT-a s različitim položajima otvora

Model	3D non-edge-glued (manufacturer 1) / 3D bez lijepljenog ruba (proizvođač 1)			
	Frequencies, Hz Frekvencija, Hz	Difference, % Razlika, %	Deflection, mm Pomak, mm	Difference, % Razlika, %
P1	16.6	/	12.5	/
PO1	15.7	-5.4	15.4	23.2
PO11	15.4	-7.2	15.3	22.4
PO12	15.3	-7.8	17.5	40.0
PO13	14.0	-15.7	16.0	28.0
PO14	13.6	-18.1	16.3	30.4

numerical analysis show that the slight decrease of the main structural characteristics of the CLT floor panels is achievable with an adequate geometrical position of the opening in the floor.

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