Effect of Inter-panel Connections on Modal Properties of Cross-Laminated Timber Floors

Vitomir Racic(✉), Marija Nefovska-Danilović, Marija Milojević,
and Miroslav Marjanović

Faculty of Civil Engineering, University of Belgrade, Bulevar Kralja Aleksandra 73, 11000
Belgrade, Serbia
*vracic@grf.bg.ac.rs

Abstract. Cross-laminated timber (CLT) floors are typically composed of prefabricated CLT panels assembled on a construction site. The actual connections are commonly disregarded at design stage. CLT floors are modelled either as a monolithic slab or more frequently as a collection of CLT panels with no connections. This paper presents a numerical study designed to demonstrate the effect of two common inter-panel connections, i.e. single surface spline and half-lapped joint, on vibration modes of various CLT floor configurations. The inter-panel connections are modelled as an equivalent 2D elastic strip between the CLT panels. This uncomplicated yet robust approximation of reality can be used readily in design practice, regardless finite element (FE) software used to determine modal properties of a floor. The corresponding monolithic floors and those without inter-panel connections are studied for comparison. The results showed that the common practice of modelling CLT floors either as monolithic slabs or as a set of independent panels should come to an end.

Keywords: Cross-laminated timber · Single surface spline · Half-lapped joint · Low-frequency floor · High-frequency floor

1 Introduction

Emergence of new construction techniques and light yet high-strength building materials, have made vibration serviceability assessment (VSA) the governing criterion for design of long-span structures [1], and timber floors are no exception [2–7]. Hamm et al. [8] showed that a significant percent of timber floors that fulfill ultimate limit state (ULS) design criteria fail to satisfy VSA requirements. The Canadian CLT Handbook [9] warns that bare cross-laminated timber (CLT) floors differ from traditional lightweight wood joisted floors, thus the traditional methods and criteria for VSA may not be applicable to CLT floors.

CLT is a multilayer composite made by gluing together layers of solid thin wood boards in a crosswise fashion [10]. Apart from outstanding strength and rigidity, dimensional stability, aesthetic quality and fire resistance, CLT is a highly sustainable construction material. Its low carbon footprint particularly affirms its use in residential and

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
M. P. Limongelli et al. (Eds.): EVACES 2023, LNCE 432, pp. 589–598, 2023.
https://doi.org/10.1007/978-3-031-39109-5_60

commercial buildings [10, 11]. In Europe, design of CLT structural elements is guided by national annexes of the Eurocode 5 [12]. Analytical solutions cover only relatively simple plate geometries and boundary conditions. Therefore, for the most real cases in engineering practice, CLT structures are modelled using finite element method (FEM) based on the relatively simple equivalent single layer (ESL) laminate theories [13].

Regarding VSA, Eurocode 5 [12] limits the fundamental frequency of a floor to 8 Hz to prevent resonant vibrations due to pedestrians walking. This frequency limit is not related to the timber as a building material but has stemmed from a false assumption that walking excitation has no power to cause vibration serviceability problems above 8 Hz [1]. More recent studies suggest the frequency cut-off as high as 14 Hz [14]. In any case, the cut-off frequency is just a decision factor for floor classification to so-called "low-frequency floors" that can develop resonant response under walking excitation and "high-frequency floors" that show a series of brief transient responses due to each footfall [1, 14]. For more information about pedestrian-induced vibrations of both types of CLT floors and the influence of the inter-panel connections on the vibration levels, a reader is directed to a recent publication by Milojevic et al. [15].

Influence of the connections on both free and forced vibrations of CLT floors is often neglected in numerical modelling, treating a multi-panel floor as a monolithic slab or with no inter-panel connections at all [12, 16, 17]. This paper presents an extensive numerical study on the influence of two frequently used connection types on vibration modes of both low- and high-frequency CLT floors. The same analysis was carried out for the corresponding monolithic and no connection floors for comparison.

