Experimental modal analysis of cross-laminated timber floors

M Nefovska-Danilović[1,2], V Racic[1], M Milojević[1], Z Mišković[1] and S Savatović[1]

[1]University of Belgrade, Faculty of Civil Engineering, Bulevar kralja Aleksandra 73, Belgrade, Serbia

[2]marija@grf.bg.ac.rs

Abstract.
Cross-laminated timber (CLT) floors have gained in popularity due to their outstanding strength, aesthetic appeal, good fire resistance, and high level of prefabrication. However, due to their high stiffness-to-weight ratio, CLT floors are highly susceptible to pedestrian-induced vibrations. In design practice, vibration serviceability is usually assessed by assuming a floor as a set of CLT panels with no inter-panel connections, which leads to overestimation of the vibration response. In this paper, an experimental dynamic testing was carried out to identify modal properties and pedestrian-induced response of two CLT floors with different number of panels in a floor assembly. Influence of the inter-panel connections on the floor modal properties and pedestrian-induced vibration response is particularly studied and discussed.

1. Introduction

The construction industry contributes a significant percentage of carbon emission globally. Therefore, using renewable structural materials is beneficial from the sustainability perspective. Building with timber has gained unstoppable popularity. After decades of dominance of concrete and steel civil engineering structures, the revival of timber structures started with low-rise residential buildings due to the limited size and mechanical properties of the raw timber material. However, the emergence of cross-laminated timber (CLT) in the 1990s made timber structures competitive against reinforced concrete and steel structures for multi-storey buildings as well [1-3].

CLT is a prefabricated engineering wood product, usually composed of an odd number of crosswise glued layers. Apart from being eco-friendly, CLT is characterized by outstanding strength, stiffness, fire resistance, aesthetics, and speeds up construction. However, due to the high stiffness-to-weight ratio, lightweight long-span CLT floor systems are susceptible to vibration induced by human cyclic activities, such as walking, running and jumping. Excessive vibration can lead to occupants' discomfort or malfunction of vibration-sensitive equipment [4]. CLT floors are more complex when compared to monolith reinforced concrete floors. Connections between adjoining CLT panels, boundary conditions, orthotropic properties of timber and crosswise layer arrangement can significantly affect modal properties and dynamic response of the assembled floor [4].

Available closed-form analytical expressions for calculation of modal properties of CLT floors are based on the beam theory and are limited to conventional boundary conditions (simply supported or fixed). However, CLT panels behave as two-dimensional plate elements having flexural, transverse and torsional modes. Transverse and torsional modes cannot be predicted using the simple beam-based analytical expressions. Consequently, more advanced expressions based on the plate theory accounting for orthotropic behavior of CLT are required. Nowadays, using finite element-based (FE) software, modal properties of CLT floors can be efficiently extracted.

CLT floors are usually composed of panels up to 3m wide. Panels are connected on site using fasteners and self-tapping screws. Two most commonly used inter-panel connections are half-lapped joint and single surface spline (Figure 1). In design practice, evaluation of modal properties and vibration response due to pedestrian-induced loading is usually carried out assuming there is no connection between the panels. Consequently, when assessing vibration serviceability, CLT floor is often treated as one-way slab, which results in an overestimation of its response to pedestrian-induced vibrations. However, recent studies have shown that inter-panel connections significantly affect the modal properties of CLT floors and consequently it's vibration response [5-8].

The study presented in the paper aims to investigate modal properties of CLT floors composed of one and two panels, as well as to evaluate more reliably the extent to which inter-panel connections affect modal properties and vibration response of CLT floors.

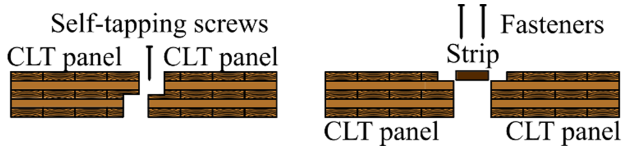


Figure 1. Half-lapped joint (left) and single spline (right) connections of CLT floors.

