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HUMAN-INDUCED VIBRATIONS OF CROSS-LAMINATED TIMBER FLOORS

Abstract

This paper discusses vibration serviceability assessment of cross-laminated timber (CLT) floors induced by human activities, with special emphasis on vibrations induced by walking. In the first part current design criteria for vibration serviceability check of timber and CLT floors were analyzed in line with the more general vibration performance-based approach applicable to any floor structure regardless of the material used. The second part focuses on the ongoing research achievements in the design of vibration resistant CLT floors carried out at the Faculty of Civil Engineering, University of Belgrade. In addition, challenges for future research were formulated as well.

Keywords: vibration servceability, pedestrian dynamic load, CLT, walking frequency, hybrid floors

ВИБРАЦИЈЕ МЕЂУСПРАТНИХ КОНСТРУКЦИЈА ОД УНАКРСНО ЛАМЕЛИРАНОГ ДРВЕТА ИЗАЗВАНЕ ЉУДСКИМ АКТИВНОСТИМА

Сажетак

У овом раду анализирана је процјена вибрација међуспратних конструкција од унакрсно-ламелираног дрвета, које су изазване људским активностима, са посебним акцентом на вибрације изазване ходањем. У првом дијелу, приказане су тренутно коришћене методе за процјену вибрација дрвених и CLT међуспратних конструкција, као и општија метода заснована на евалуацији нивоа вибрација, која се може примијенити у анализи било које међуспратне конструкције, без обзира на материјал од кога је направљена. У другом дијелу рада, дат је приказ резултата истраживања у области развоја CLT међуспратних конструкција отпорних на вибрације, које се спроводи на Грађевинском факултету Универзитета у Београду. Поред тога, формулисани су изазови у будућем истраживању.

Кључне ријечи: гранично стање употребљивости на вибрације, пјешачко динамичко оптерећење, CLT, хибридне међуспратне конструкције

1. INTRODUCTION

Nowadays, almost 40% of the global carbon emissions come from the construction sector: 30% from operational carbon associated with energy used to operate the building, and 10% from embodied carbon generated during the production, transport and construction of building materials [1]. This rate is expected to grow drastically: recent studies have indicated that carbon emission from building materials and processes will be responsible for almost half of the carbon emission by 2050. To meet the goals of the Paris Agreement, construction sector needs to reach net-zero carbon emissions by 2050, while new buildings will have to be net-zero carbon starting from 2023, [2]. Moreover, during the next 40 years the total building floor area is expected to double by approximately 230 bn m^2 of new floors. Considering all the points mentioned above, the key question is how to fulfill the demands of the global real estate market while also attaining net-zero carbon buildings. One of possible pathways to reduce embodied carbon in civil engineering is using renewable materials such as wood.

Due to the limited size and mechanical properties of the raw timber material, its traditional use remains widespread for housing and low-rise buildings. However, after decades of dominance of concrete and steel civil engineering structures, a significant shift in the construction sector emerged in the 1990s with the invention of cross-laminated timber (CLT). CLT is a plate-like engineered wood-based product assembled of several (usually odd) thin layers arranged and glued in a crosswise manner, Figure 1. Its outstanding strength, stiffness and aesthetic appeal, combined with high level of prefabrication, construction speed and good fire resistance, position CLT as a highly competitive alternative to traditional building materials like concrete and steel. This has been confirmed through a wide range of applications on residential, public, and commercial multi-story buildings across Europe and North America over the past decade, in which key load-bearing structural elements – walls and floors were made entirely of CLT. Typically, the width of CLT panels ranges from 2.5 to 3 meters, while the length can extend up to 20 meters. Panels are connected together on site using fasteners and self-tapping screws, forming multi-panel floor structures.