2 Properties of CLT Floors

Production and transportation to a construction site limit the size of the panels to 3 m by 20 m. Inter-panel connections (Fig. 1) along the longer edges (i.e. the span) that transfer in-plane shear forces and bending moments are commonly formed in situ.

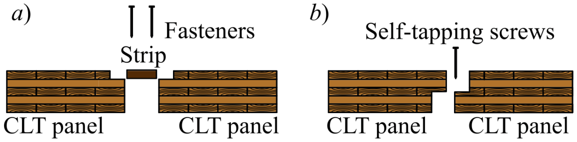

Fig. 1. Two types of CLT inter-panel connections: a) single surface spline; b) half-lapped joint.

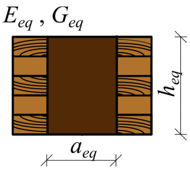

Fig. 2. Equivalent elastic strip.

Although inter-panel connections are relatively complex, here they are modelled using a simple equivalent two-dimensional (2D) homogeneous elastic strip that is linked rigidly to the neighboring panels (Fig. 2). The geometric and mechanical properties of the elastic strip are determined to match the shear and rotational stiffnesses of the actual connection, as elaborated in Milojevic et al. [15]. For both connection types, the height of the strip h_{eq} is set equal to the height of the actual CLT panels, while the adopted width of the elastic strip is $a_{eq} = 90$ mm [15]. The resulting elastic strip properties are:

- for the single surface spline: $E_{eq} = 2.96$ MPa, $G_{eq} = 10$ MPa,
- for the half-lapped joint: $E_{eq} = G_{eq} = 4.105$ MPa.

Although the model is suitable for both 2D and 3D FE modelling, focus of the present study is on 2D rectangular floors only.

Table 1. Considered scenarios by means of frequency levels, boundary conditions and inter-panel connection types (Examples 1–2).

Example	Floor Type	Boundary Conditions	Connection
Example 1	LFF	SFSF	monolithic slab
			no connection
			single surface spline
			half-lapped joint
		SSSS	monolithic slab
			single surface spline
			half-lapped joint
Example 2	HFF	SFSF	monolithic slab
			single surface spline
			half-lapped joint
		SSSS	monolithic slab
			single surface spline
			half-lapped joint

Note: S – simply-supported edge; F – free edge

Table 2. Mechanical properties of C24 timber class lumber used in the CLT panels

E_L	$E_T = E_R$	$G_{LT} = G_{LR}$	G_{RT}	ν_{LT}	ν_{LR}	ν_{RT}	ρ
11000 N/mm^2	370 N/mm^2	690 N/mm^2	50 N/mm^2	0.49	0.39	0.64	420 kg/m^3

3 Modal Properties of CLT Floors

The next two subsections illustrate results of the modal analysis simulated for examples of LFFs (Sect. 2.1) and HFFs (Sect. 2.2) with different combinations of free (F) and simply supported (S) boundary conditions around the four edges. Four connection types between the panels are studied: (i) rigid (monolithic) slab, (ii) absence of connections, (iii) single surface spline and (iv) half-lapped joint, as summarized in Table 1. The cut-off frequency between the low-frequency floors (LFF) and high-frequency floors (HFF) was set to 10.5 Hz, according to Arup's guideline for VSA of floor structures [16]. Natural frequencies, modal masses, modal stiffnesses and mode shapes were exported from FE models of the floors developed in Abaqus CAE [18]. The multilayer CLT panels were modelled using S4R element, while each layer was modelled as a C24 unidirectional lamina with the material properties listed in Table 2. The mechanical properties of CLT were adopted according to [19–22]. The mesh size was 0.05 m. In all examples the additional mass of non-structural elements including 10% of the live load was 150 kg/m^2.

