WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA

Advancing Timber for the Future Built Environment

VIBRATION BEHAVIOR OF CLT FLOORS IN A 5-STORY BUILDING PROTOTYPE UNDER HUMAN-INDUCED EXCITATION

Alexander Opazo-Vega[1], Alan Jara-Cisterna[2], Franco Benedetti[3], Manuel Suazo[4], Victor Rosales[5]

ABSTRACT: This paper presents the results of the vibration performance of two CLT slabs in a 5-story building. The CLT slabs are 165 mm thick, 4.2 m long, and 6.6 m wide, with different non-structural cladding on their top and bottom faces. The experimental campaign considered two types of vibration tests. The first was a modal impact test to determine the main dynamic properties of the slabs. For this purpose, seven uniaxial accelerometers were installed on the slabs. The second was a walking test in which people of different body masses walked on the CLT slabs at different step frequencies along a predefined trajectory. The vibration dose value (VDV) and one-step root mean square velocity (OS-VRMS) indicators were used to evaluate the level of vibrations in the CLT slabs. Three relevant dynamic properties were detected, with vibration frequencies between 23 Hz and 36 Hz and damping ratios between 2.4% and 4.2%. The results suggest that in real buildings, the vibration performance of CLT floors could be better than the estimations from some standards; therefore, future work is required to calibrate the numerical models of the CLT slabs to have more accurate predictions.

KEYWORDS: mass timber slabs, vibration dose value, radiata pine CLT panels, in-situ assessment, walking load

1 – INTRODUCTION

In recent years, CLT panels have been increasingly used as an efficient construction alternative for slabs in buildings. The structural design of these slabs is generally controlled by serviceability, especially under human-induced vibrations. Therefore, several researchers have studied the vibration performance of CLT slabs for different wood species, panel dimensions, support conditions, joint types, walking step frequencies, and walking patterns [1-9]. While most studies have focused on CLT slab prototypes under idealized laboratory conditions, our research delves into the practical implications of the vibration performance of CLT slabs in real buildings. Therefore, our study aims to fill this research gap by evaluating the vibrational performance of two CLT slabs in a 5-story building.

2 – BACKGROUND

The CLT slabs evaluated are located in the "Torre CLT Pymelab" building, a collaborative project built with the contribution of companies from Chile's timber and construction industries. Fig. 1 shows some constructive details.

3 – PROJECT DESCRIPTION

The two CLT slabs evaluated have the following characteristics: (i) they were made with C24 grade radiata pine timber (density 478 kg/m^3) and polyurethane adhesive, (ii) they have five layers of 33 mm, giving a total thickness of 165 mm, (iii) they have to cover an area of 4.2 m by 6.6 m, by five panels with widths between 1.2 m and 1.5 m and lengths of 4.1 m, (iv) the slab-to-slab joints are of the screwed double spline type, (v) the wall-to-slab joints are made with self-drilling screws and metal connectors, and (v) they have different types of upper and lower non-structural elements.

Fig. 2 shows the schematic plan views of the two slabs analyzed. The main differences between the two slabs are the position of the stairwells and the type of non-structural cladding beneath the slabs. Slab #1 has false ceilings consisting of a light timber framework and plasterboards, while slab #2 has no non-structural cladding.

[1] Alexander Opazo-Vega, Department of Civil and Environmental Engineering, University of Bio-Bio, Centro de Excelencia para la Industria de la Madera (CENAMAD), Pontificia Universidad Católica de Chile, Concepción, Chile, aopazove@ubiobio.cl

[2] Alan Jara-Cisterna, Department of Civil and Environmental Engineering, University of Bio-Bio, Concepción, Chile, afjara@ubiobio.cl

[3] Fanco Benedetti, Department of Civil and Environmental Engineering, University of Bio-Bio, Centro de Excelencia para la Industria de la Madera (CENAMAD), Pontificia Universidad Católica de Chile, Concepción, Chile, fbenedet@ubiobio.cl

[4] Victor Rosales, Department of Construction Sciences, University of Bio-Bio, Centro de Excelencia para la Industria de la Madera (CENAMAD), Pontificia Universidad Católica de Chile, Concepción, Chile, vrosaleg@ubiobio.cl