2. Experimental modal analysis and numerical modelling

Experimental study was carried out at the Faculty of Civil Engineering in Belgrade to determine the modal properties and pedestrian-induced vibration response of bare floors made of one and two 5-ply CLT panels. Each panel was 6m long, 1.7m wide and 150 mm thick. The panels were connected using 80 mm wide half-lap joints and 140 mm long self-tapping screws, spaced at 250 mm. Details of the half-lap joint are shown in Figure 2. The floors were supported by two timber beams mounted over a steel frame, as shown in Fig. 3. Panel-to-beam connection was made using 200 mm long screws spaced at 250-300 mm intervals, as illustrated in Figure 2.

Broad-band excitation applied to both floor specimens was generated using a portable music shaker with amplifier for ambient vibration simulation in the frequency range 5-200 Hz. Position of the shaker and its connection to the supporting steel frame is shown in Fig. 4. Acceleration time histories were measured for 30 minutes using 16 uniaxial accelerometers MEMS 2240-002 [9] and recorded by a 16-channel data acquisition system with a sampling frequency of 600 Hz. The recorded signals were then processed in ARTeMIS software [10] to obtain natural frequencies, mode shapes and damping ratios of the floors.

Numerical models of the investigated CLT floors were developed using commercial software Abaqus CAE [11]. The CLT panels were modeled using 4-node S4R shell element with reduced integration and a composite layer section. Each layer was modelled as a C24 unidirectional lamina, with the material properties listed in Table 1. Material properties that most significantly affect modal properties of the investigated floors are the longitudinal modulus of elasticity E_L and mass density ρ. These parameters were extracted from the experimental static testing carried out prior to the dynamic experimental testing, while other material parameters were adopted from [12]. Supporting steel frame was modeled using 1560 B31 beam 2-node finite elements, with modulus of elasticity E = 210 GPa, Poisson's ratio ν=0.3 and mass density ρ = 7850 kg/m^3.

Two parallel transverse edges of the CLT panels were connected to the supporting structure using a tie constraint boundary condition, which ensures equal translations between the panel and supporting structure in all directions. The mesh size was 0.05 m.

The half lap joint was modelled using an equivalent isotropic elastic strip. More details on the modelling of inter-panel connections can be found in [13, 14]. The adopted width of the elastic strip was 80 mm, yielding the elastic and shear modulus equal to 8.8 MPa.

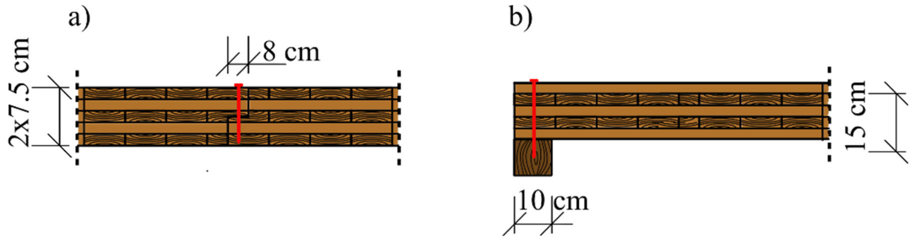


Figure 2. (a) Detail of the half-lap joint, (b) Panel-to-beam connection.

Table 1. Material properties of the C24 timber class used in CLT panels.

E_L	$E_T = E_R$	$G_{LT} = G_{LR}$	G_{RT}	ν_{LT}	ν_{LR}	ν_{RT}	ρ
11242 N/mm^2	370 N/mm^2	690 N/mm^2	50 N/mm^2	0.37	0.42	0.47	424 kg/m^3

Figure 3. Steel frame.

Figure 4. Music shaker and its connection with the supporting frame.