3.1 Example 1: Low-frequency Floor (LFF)

This is a 5-layer square CLT floor with a total thickness h = 5 × 4 cm = 20 cm, side length a = 6 m, hence side-to-thickness ratio a/h = 30. Such a large CLT floor must be assembled using two 3 × 6 m panels (see Fig. 3). The modal properties due to three combinations of boundary conditions and four inter-panel connections, as listed in Table 1, are elaborated in the next three sub-sections.

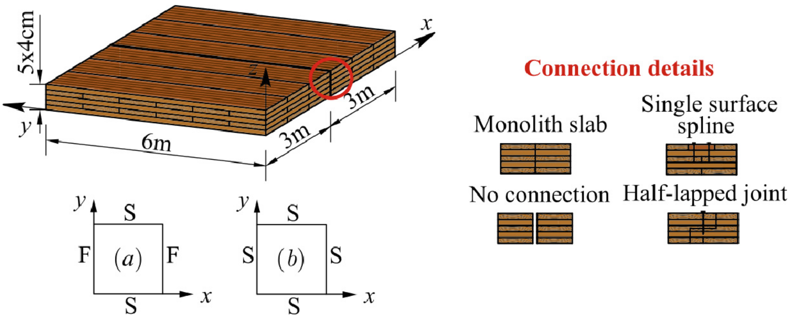

Fig. 3. 6 m × 6 m square CLT floor composed of two panels with different boundary conditions a) SFSF; b) SSSS. Connection details of four considered scenarios are illustrated schematically.

One-way SFSF Floor. The floor is simply supported along two parallel edges and free along the other two (Fig. 3a). The outer layers are parallel to the span (*y*) direction to maximise the bending rigidity in this direction. Simply supported boundary conditions were assigned to the floor edges parallel to the x-axis by constraining the displacements in the x and z (vertical) directions. Edges parallel to the y-axis remained free.

Modal properties for all modes up to 30 Hz are listed in Table 3, while the corresponding mode shapes are illustrated in Fig. 4. Indexes *i* and *j* are the numbers of half sine waves in the mode shapes along the x and y axes, respectively. All the mode shapes in the figure are arranged in the columns according to different combinations of (i, j) values. The monolithic floor is selected for comparison. So, its natural frequencies are arranged in increasing order. Note that this is not the case for other connection types.

Table 3. Natural frequencies and modal masses of 6m × 6m CLT floor (SFSF) for all considered scenarios (* - mode shapes arising in pairs due to the symmetry).

Mode	Monolithic slab		No connection*		Single surf. Spline		Half-lapped joint	
	Frequency [Hz]	Modal Mass [kg]	Frequency [Hz]	Modal Mass [kg]	Frequency [Hz]	Modal Mass [kg]	Frequency [Hz]	Modal Mass [kg]
(1,1)	6.60	3981.5	6.60	2061.4	6.55	3846.6	6.55	3850.0
(2,1)	7.66	1481.8	9.65	732.73	7.46	1496.7	7.45	1506.6
(3,1)	13.01	1154.7	/	/	9.63	1417.3	9.66	1414.3
(1,2)	23.38	3846.7	23.38	2046.2	23.16	2914.7	23.16	2893.8
(2,2)	24.33	1595.0	26.45	789.25	24.14	1618.8	24.11	1649.0
(4,1)	24.48	1167.5	/	/	23.63	1229.4	22.86	1296.2
(3,2)	28.09	1273.1	/	/	26.06	1388.5	26.06	1384.8