[5] Manuel Suazo, Department of Construction Sciences, University of Bio-Bio, Concepción, Chile, msuazo@ubiobio.cl

https://doi.org/10.52202/080513-0053

Figure 1.Construction details of the CLT slabs

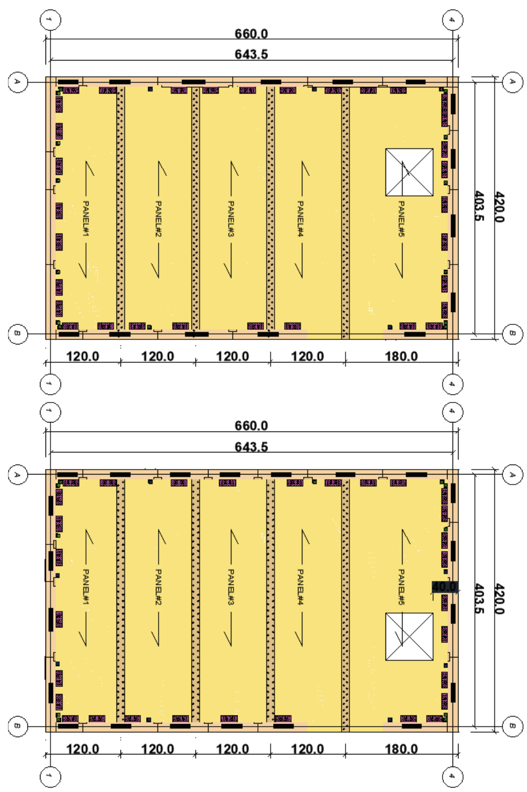


Figure 2. Plan view of the CLT slabs analyzed (top: slab#1, bottom:slab#2)

4 – EXPERIMENTAL SETUP

4.1 MODAL IMPACT TESTS

In the first stage, modal impact tests were carried out to determine the dynamic properties of the slabs. In these tests, blows were applied in the vertical direction with a modal impact hammer (model 086D20, PCB Piezotronics, Depew, NY, USA). The vertical impacts were applied at 25 points distributed across the CLT slabs, forming a five-by-five rectangular grid. Each point on the grid was hit three times to give the tests greater statistical reliability.

On the other hand, the slabs' vibratory response was measured by seven uniaxial accelerometers (model 603C01, IMI sensors, Depew, NY, USA). The accelerometers had a sensitivity of 100 mV/g and a bandwidth resolution of 0.00035 g. The data acquisition system consisted of a multi-channel dynamic signal acquisition module (model NI 9234) assembled in a Compact DAQ chassis (model cDAQ-9174, National Instruments, Austin, TX, USA) and connected via USB to a laptop computer. Finally, the vibratory response associated with each impact was sampled at 826 Hz. For each blow, 7500 samples were acquired over 9 seconds. Fig. 3 shows the position of the impact points and the accelerometers on the CLT slabs.

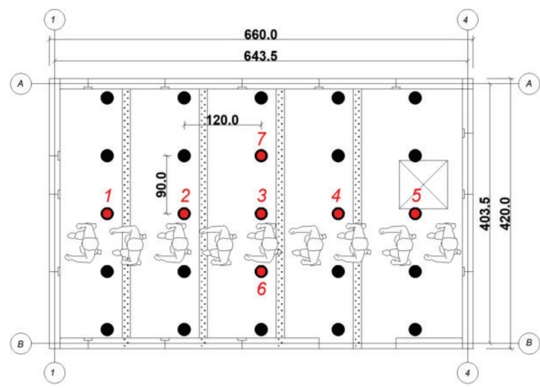


Figure 3. Impact grid positions (black circles) and accelerometers positions (red circles)

The frequencies and vibration modes of the CLT slabs were identified using the Polyreference Time Domain method (PTD). This method was developed by Vold [10] and is one of the most widely used in practice because it even allows identifying closely spaced frequencies [11]. In addition, it works simultaneously with multiple references (e.g., multiple accelerometers), which generates a better estimation of the modal shapes. In general terms, the PTD method extracts modal parameters of a system (e.g., poles and modal participation factors) from the modal decomposition in the time domain.. The identification of all dynamic properties was performed in the ABRAVIBE toolbox [11].

4.2 WALKING TESTS

In the second stage, walking tests were carried out on the CLT slabs to evaluate their vibratory performance. The walks were carried out by 4 people, who moved along the center of the slabs at five different frequency steps: 1.4 Hz, 1.6 Hz, 1.8 Hz, 2.0 Hz, and 2.2 Hz. Each walk lasted 15 seconds. Fig. 3 shows the trajectory used in the walks.