CLT is a lightweight material having a high stiffness-to-weight ratio. CLT floors possess enough stiffness to span relatively large distances. However, due to their low weight, CLT floors may exhibit excessive vibrations induced by human activities such as walking, running or jumping. While these vibrations may not cause structural damage, they can lead to discomfort for occupants or malfunctions in vibration-sensitive equipment [3]. Consequently, vibration serviceability has become a growing concern in the construction industry, governing the design of lightweight long-span floors in modern buildings. This implies that the shape and dimensions of the floor are dictated by vibration requirements rather than strength considerations. Although extensive research has been conducted on this issue in the past few decades, the focus has predominantly been on floors made of concrete and steel-concrete composites, resulting in the development of relevant design guidelines [4-7]. These guidelines exploit the vibration performance approach which suggests vibration serviceability (VS) assessment based on the evaluation of the vibration response level in terms of acceleration or velocity. On the other hand, provisions in Eurocode 5 refer to vibration performance of traditional timber joist floors having fundamental frequency greater than 8 Hz [8]. Recently, several studies have been carried out to address the most important factors affecting the vibration performance of CLT floors, [9], [10]. It has been shown that CLT floors exhibit different behavior from traditional lightweight timber joist floors. Based on experimental data, in the Canadian CLT Handbook an empirical method for VS assessment has been proposed by relating the fundamental frequency and static deflection of the CLT floor, [11]. The method is simple but has limited ranges of applicability. Moreover, both Eurocode 5 and CLT Handbook limit the fundamental frequency of traditional timber floors and CLT floors to 8 Hz respectively, to avoid resonant vibration response. Recent studies have shown that the cut-off frequency between the low frequency floors having resonant response and high frequency floors having transient response is even 14Hz [12]. This clearly confirms that CLT floors may have strong dynamic response in both low and high frequency range. In addition, existing empirical design methods do not account for other design considerations that can significantly affect the vibration response of CLT floors, such as additional floor mass, orthotropic behavior of CLT, inter-panel connections, damping, different types of boundary conditions, amongst others. Consequently, they can lead to cost-ineffective floor solutions in terms of spending more material to improve vibration performance, which is unacceptable from the carbon emission standpoint.

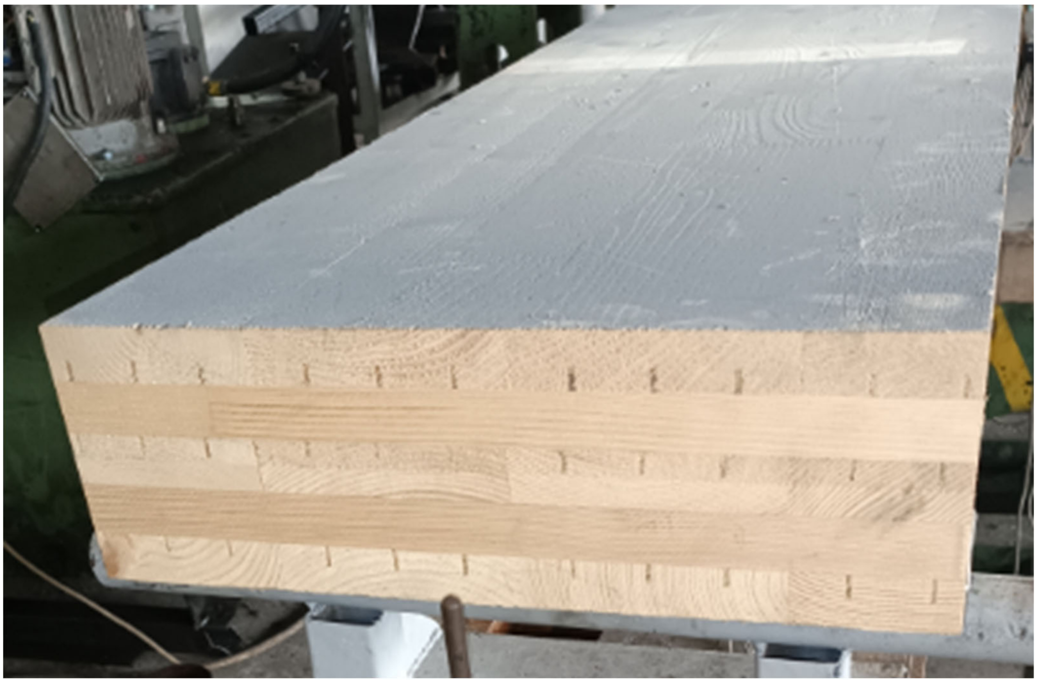


Figure 1. A 5-ply CLT panel

Recent studies have confirmed that design methods for vibration of both CLT and traditional timber floors need updating, including more reliable calculation methods for vibration response assessment, such as vibration performance-based methods [13], [14].