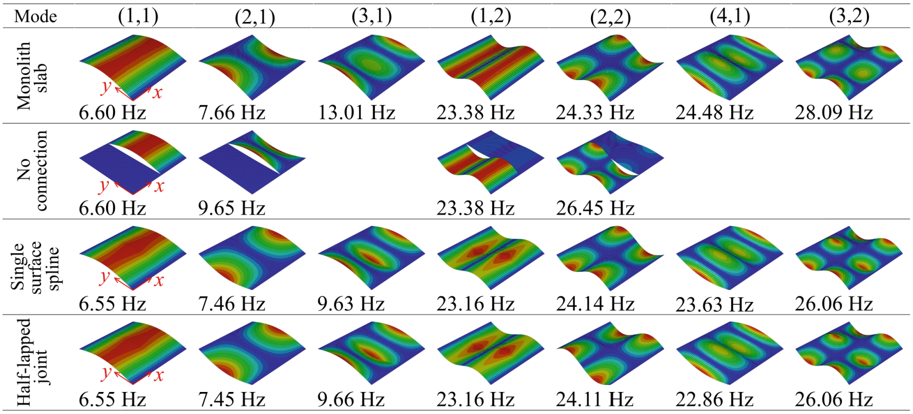

Fig. 4. Mode shapes and associated natural frequencies of 6m × 6m square CLT floor (SFSF), considering different inter-panel connection types.

The modes of the floor without inter-panel connections are apparently different in comparison with other three cases. Each panel is an independent (local) floor-strip. There is almost no difference between natural frequencies and mode shapes for modes (1,1) and (1,2) since all the flexing is just along the span, i.e. parallel to the free y-axis. However, the modal mass of the monolithic floor is almost twice the modal mass of a single panel, which can yield dramatically different vibration responses. When the flexing is added in the opposite *x*-direction (i.e. for $i > 1$), the results diverge with every increment in *i*. For mode (2,1), a single panel has approximately 26% higher natural frequency than the monolithic floor. For mode (3,1), the frequency is higher than 30 Hz (outside the target frequency range), and there are multiple differences with the monolithic floor.

For the majority of the modes, there are almost no differences between the modal properties of the floors assembled with the different two types of the joint connections. Only for mode (4,1) there is a 3.25% relative error (rows 3, 4 in Fig. 4). This is due to different shear modulus values (10 GPa vs. 4.01 GPa) incorporated in the corresponding elastic strip model properties. Both floors expectedly have lower natural frequencies than the monolithic reference. The surface spline connection makes a closer match with the relative error of 3.5% in comparison to 6.6% of the half-lapped joint connection. Moreover, the position of mode (4,1) for each connection type is rather different (Fig. 4). In case of the half-lapped joint connection, 22.86 Hz comes at the fourth place, while 23.63 Hz is the fifth in case of the spline connection. Neither of them matches the mode shape and/or natural frequency of the corresponding monolithic floor.

Another significant mismatch is for mode (3,1). This mode bends all along the connection line, so the bending stiffness of the strip is fully engaged. The connection line is also the axis of symmetry for this mode, which means that the rotational stiffness of the equivalent strip is fully operating in this mode. While there is a negligible difference between the connection types, the values are nearly 26% lower than that of the monolithic floor. This means that the influence of the connection is very considerable in this mode. Considering together modes (3,1) and (4,1), it is apparent that the modal properties are more sensitive to the rotational stiffness than the bending stiffness of the inter-panel connection line.

SSSS Floor. In this case, the floor is simply supported along all four edges (Fig. 3b). natural frequencies, modal masses and mode Shapes are presented in Table 4 and illustrated in Fig. 5.

Table 4. Natural frequencies and modal masses of 6 m × 6 m square CLT floor (SSSS) for all considered scenarios.

Mode	Monolithic slab		Single surface spline		Half-lapped joint	
	Frequency [Hz]	Modal Mass [kg]	Frequency [Hz]	Modal Mass [kg]	Frequency [Hz]	Modal Mass [kg]
(1,1)	8.28	2124.2	7.37	1505.0	7.38	1508.7
(2,1)	16.50	2128.1	16.08	2174.7	15.79	2216.1
(1,2)	24.41	2133.5	23.70	1463.4	23.69	1448.8
(2,2)	29.29	2122.2	28.80	2192.1	28.52	2248.6
(3,1)	>30	/	24.15	1263.8	24.20	1255.0

The floors composed of two connected panels show very close results and consistently lower natural frequencies than the corresponding monolithic plate. The SSSS case is particularly interesting as there is a significant difference of about 11% in the first natural frequency. Diverse order of mode shapes, observed previously in the case of SFSF floors, is also present here. Mode shapes for the fourth and fifth mode appear again in the reverse order when compared to the monolithic slab. This is clearly the result of how these shapes bend in the proximity of the connection line, as elaborated in the case of SFSF floor.