The vibrational performance of the slabs was evaluated using two indicators. The first indicator used was the root mean square of the velocity response generated by each step (*OS-VRMS*). This performance indicator is being included in the latest update of Eurocode 5 for high-frequency floors, which are distinguished by having an impulsive (non-resonant) dynamic response to people walking. In general terms, *OS-VRMS* measures the average of the vertical velocity response on a floor generated by a step, in a very short instant of time (less than 1 second). The analytical expression of *OS-VRMS* is shown in (1).

https://doi.org/10.52202/080513-0053

$$v_{RMS} = \left(\frac{1}{\tau} \int_0^{\tau} v_w^2(t)dt \right)^{0.5} \qquad (1)$$

where v_w is the velocity response, and τ is the duration of one step.

The values obtained from *OS-VRMS* are compared with different limits proposed by Eurocode 5, allowing the performance level of the floors to be classified into six categories, as shown in Table 1.

Table 1: Limit values for OS-VRMS indicator

OS-VRMS limits (m/s)	**Floor performance levels**					
	I	II	III	IV	V	VI
	0.0004	0.0008	0.0012	0.0024	0.0036	0.0048

Eurocode 5 indicates that a residential floor in a multi-family block would have a quality vibratory performance if classified in one of the first three categories (I, II, or III). If the floor is classified in category IV, it is considered to have an intermediate performance. Finally, if the floor is in category V, it is considered to have a performance that just meets the requirements, typical of cheaper floors.

The vibration dose value (*VDV*) was the other vibration performance indicator. This indicator is proposed by the BS6472 standard, and is a measure of the accumulation of the level of vertical accelerations caused by people walking. The analytical expression of the *VDV* indicator is shown in (2).

$$VDV_{\tau} = \left(\int_0^{\tau} a_w^4(t)dt \right)^{0.25} \qquad (2)$$

where, a_w is the frequency-weigthed vertical acceleration, and τ is the duration of a walk.

The VDV_{τ} value obtained in a walk must be brought to the scale of a 16-hour day. Accordingly, the VDV_{τ} obtained must be amplified by a factor considering that the walk will be repeated several times in a 16-hour day. If a walk can be repeated 32 times in 16 hours, the amplification factor is 2.38 (VDV_{day}=2.38*VDV_{τ}). Finally, this VDV_{day} is compared with the limit values proposed by the BS6472 standard, which are shown in Table 2.

Table 2: Limit values for VDV indicator

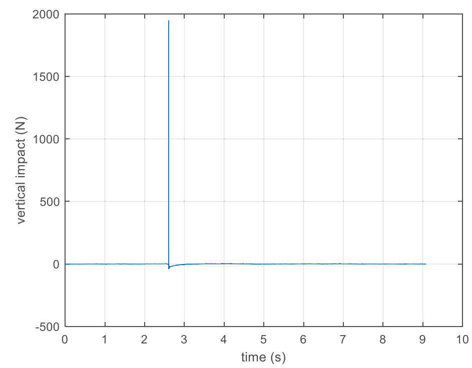
VDV_{day} (m/s^1.75)	**Vibration dose value ranges**		
	Low probability of adverse comment *	***Adverse comment possible***	***Adverse comment probable *****
Residential building 16h day	0.2 to 0.4	0.4 to 0.8	0.8 to 1.6

*Below these ranges adverse comment is not expected. **Above these ranges adverse comment is very likely.

5 – RESULTS

5.1 DYNAMIC PROPERTIES OF THE CLT SLABS

The dynamic properties of the floors were obtained through modal impact tests. Fig. 4 shows a set of typically measured records of an impact and an acceleration response on the CLT slabs.



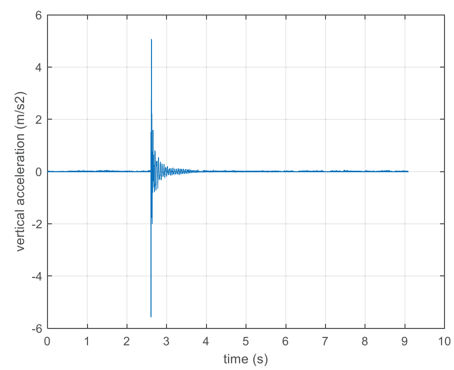


Figure 4. Impact signal (top) and acceleration signal adquired on a CLT slab

With the signals acquired in the modal impact tests, stabilization diagrams were calculated, from which it was possible to identify three sets of vibration frequencies, damping ratios, and modal shapes. One of the typical stabilization diagrams obtained from the measurements is shown in Fig. 5.