This paper aims to present research achievements in the design of vibration-resistant CLT floors subjected to human-induced dynamic loading, with specific emphasis on the ongoing work at the University of Belgrade, Faculty of Civil Engineering (FCEUB).

After the introduction section, Section 2 describes fundamentals of dynamic of modelling of walking force models. Section 3 deals with different approaches used for VS assessment of CLT floors, while research developments within the ongoing research project at FCEUB were presented in Section 4. Finally, Section 5 summarizes conclusions and further research directions.

2. HUMANS AS SOURCE OF FLOOR VIBRATIONS

To prevent excessive floor vibrations and discomfort of human occupants in buildings, reliable and accurate prediction of floor vibration is necessary in the design stage. This involves consideration the following key aspects of VS assessment:

- **vibration source** - dynamic load induced by human activities,
- **vibration path** - the floor structure and its modal properties (natural frequencies and mode shapes, modal mass and damping),
- **vibration receiver** - humans or vibration sensitive equipment.

Floors occupied by people are subjected to dynamic loads induced by human activities such as walking, jumping or running. Given that walking is the most common human activity, particular attention will be devoted to it.

Extensive experimental research has shown that a pedestrian in normal walking makes about 1.5 to 2.5 steps per second. This means that the frequency of normal walking - f_p ranges from 1.5 to 2.5 Hz (on average around 1.8 Hz). Dynamic force is quasi periodic, while its Fourier spectrum exhibits peak amplitudes corresponding to f_p (first harmonic), $2f_p$ (second harmonic), $3f_p$ (third harmonic), $4f_p$ (fourth harmonic) and $5f_p$ (fifth harmonic) as can be seen in Figure 2. The strongest peak corresponds to the frequency of the first harmonic which is equal to the walking frequency. In addition, amplitudes in the Fourier spectrum can be detected in the frequency range up to 50Hz.

As a result of the total lack of available walking force models that can describe the full amplitude spectrum of the measured walking force signals, two different mathematical models of walking-induced dynamic force were developed in recent studies. The first is the harmonic walking force model proposed to evaluate vibrations of low-frequency floors that can exhibit resonant vibration response, Figure 3 (left). The second model is based on impulses used to evaluate vibration response of high-frequency floors, that can exhibit transient response, Figure 3 (right). More details on the force modes will be given in the next section.

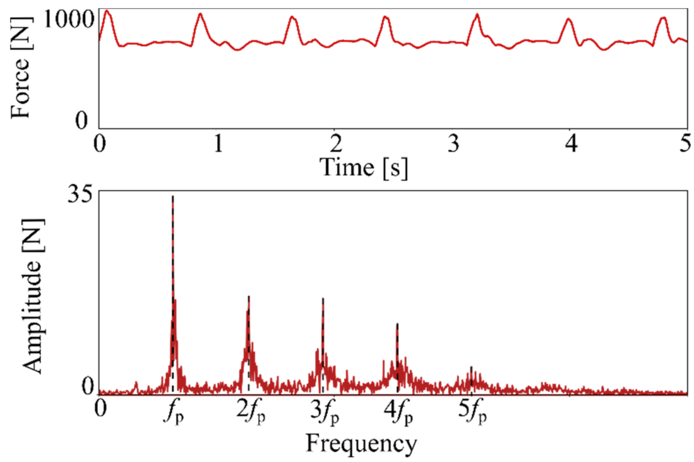


Figure 2. Time and frequency domain signal of a measured vertical force generated by walking