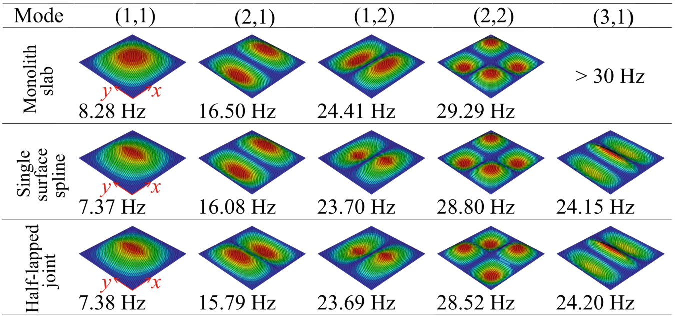

Fig. 5. Mode shapes and associated natural frequencies of 6 m × 6 m square CLT floor (SSSS), considering different inter-panel connection types.

3.2 Example 2: High-frequency Floor (HFF)

The study elaborated in this section is nominally similar to that presented in Sect. 2.1. A 5-layer square CLT floor with the total thickness h = 5 × 4 = 20 cm and the side length a = 4 m (thus a/h = 20) was considered. As in Sect. 2.1, the floor was modelled as a monolithic slab, as well as an assembly of two 2 m × 4 m panels connected with a single surface spline and half-lapped joint (Fig. 6). The influence of the connections on the modal properties and vibration responses due to pedestrian-induced excitation was studied in the next two subsections for the SFSF and SSSS boundary conditions.

One way Floor SFSF. The floor is simply supported along the edges parallel to the x-direction and free along the edges in the y-direction (Fig. 6a). The outer layers are oriented in the y (span) direction. The results of the modal analysis are presented in Table 5, while the mode shapes are illustrated in Fig. 7.

There are negligible differences (approximately 1.5%) in the natural frequencies that correspond to the first and second modes of vibration for all three cases. However, the third natural frequencies of the floors with inter-panel connections are about 26% lower when compared with the monolithic slab. As in the case of LFF studied in Sect. 2.1, such large differences are present for modes that flex and rotate most in the close proximity of the connection line.

SSSS Floor. As in Sect. 2.1, the floor is simply supported along all four edges (Fig. 6b). The increased flexibility of the inter-panel connections resulted in an average decrease of the natural frequencies by 12% and 7% for the first two modes, respectively, when compared to the monolithic slab (Table 6).

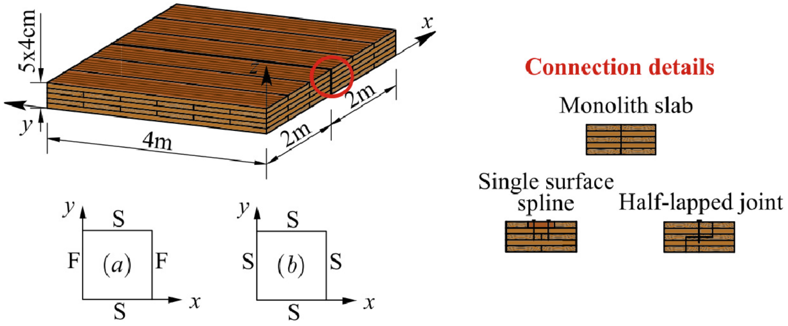

Fig. 6. 4 m × 4 m square CLT floor composed of two panels with different boundary conditions a) SFSF; b) SSSS. Connection details of four considered scenarios are illustrated schematically.