2.1. Modal testing

2.1.1. Single-panel floor

Figure 5 shows a grid for arrangement of 15 accelerometers placed on a single CLT panel labeled A1/1. Table 2 shows the modal properties of the CLT panel obtained from both the experimental testing and numerical analysis. Based on a visual inspection, it can be concluded that there is a strong correlation between the first five experimentally and numerically obtained mode shapes. Relative error between the experimentally measured and numerically simulated natural frequencies is less than 2%, with the exception of 7.8% for the second vertical mode (mode 3 in Table 2).

The measured natural frequencies of the first five mode shapes are lower than their numerical counterparts. This suggests that the actual boundary conditions are more flexible.

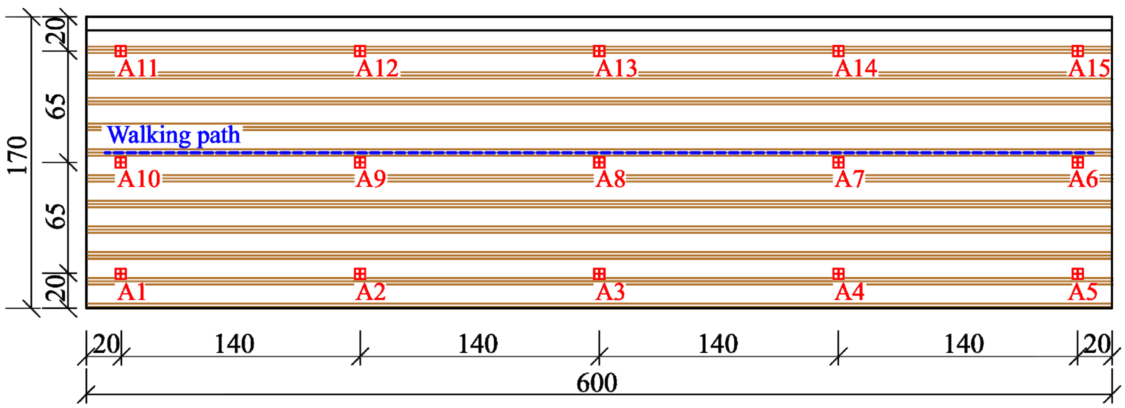


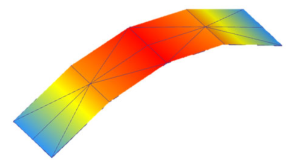
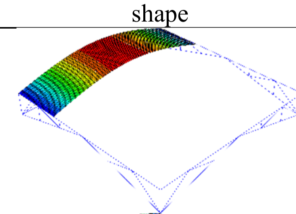
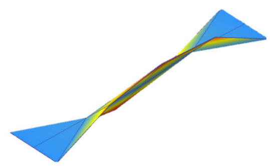
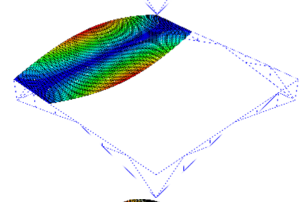
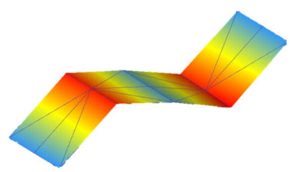
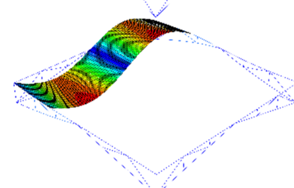
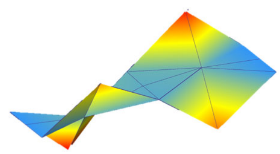
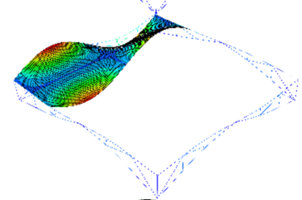
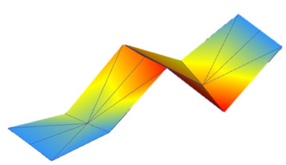
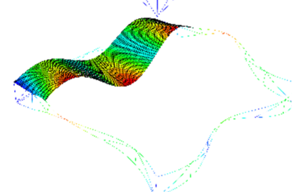
Figure 5. Experimental setup of a single-panel floor.