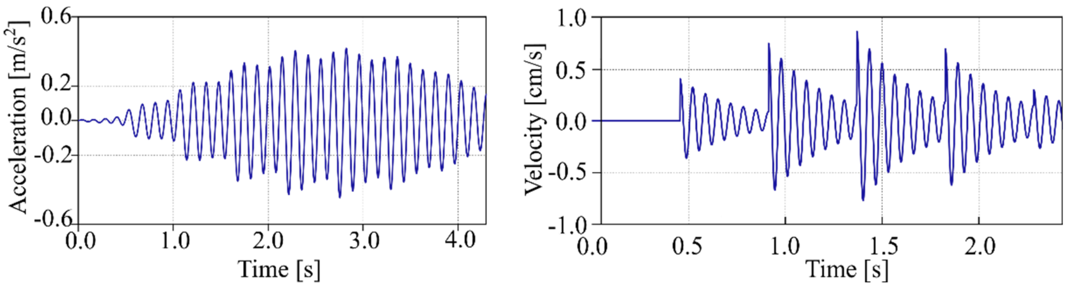


Figure 3. Vibration response of low-frequency floor (left) and high-frequency floor (right)

3. EMPIRICAL METHODS FOR VS ASSESSMENT OF CLT FLOORS

Popular design criteria for vibration serviceability check of timber floors restrict excessive vibrations by limiting the fundamental frequency, static deflection [15], or by relating the fundamental frequency and static deflection [8], [11]. Most of them are empirical methods, formulated based on data collected through experimental studies. Basic idea behind these methods is, when used correctly, they simplify VS assessment procedure and avoid dynamic modelling. In this section two most commonly used design methods in engineering practice will be elaborated.

3.1. CLT HANDBOOK METHOD

According to the Canadian CLT Handbook [11], the vibration-controlled span of a CLT floor is calculated as:

$$L \leq 0.11 \frac{\left(\frac{EI_{eff}}{10^6} \right)^{0.29}}{m^{0.12}} \tag{1}$$

where EI_{eff} is the effective bending stiffness in the major strength direction for a 1-m wide panel (Nm^2), while m is the linear mass of CLT for a 1-m wide panel (kg/m). Although simple, this empirical approach has a limited range of applicability. It was derived from experimental testing conducted on single-span bare CLT panels supported on walls. Furthermore, the reliable estimation of vibration performance can be obtained only in cases where floor layouts closely match those to which expression (1) was calibrated.

As can be seen from Equation (1), estimation of vibration performance depends on the bare panel properties, without considering additional mass, damping, floor layouts and different support conditions, as well as dynamic load induced by building occupants. Moreover, according to the handbook, CLT floors are characterized as high-frequency floors having fundamental frequency greater than 9 Hz, i.e. they exhibit only transient-like vibration response due to each footfall, with peak values mainly governed by the stiffness and mass of the floor. Such approach assumes that only high-frequency floors can have good vibration performance. However, high-frequency floors can exhibit vibration serviceability issues as well. Consequently, this frequency limitation is unacceptable from the ecology and carbon emission perspective.

3.2. HAMM'S DESIGN METHOD

Based on a comprehensive study carried out on approximately 100 timber floors including 38 mass timber floors, Hamm et al. [16] proposed design procedure for VS assessment of both traditional timber joist and CLT floors. The procedure is applicable to floors with fundamental frequency greater than 4.5 Hz and requires classification of the floor into one of three floor classes as given in Table 1. Moreover, the cut-off frequency f_{lim} is introduced to distinguish between low and high frequency floors. Both low and high frequency floors should meet the stiffness criterion in terms of deflection due to a 2 kN point load calculated as:

$$w = \frac{2l^3}{48EI_l b_w} \leq w_{\lim} \tag{2}$$

where l is the floor span, EI_l is the bending stiffness in the longitudinal direction (including the screed stiffness), while b_w is given as:

$$b_w = \min \begin{cases} b_{ef} = \dfrac{l}{1.1}\sqrt[4]{\dfrac{EI_b}{EI_l}} \\ b \end{cases} \tag{3}$$

In Equation (3), b is the floor width, while EI_b is the effective bending stiffness in the transverse direction. Deflection limit values are given in Table 1.