Table 5. Natural frequencies and modal masses of 4 m × 4 m square CLT floor (SFSF) for all considered scenarios.

Mode	Monolithic slab		Single surface spline		Half-lapped joint	
	Frequency [Hz]	Modal Mass [kg]	Frequency [Hz]	Modal Mass [kg]	Frequency [Hz]	Modal Mass [kg]
(1,1)	14.06	1768.70	13.89	1615.90	13.89	1609.3
(2,1)	15.82	660.66	15.63	674.63	15.58	685.03
(3,1)	26.50	543.04	19.58	632.49	19.62	631.51

Table 6. Natural frequencies and modal masses of 4 m × 4 m square CLT floor (SSSS) for all considered scenarios.

Mode	Monolithic slab		Single surface spline		Half-lapped joint	
	Frequency [Hz]	Modal Mass [kg]	Frequency [Hz]	Modal Mass [kg]	Frequency [Hz]	Modal Mass [kg]
(1,1)	17.49	948.40	15.33	667.76	15.34	666.48
(2,1)	33.52	950.84	31.85	998.36	30.42	1046.70

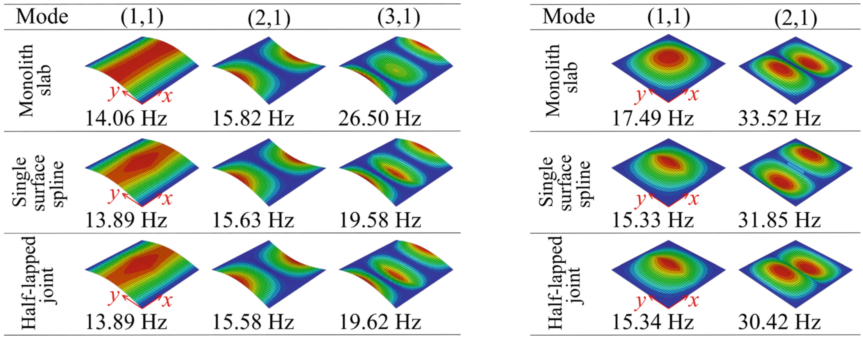

Fig. 7. Mode shapes and associated natural frequencies of 4 m × 4 m square CLT floor (left-SFSF, right-SSSS), considering different inter-panel connection types.

4 Discussion and Conclusions

Codes of practice and guidelines portray CLT floors either as monolithic slabs or as a set of panels with no connections. Numerical models of various CLT floors studied in this paper showed that the actual inter-panel connections should be included in the modal analysis. In case of the total absence of connections, each panel behaves dynamically as an individual floor. Hence, the results are not easily comparable to other two cases.

Two commonly used inter-panel connections, i.e. single surface spline and half-lapped joint, were modelled based on the analogy with the equivalent elastic strip. The strip properties were calculated to match the rotational and shear stiffnesses of the actual connections. Based on the visual observation of mode shapes and comparison between values of the natural frequencies of floors modelled as monolithic slabs and panels with connections, it could be concluded that the differences are the biggest for modes in which the modal coordinates are the largest along the connection line. This is when the connection line moves dominantly with respect to the rest of the floor. Moreover, such a comparison suggest that the modal properties are more sensitive to the rotational stiffness of the connection than to the bending stiffness. Changing boundary conditions also made a difference. Adding supports parallel to the panel orientation resulted in mode shapes flexing also along the minor strength direction. The connections affect significantly mode shapes and the bending stiffness of the floor in the minor direction when they coincide with the peak of the mode shape.

The models of floors with single surface spline and half-lapped joint produce virtually the same modal properties. A logical extension of the presented study should include a comparative analysis between the modal properties of floors with various models of the inter-panel connections, once these models have been made readily available in the academic literature.

Acknowledgments. 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. We are also very grateful to Mr. Ewan Macpherson for constructive discussions about his research on the rotational stiffness of half-lapped joints.