2.1.2. Two- panel floor

In this scenario, two CLT panels (A1/1 and A1/2) are joined using a half lap joint resulting in a 3.46x6.0 m floor structure (Figure 6). Since there were only 16 accelerometers available, the modal testing of a two-panel floor was carried out in two swipes. Positions of the accelerometers in the first swipe was exactly the same as in Figure 5, i.e. all 15 accelerometers were arranged at the first panel only. An additional accelerometer A16 was placed next to accelerometer A9 as a reference point between the swipes. In the second swipe, the 15 accelerometers were translated to the second panel as shown in Figure 7, so A1 becomes A17, A2 becomes A18, etc.

Results of both experimental testing and numerical analysis are shown in Table 3. As expected, the fundamental frequency of the two-panel floor was found to be slightly lower than the corresponding fundamental frequency of the one-panel floor. Furthermore, there was a significant drop in the natural frequency of the first torsional mode (mode 2 in Tables 2 and 3). In addition, as the mode shape order increases and the shapes become more flexed, difference between the natural frequencies of single-panel and two-panel floors increases. Good correlation was achieved between the experimentally obtained and numerically simulated natural frequencies and mode shapes. The largest difference of 10% was observed for mode (1,2), similar to the case of the single-panel floor. Similar damping values were detected for the fundamental mode in both the single-panel and two-panel floors. Generally, the single-panel floor exhibited higher damping values compared to the two-panel floor, with the exception of mode (1,2).

Table 2. Modal properties of the single CLT panel.

Mode	Description	Experimental testing			Numerical analysis	
		f_{exp} [Hz]	Damping [%]	Mode shape	f_{FEA} [Hz]	Mode shape
1	(1,1)	8.6	0.60		8.70	
2	(2,1)	17.6	1.6		18.1	
3	(1,2)	29.2	0.97		31.5	
4	(2,2)	42.8	0.63		42.8	
5	(1,3)	65.4	1.8		64.2	

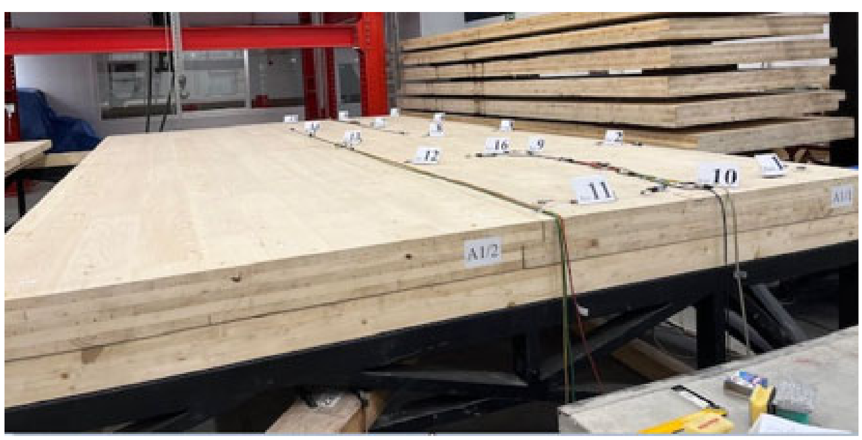
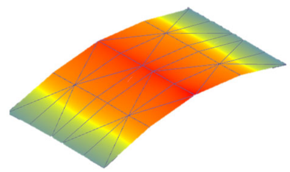
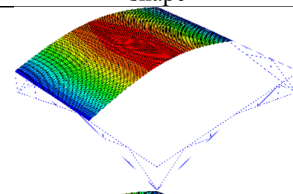
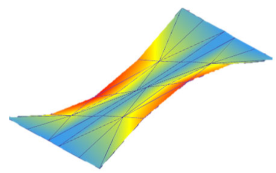
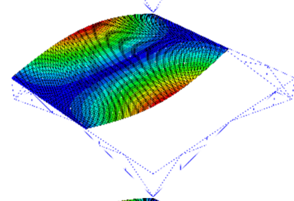
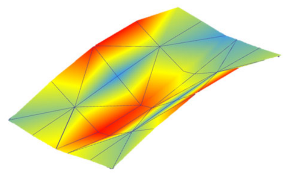
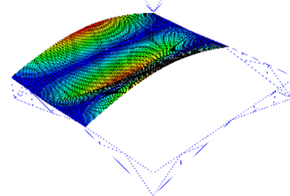
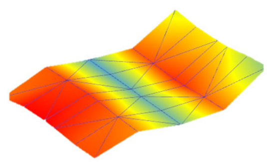
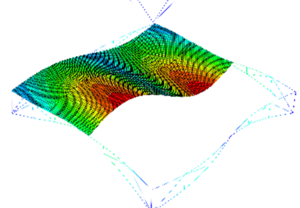
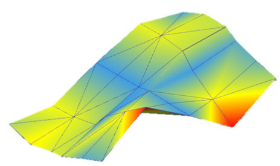
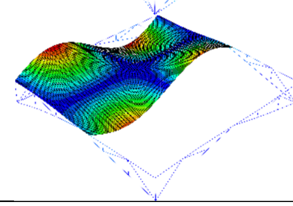