For low frequency floors, additional criterion is introduced in terms of acceleration induced by dynamic harmonic force with walking frequency equal half or third the fundamental frequency of the floor. Maximum resonant response of the floor is calculated as:

$$a = \frac{F_{dyn}}{2M\varsigma} = \frac{0.4F_n}{2M\varsigma} \leq a_{\lim} \tag{4}$$

where:

ς is the modal damping ratio,

M is the modal mass,

F_{dyn} is total dynamic force that includes factor of 0.4 considering that the force on the floor is acting during a limited time and not always in the midspan,

F_n is amplitude of the n^{th} harmonic of the force (F_2 = 140 N, F_3 = 70 N).

3.3. VIBRATION PERFORMANCE-BASED APPROACH

Based on the discussion in the previous section, it is evident that empirical-based methods are unreliable often leading to overestimation of the vibration response and consequently to cost-ineffective floor solutions. Hamm et al. [16] made a step forward introducing additional acceleration criterion but only for low frequency floors.

On the other hand, vibration performance-based approach is well developed and integrated into several design guidelines for VS assessment of concrete and steel-concrete composite floors. This approach is based on the evaluation of the vibration response level which is then compared to a predefined threshold value. Moreover, it accounts for three key components of the VS assessment: vibration source, floor's modal properties and receiver's response to floor vibrations.

The approach is general and based on the modal superposition method for calculation of the footfall induced floor vibrations. To account for arbitrary floor layouts, support conditions, effects of non-structural elements such as partitions, modal properties are determined from the finite element analysis (FEA).

Arup's design guideline [17] offers a model of pedestrian vertical loading that applies to any type of floor structure regardless of the material. Here, the cut-off frequency between the low-frequency floors and high-frequency floors is set to 10.5 Hz. Key features of this guideline will be elaborated in the following sections.

Table 1. Floor classes and corresponding limit values [16]

	Class I	Class II	Class III
Vibration demands	Floors with high demands	Floors with low demands	Floors without demands
Description of vibration perception	Vibrations are not perceptible or only perceptible when concentrating on them. Vibrations are not annoying.	Vibrations are perceptible but not annoying.	Vibrations are clearly perceptible and sometimes annoying.
Type of use	Corridors with low spans, floors in apartment or office buildings	Floors in single-family houses	Floors under non-residential rooms or roof spaces
Frequency criterion	f_{lim} = 8 Hz	f_{lim} = 6 Hz	-
Stiffness criterion	w_{lim} = 0.5 mm	w_{lim} = 1.0 mm	-
Acceleration criterion	a_{lim} = 0.05 m/s^2	a_{lim} = 0.1 m/s^2	-

3.3.1. LOW-FREQUENCY FLOORS

Floors with a fundamental frequency below 10 Hz are likely to develop resonant response induced by one of the first four harmonics of the walking force. In this case, the walking force model is defined as a sum of four harmonics described by a Fourier series:

$$F(t) = W\sum_{i=1}^{4} DLF_i \sin\left(2\pi i f_p t\right) = \sum_{i=1}^{4} F_i \sin\left(2\pi i f_p t\right) \tag{5}$$

where W is the weight of a pedestrian, f_p is the walking frequency, while DLF_i is the dynamic load factor corresponding to the i-th harmonic. The frequency of each harmonic is an integer multiple (i = 1–4) of the selected walking frequency in the range 1.5–2.5 Hz. Design values of the dynamic load factors are given in Table 2.

The guideline suggests that all modes up to 15 Hz can significantly contribute to the vibration response and therefore should be identified and included in the analysis. For a walking frequency f_p, the maximum amplitude of resonant response of the n-th mode to each of the four harmonics i is calculated as:

$$a_{n,i} = \frac{\mu_{e,n} \cdot \mu_{r,n} \cdot F_i}{2M_n \varsigma_n} \tag{6}$$

where:

$F_i = W \cdot DLF_i \quad i = 1,2,3,4$,

M_n is the modal mass,

ς_n is the modal damping,

$\mu_{e,n}, \mu_{r,n}$ are the mode shape values at the excitation (e) and response (r) points in each mode n, respectively.