The three modal shapes that were identified with the impact tests are shown in Fig. 6. The first modal shape clearly shows all the CLT panels moving in a solidarity way in the vertical direction and the same sense. On the other hand, the rest of the modal shapes show vertical movements where certain sectors move in opposite senses. The experimentally obtained modal shapes were quite similar to those theoretically expected, demonstrating the joints' effectiveness in generating a unified floor structure in both the strong and weak axes of the CLT panels.

https://doi.org/10.52202/080513-0053

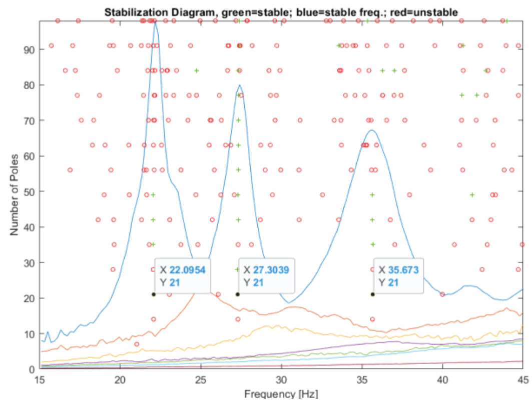


Figure 5. Typical stabilization duagram obtained from impact tests

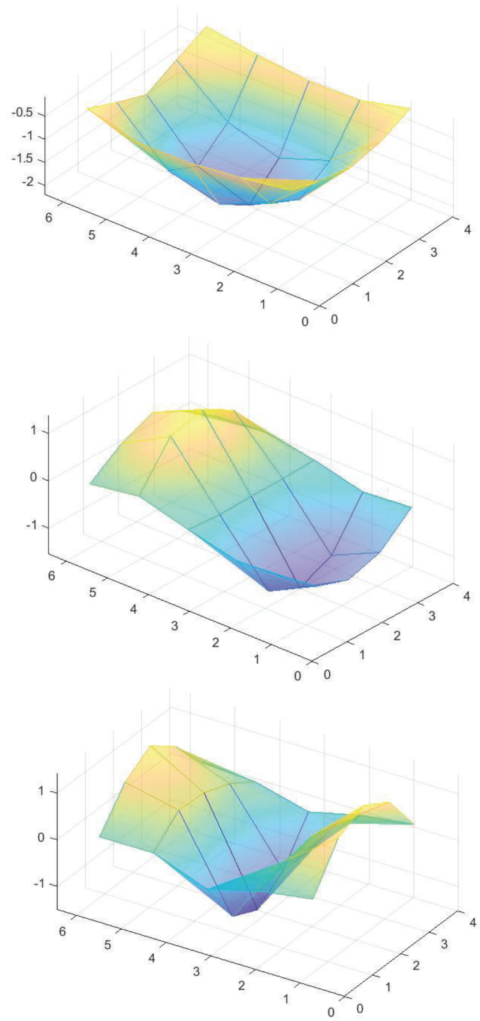


Figure 6. Experimental modal shapes of CLT slabs

On the other hand, the average values of the vibration frequencies and the damping ratios of the three vibration modes are shown in Tables 3 and 4.

Table 3: Vertical vibration frecuencies of the CLT slabs

CLT Slab#	Frequency					
	f_1		f_2		f_3	
	Mean (Hz)	CoV* (%)	Mean (Hz)	CoV* (%)	Mean (Hz)	CoV* (%)
1	22.3	1.1	27.1	0.9	36.3	2.1
2	23.1	0.2	27.2	0.5	35.3	1.2

*Coefficient of variation

Table 4: Damping ratios of the CLT slabs

CLT Slab#	Damping ratio					
	ξ_1		ξ_2		ξ_3	
	Mean (Hz)	CoV* (%)	Mean (Hz)	CoV* (%)	Mean (Hz)	CoV* (%)
1	2.8	15.9	3.3	21.1	4.1	0.23
2	1.9	16.6	2.1	14.8	4.3	12.1

*Coefficient of variation

Tables 3 and 4 show that slab #1 has a smaller frequency, f_1, than slab #2. Besides, the slab #1 has a larger damping ratio, ξ_1, than slab #2. These differences in the fundamental properties of the slabs are mainly due to the fact that slab #1 has non-structural elements in its lower surfaces, while slab #2 does not. The presence of non-structural elements increases the slab's mass, decreasing the vibration frequency. On the other hand, it is known that another effect of the presence of non-structural elements is to increase the damping ratio. Therefore, this variation in the slabs' fundamental dynamic properties was expected.