Figure 6. Experimental setup of two-panel CLT floor.

Table 3. Modal properties of the two-panel CLT floor.

Mode	Description	Experimental testing			Numerical analysis	
		f_{exp} [Hz]	Damping [%]	Mode shape	f_{FE} [Hz]	Mode shape
1	(1,1)	8.4	0.58		8.50	
2	(2,1)	11.6	0.65		11.6	
3	(3,1)	20.3	0.55		19.1	
4	(1,2)	25.8	3.4		28.5	
5	(2,2)	32.5	0.40		34.2	

2.2. Walking tests

A test subject (male, 41 years, 48 kg, 160 cm) was walking along a straight path on both single panel and two-panel CLT floors, as illustrated in Figure 7. As the fundamental frequency of the single-panel was 8.61 Hz, he controlled his footfall rate by following regular metronome beats at 2.15 Hz. In this way, he could induce resonance due to the fourth harmonic of walking loading. In case of the two-panel floor having the natural frequency 8.4 Hz, the same effect was achieved by the metronome controlled walking at 2.1 Hz. Dynamic response was measured using 16 accelerometers. In the single-panel test, position of the accelerometers was the same as during the modal testing (see Figure 5). In the two-panel test, seven accelerometers were kept on the first panel, while the remaining nine were placed on the second panel, as illustrated in Figure 7.

Figure 8 shows the acceleration time histories and their Fast Fourier transform (FFT) amplitude spectra recorded at point A8 for the single-panel and two-panel floors. Both floors showed near-resonant response. The single-panel floor had a peak acceleration response at 1.38 m/s^2, while for the two-panel floor the peak acceleration was at 0.70 m/s^2, which is nearly half the acceleration amplitude of the single-panel floor. This can be attributed to the double mass of the two-panel floor. Note that neglecting the inter-panel connection and treating the two-panel floor as a set of independent panels would result in a significant overestimation of the floor's response.