More details regarding the vibration response calculation can be found in [17]. From Equation (6) it is evident that in resonance, the calculated response is inversely proportional to the floor's modal mass and damping. While reliable estimation of the modal mass can be obtained from the FEA, damping can be reliably estimated only through experimental testing.

Table 2. Dynamic load factors [17]

Harmonic number	Forcing frequency [Hz]	Design value of *DLF*
1	1 – 2.8	$0.41(f\text{-}0.95) \leq 0.56$
2	2 – 5.6	$0.069 + 0.0056f$
3	3 – 8.4	$0.033 + 0.0064f$
4	4 – 11.2	$0.013 + 0.0065f$

3.3.2. HIGH-FREQUENCY FLOORS

Floors with a fundamental frequency greater than 10 Hz are categorized as high-frequency floors, exhibiting a transient response characterized by a rapid decay between two footfalls. The walking model is based on a series of vertical impulses corresponding to each footfall. Design value of a vertical impulse which simulates a single footfall is defined as:

$$I_{eff,n} = 54\frac{f_p^{1.43}}{f_n^{1.3}} \quad [Ns] \tag{7}$$

where f_n is the natural frequency corresponding to the n-th mode shape.
The velocity time history due to a single footfall at a particular location on the floor is calculated as:

$$v_n(t) = \hat{v}_n e^{-2\pi\varsigma_n f_n t}\sin(2\pi f_n t) = \frac{\mu_{e,n} \cdot \mu_{r,n} \cdot I_{eff,n}}{M_n} e^{-2\pi\varsigma_n f_n t}\sin(2\pi f_n t) \tag{8}$$

The procedure developed in the guideline is based on the modal superposition method advocating that all mode shapes with natural frequencies up to twice the fundamental frequency should be included in the vibration response calculation. Finaly, the total response to each footfall is calculated by summing the velocity responses in each mode:

$$v(t) = \sum_{n=1}^{N} v_n(t) \tag{9}$$

3.4. HUMAN PERCEPTION OF VIBRATIONS

Vibrations induced by building occupants may be annoying, causing people's discomfort and affecting usability of a structure. Human perception of vibration is highly subjective. It depends on the vibration amplitude and frequency, exposure time, body posture and direction, [18]. When human perception of vibrations is the primary criterion, the vibration level is assessed based on calculated averages of acceleration or velocity. The root mean square (RMS) is commonly used averaging technique that accounts for changes in amplitude over time and is frequently applied to both transient and resonant vibration responses. An RMS value of a time domain signal *x(t)* calculated over a certain averaging time *T* is defined as:

$$x_{RMS}(t) = \sqrt{\frac{1}{T}\int_0^T x(t)^2\, dt} \tag{10}$$

ISO 10137 standard [3] defines base curves for human perception of vibration with respect to the frequency and the orientation of the vibration relative to the axes of the human body. The baseline curve given in Figure 4 (left) defines the RMS acceleration level corresponding to the vertical *z* - axis. Apparently, people are most sensitive to vibrations in the frequency range between 4 – 8 Hz, where the baseline RMS acceleration perceptible by humans is equal to 0.005 m/s^2. For frequencies higher than 8 Hz, the RMS threshold value linearly increases. For high-frequency floors for which vibration response is calculated in terms of velocity, human perception is evaluated based on the curve presented in Figure 4 (right), with the RMS velocity level perceptible by humans equal to 10^{-4} m/s.