5.2 VIBRATION PERFORMANCE OF THE CLT SLABS

The vibratory responses of the slabs obtained in the walking tests were impulsive, where the vibration generated by each step decayed before the next step without reaching any resonance. These vibratory results were consistent with the high vibration frequencies obtained in the slabs. A typical response obtained in the slabs is shown in Fig. 7.

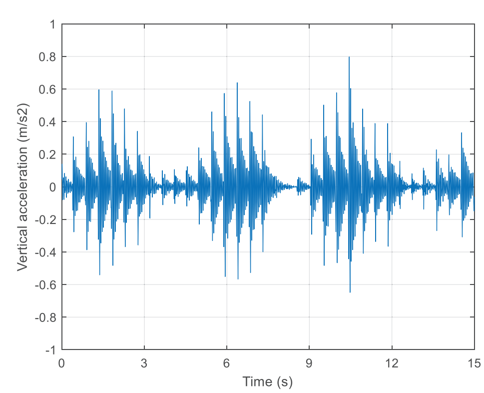


Figure 7. Vertical acceleration induced by a 2.2Hz walk on slab#1

With the accelerations obtained in the walking tests, the *VDV* indicators could be calculated directly. However, to calculate the *OS-VRMS* indicators, it was necessary to integrate the accelerations to obtain velocities and then calculate the RMS value of the velocities generated by each step. Fig. 8 shows an example of the velocity signal obtained.

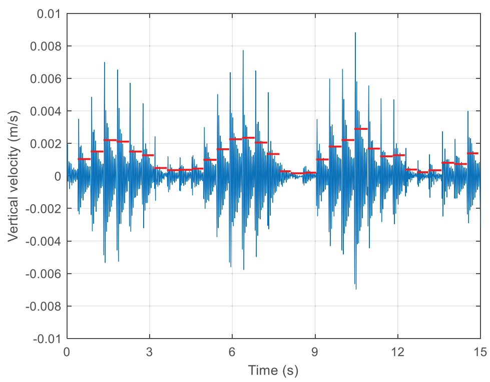


Figure 8. Vertical velocity induced by a 2.2Hz walk on slab#1 (red lines indicates de RMS value for each step)

Fig. 9 shows the box plots that summarize all the results obtained from the VDV_{day} indicators in the two slabs. In addition, the limit values proposed by the BS6472 standard that were mentioned in Table 2 are also shown for reference.

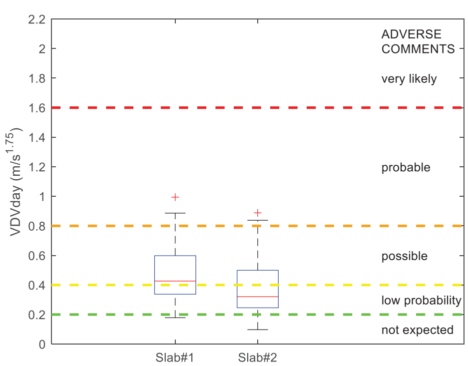


Figure 9. Boxplots for the VDVday indicators on slabs #1 and #2 (outliers are indicated with a red cross)

Each box plot shown in Fig. 9 contains a total of 60 VDV_{day} values, which corresponded to the responses of accelerometers #3, #4 and #5 induced by the walking of 4 people at 5 different step frequencies.

As can be seen in Fig. 9, according to the VDV_{day} indicator, the vibration performance of the floors was excellent since most of the values obtained remained in the zones of low probability of adverse comments from users regarding the level of vibrations in the floors ($VDV_{day} < 0.8$ m/s$^{1.75}$). In addition, slab#2 performed slightly better than slab#1, as it has a higher fundamental vibration frequency (f_1).

On the other hand, Fig. 10 shows the box plots that summarize all the results obtained from the *OS-VRMS* indicators in the two slabs. Besides, the limits proposed by Eurocode 5 and mentioned in Table 1 are also shown.

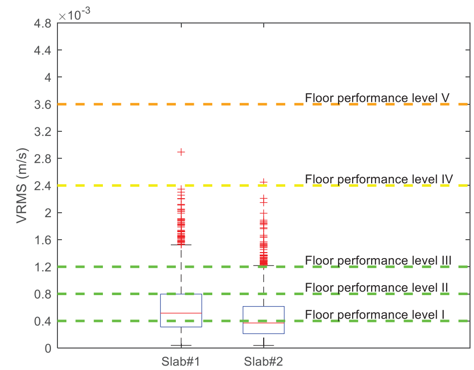


Figure 10. Boxplots for the OS-VRMS indicators on slabs #1 and #2 (outliers are indicated with a red cross)

It is important to mention that each box plot in Figure 10 contains around 1500 *OS-VRMS* values. This large number of values is explained by the fact that each walk generated between 20 and 30 steps, for 4 people walking at 5 step frequencies, and measuring on 3 accelerometers.