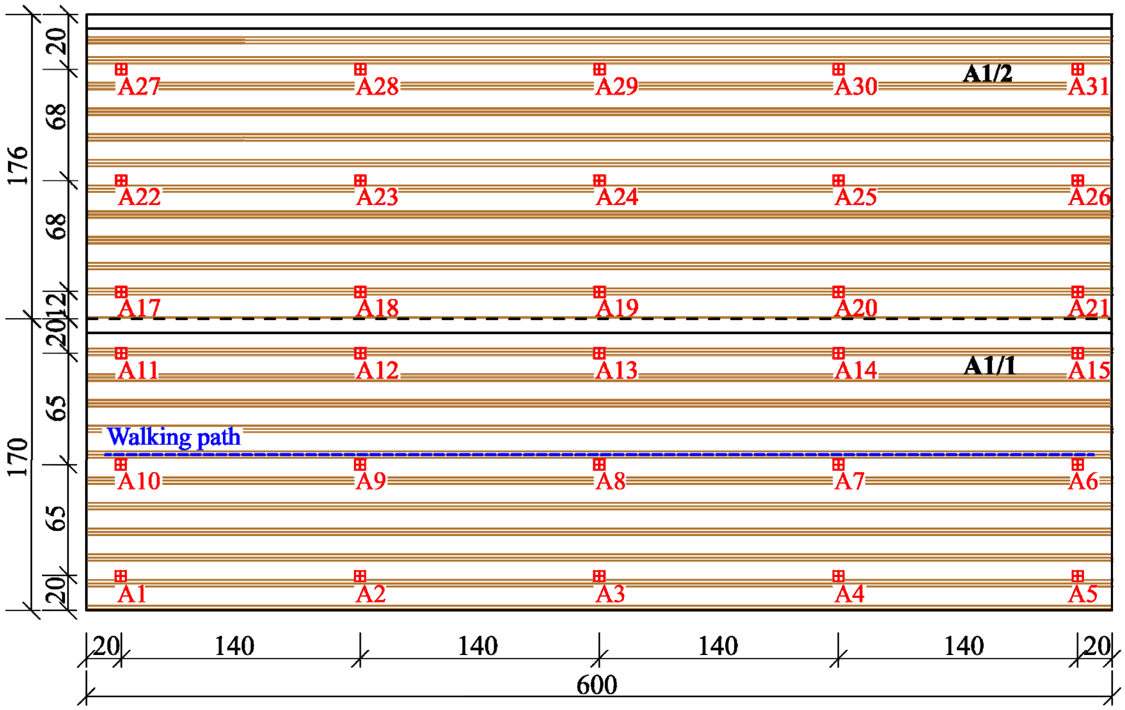


Figure 7. Experimental setup of walking tests for two-panel floor.

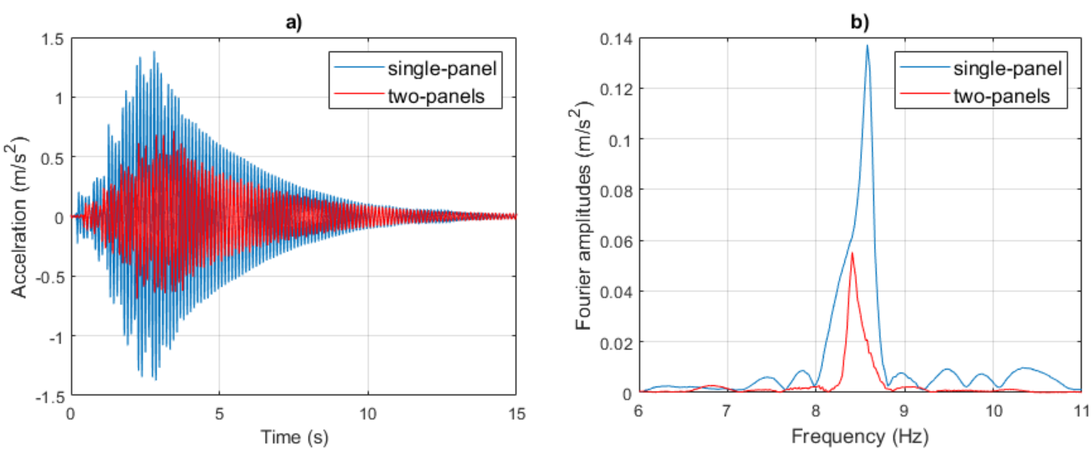


Figure 8. Acceleration time history (a) and FFT amplitude spectra (b) recorded at location A8.