Acceptable vibration levels are often assessed using the so-called response factor, or R factor, which represents the ratio between the measured (or predicted) vibration level and the corresponding threshold of perception:

$$R = \frac{a_{RMS}}{0.005} \quad or \quad R = \frac{v_{RMS}}{10^{-4}} \tag{11}$$

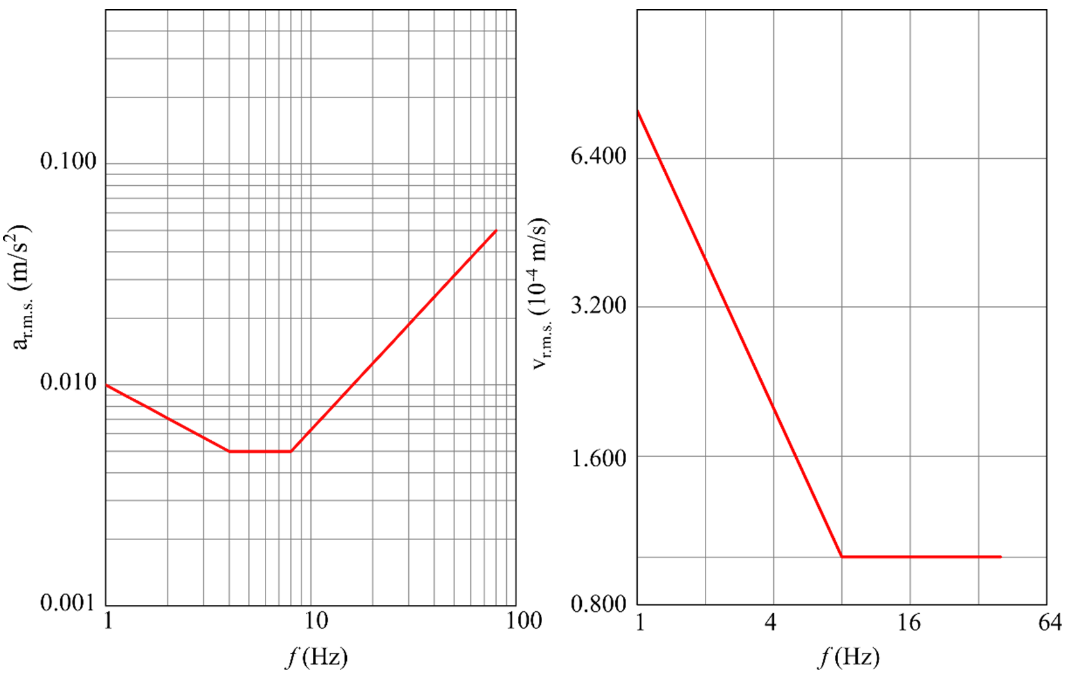


Figure 4. RMS acceleration and velocity baseline curves after ISO 10137 [19]

Table 3. Vibration performance targets according to ISO 10137 [19]

Type of building	Time	R factor
Critical working areas (hospitals, precission laboratories, operating theatres)	Day/Night	1
Residential	Day	2 to 4
	Night	1.4
Quiet office, open-plan	Day/Night	2
General office (schools, offices)	Day/Night	4
Workshops	Day/Night	8

4. ONGOING RESEARCH AT FCEUB

This section deals with selected research in which the author is involved within the ongoing research project at FCEUB. The research focus is on the development of vibration-resistant CLT floor solutions to represent sustainable and cost-effective alternative to the conventional concrete and steel-concrete composite floors through an extensive experimental testing and numerical simulations.

4.1. DEVELOPMENT OF COMPUTATIONAL TOOL FOR EVALUATION OF VIBRATION RESPONSE

Hindu software is a novel computational tool for VS assessment of floors, which is being developed within the research group. It is designed as Python-based software with a user-friendly graphical interface (GUI). Based on the input parameters (floor geometry, modal properties, walking path, walking frequency etc.), it provides quick vibration response calculation and effective visualization of calculated responses [19]. The software is fully functional, but still in the development phase. All numerical simulations that will be presented in the following sections were carried out using the *Hindu* software. Figures 5-6 illustrate some of the key components of the software.