References

1. Pavic, A., Reynolds, P.: Vibration serviceability of long-span concrete building floors. Part 1: review of background information. Shock Vibrat. Digest **34**(3), 191–211 (2002)
2. Weckendorf, J., Ussher, E., Smith, I.: Dynamic response of CLT plate systems in the context of timber and hybrid construction. Compos. Struct. **157**, 412–423 (2016)
3. Ussher, E., Smith, I.: Predicting vibration behaviour of cross laminated timber floors. IABSE Sympos. Rep. **104**(19), 1–8 (2015)
4. Ussher, E., Arjomandi, K., Weckendorf, J., Smith, I.: Predicting effects of design variables on modal responses of CLT floors. Structures **11**, 40–48 (2017)
5. Huang, H., Gao, Y., Chang, W.S.: Human-induced vibration of cross-laminated timber (CLT) floor under different boundary conditions. Eng. Struct. **204**, 110016 (2020)
6. Wang, C., Chang, W.S., Yan, W., Huang, H.: Predicting the human-induced vibration of cross laminated timber floor under multi-person loadings. Structures **29**, 65–78 (2021)
7. Thiel, A., Schickhofer, G.: Design methods for cross laminated timber concerning floor vibrations: A comparability study. Research Report, Holz.bau Forschungs GmbH (98860) (2012)
8. Hamm, P., Richter, A., Winter, S.: Floor vibrations – new results. In: World Conference on Timber Engineering WCTE2010. Riva del Garda, Italy (2010)
9. Erol, K., Sylvain, G.: Canadian CLT Handbook 2019 edn. FPInnovations, Pointe-Claire, Quebec (2019)
10. Brandner, R., Flatscher, D., Ringhofer, A., Schickhofer, G., Thiel, A.: Cross laminated timber (CLT): overview and development. Eur. J. Wood Wood Prod. **74**(3), 331–351 (2016)
11. Brandner, R.:: Production and technology of Cross Laminated Timber (CLT): State-of-the-art Report. In: Focus Solid Timber Solutions – European Conference on Cross Laminated Timber (CLT), Graz, Austria (2013)
12. EN 1995-1-1: Eurocode 5: Design of timber structures - Part 1-1: General - Common rules and rules for buildings. European Committee of Standardization (CEN), Bruxelles, Belgium (2004)
13. Reddy, J.N.: Mechanics of Laminated Composite Plates and Shells: Theory and Analysis. CRC Press, Boca Raton (2004)
14. Mohammed, A.S., Pavic, A., Racic, V.: Improved model for human induced vibrations of high-frequency floors. Eng. Struct. **168**, 950–966 (2018)
15. Milojević, M., Racic, V., Marjanović, M., Nefovska-Danilović, M.: Influence of inter-panel connections on vibration response of CLT floors due to pedestrian-induced loading. Eng. Struct. **277**, 115432 (2023)
16. Willford, M.R., Young, P.: A Design Guide for Footfall Induced Vibration of Structures. MPA The Concrete Centre, London (2007)
17. Anders, G., Johan, F.: The CLT Handbook. Swedish Wood and Research Institutes of Sweden (2019)
18. ABAQUS User Manual 6.9. DS SIMULIA Corp., Providence, Rhode Island, USA (2009)
19. DIN 1052:2004: Design of Timber Structures – General Rules and Rules for Buildings. Beuth Verlag, Berlin, Germany (2004)
20. Hearmon, R.: The elasticity of wood and plywood. Forest Products Research Special Report No. 7, HMSO London (1948)
21. EN 338: Structural Timber – Strength Classes. European Committee of Standardization (CEN), Bruxelles, Belgium (2009)
22. Unterwiese. H., Schickhofer, G.: Characteristic values and test configurations of CLT with focus on selected properties. In: Focus Solid Timber Solutions – European Conference on Cross Laminated Timber (CLT), Graz, Austria (2013)