The presence of various outliers can also be seen in Fig. 10. These atypical values corresponded to less than 5% of the total data and generally coincided with deviations in the trajectories of the people, which generated steps too close to the accelerometers. If the outliers are omitted, according to the OS-VRMS criteria, the floors also had a very good vibratory performance, ranking in the best levels I, II, and III. In addition, this vibratory indicator also confirms the trend that slab #2 has a slightly better performance than slab #1.

6 – CONCLUSIONS

The present work evaluated the vibratory performance of two CLT slabs constructed in a 5-story building. Both the VDV_{day} indicator criterion and the *OS-VRMS* indicator criterion demonstrated that the two CLT slabs have excellent vibratory performance. These results confirm the structural design stage hypotheses and demonstrate that CLT slabs can achieve the best vibratory performance. In this way, CLT slabs continue to stand out as a feasible alternative for achieving more sustainable constructions without compromising serviceability and safety standards.

The experimental results also show that CLT slabs built in real buildings have better vibratory performance than that estimated with the approximate equations in technical standards. For example, the fundamental frequencies measured in the slabs were around 30% higher than those estimated by the analytical equations of Eurocode 5. On the other hand, the 90th percentile values obtained in the measurements of the *OS-RMS* indicators were about 50% lower than those estimated by the analytical equations of Eurocode 5. These results suggest the need to continue improving CLT slabs' analytical equations and numerical

https://doi.org/10.52202/080513-0053

models to more accurately incorporate their real dynamic behavior.

7 – ACKNOWLEDGEMENTS

The authors thank ANID BASAL FB210015 for their ongoing scientific collaboration with our academic departments.

8 – REFERENCES

[1] S. Zhang, Y. Chui. "Quantifying the effect of end support restraints on vibration serviceability of mass timber floor systems: Testing." In: Engineering Structures 301 (2024), pp. 117189.

[2] M. Milojević, V. Racic, M. Nefovska-Danilović, et al. "Characterization of inter-panel connections in CLT floors using finite element model updating." In: Journal of building engineering, 97 (2024)., pp. 110682.

[3] J. Zhang, H. Huang, & B. J. Wang, "Long-term loading effect on vibration performance of CLT floors: An 896-day monitoring study." In: Engineering Structures, 316 (2024), pp. 118562.

[4] J. Zhang, C. Zhang, Y. Li, et al. "Cross-laminated timber (CLT) floor serviceability under multi-person loading: Impact of beam–panel connections." In: Engineering Structures, 296 (2023), pp. 116941.

[5] N. Simović, I. Glišović, & M. Todorović. "Design of cross-laminated timber (CLT) floors for human-induced vibrations." In: Building Materials and Structures, *66*. (2023).

[6] A. Aloisio, D. Pasca, Y. De Santis, et al. "Vibration issues in timber structures: A state-of-the-art review." In: Journal of Building Engineering 76 (2023), pp. 107098.

[7] M. Milojević, V. Racic, Marjanović, et al. "Influence of inter-panel connections on vibration response of CLT floors due to pedestrian-induced loading." In: Engineering Structures, 277 (2023), pp. 115432.

[8] A. Opazo-Vega, F. Benedetti, M. Nuñez-Decap, et al. "Non-destructive assessment of the elastic properties of low-grade CLT panels." In: Forests, 12.12 (2021), pp.1734.

[9] C. Wang, W. S. Chang, W. Yan, et al. "Predicting the human-induced vibration of cross laminated timber floor under multi-person loadings." In: Structures 29 (2021), pp. 65-78.

[10] H. Vold, J. Kundrat, G.T. Rocklin, et al. "Multi-Input Modal Estimation Algorithm for Mini-Computers." In: SAE Trans., 91 (1982), pp. 815–821.

[11] A. Brandt. "Notes on Using the ABRAVIBE Toolbox for Experimental Modal Analysis.". Available online: https: //blog.abravibe.com/2013/06/21/notes-on-using-the-abravibe-toolbox-for-experimental-modal-analysis-14/ (accessed on 1 October 2021).