Furthermore, the comparison of the free decay response of the investigated floors shows that the single-panel floor has higher damping values.

3. Conclusions

As vibration serviceability persistently governs design of long-span CLT floors, it is very important to determine reliably their modal properties such as natural frequency, modal mass and damping. Experimental testing and numerical analysis of two floor specimens studied in this paper showed that these strongly depend on parameters such as inter-panel connections, boundary conditions and orthotropic timber properties. While the effects of the latter two parameters are relatively well documented in the literature, very little is known about the former. Popular codes and guidelines for design of CLT floors either neglect the inter-panel connections or model CLT floors as monolith slabs, i.e. with the rigid inter-panel connections. The present study showed that the true nature of the inter-panel connections is somewhere in between. Experimental testing, numerical modelling, model updating, calibration and verification of the inter-panel connection models offers a plenty of room for urgently needed further research on the subject.

Acknowledgements
This research was supported by the Science Fund of the Republic of Serbia on Grant No. 7677448: *Towards Sustainable Buildings: Novel Strategies for the Design of Vibration Resistant Cross-Laminated Timber Floors - Substrate4CLT*. Authors also acknowledge the support by the Ministry of Science, Technological Development and Innovations of the Republic of Serbia, project No. 200092.

References

[1] Brandner R, Flatscher D, Ringhofer A, Schickhofer G, Thiel A 2016 Cross Laminated Timber (CLT): overview and development. *Eur J Wood Wood Prod*;**74**(3) 331–51.
[2] Cvetković R, Stojić D, Krasić S, Marković N 2015 Innovative structural CLT system in projecting and building of student houses. *Facta Universitatis – series Architecture and Civil. Engineering*, **13**(1) 57–64.
[3] Jeleč M, Varevac D, Rajčić V 2018 Cross-laminated timber (CLT) – a state of the art report *Građevinar* **70** 75–95.
[4] ISO 10137 2007 *Bases for design of structures – Serviceability of buildings and walkways against vibrations* International Organization for Standardization, Brussels.
[5] Weckendorf J, Ussher E, Smith I 2016 Dynamic response of CLT plate systems in the context of timber and hybrid construction *Compos Struct* **157** 412–23.
[6] Milojević M, Racic V, Marjanović M, Nefovska-Danilović M 2023 Influence of inter-panel connections on vibration response of CLT floors due to pedestrian-induced loading *Eng Struct* **277** 115432.
[7] Ussher E, Arjomandi K, Weckendorf J, Smith I 2017 Predicting effects of design variables on modal responses of CLT floors *Struct* **11** 40-48.
[8] Lewis K, Basaglia B, Shrestha R, Crews K 2016 The use of cross laminated timber for long span flooring in commercial buildings *World Conference on Timber Engineering* August 22-25 Vienna Austria.
[9] Silicon Designs Inc Kirkland, WA 98034 USA.
[10] ARTeMIS Modal Pro v7.2. Structural Vibration Solutions. Aalborg, Denmark, 2022.
[11] ABAQUS User Manual 6.9. DS SIMULIA Corp., Providence, Rhode Island, USA, 2009.
[12] Marjanović M, Marković N, Damnjanović E, Cvetković R 2020 Three dimensional stress analysis and design of cross-laminated timber panels using full-layerwise-theory-based finite element method. *Thin Wall Struct* **157**107156.
[13] Macpherson E, Papastavrou P, Wallwork T, Smith S, McRobie A 2018 The rotational stiffness of cross-laminated timber half-lap joints *World Conference on Timber Engineering WCTE* Seoul, Republic of Korea.
[14] Paolini A, Kollmannsberger S, Winter C, Buchschmid M, Muller G, Rabold A 2017 A high order finite element model for vibration analysis of cross laminated timber assemblies *Build. Acoust.* **24**(3) 135-58.