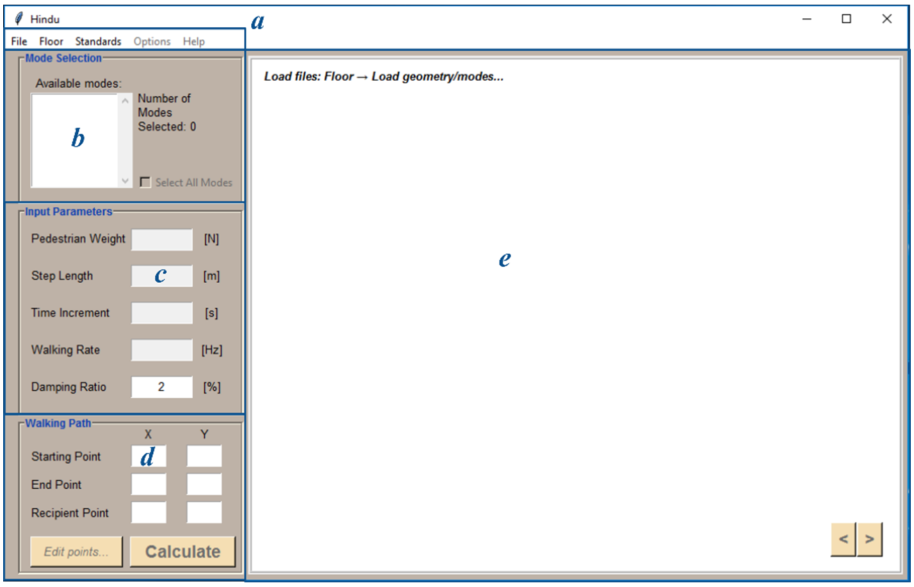


Figure 5. Main window of the Hindu software

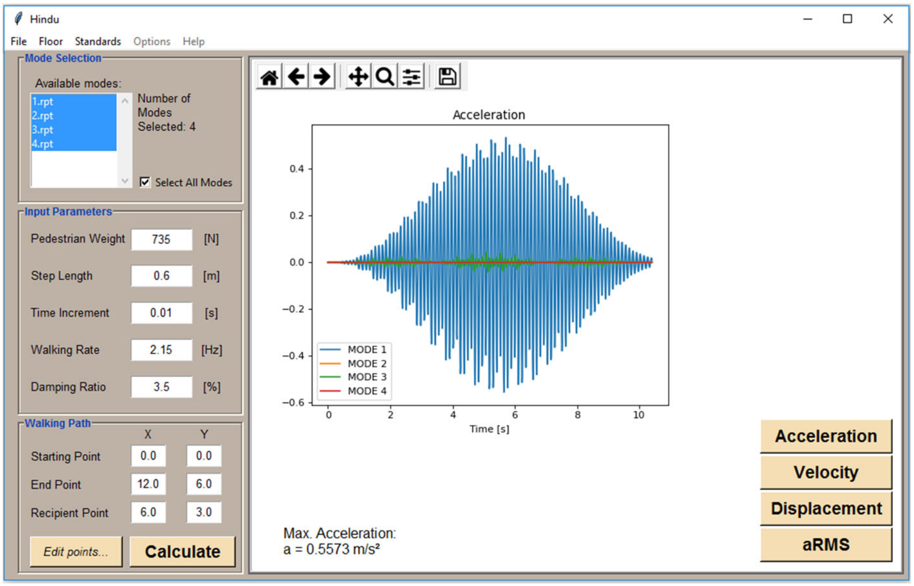


Figure 6. Visualization of the floor response

4.2. INFLUENCE OF INTER-PANEL CONNECTIONS ON VIBRATION RESPONSE

In the current design practice when assessing vibration serviceability, CLT floor is often treated as one-way slab. The influence of the inter-panel connections on the vibration response of CLT floors is neglected, treating a multi-panel floor as a monolith slab or with no inter-panel connections at all, which may result in an overestimation or underestimation of its response to pedestrian-induced vibrations. Consequently, the first focus of the research was to identify to what extent inter-panel connections affect the modal properties and vibration response of CLT floors and how they can be efficiently modelled in the numerical simulations.

Figure 7 illustrates the two commonly used inter-panel connections: half-lap joint and single spline. In numerical simulations, these connections were modelled using an equivalent elastic strip, [20]. Natural frequencies and mode shapes of a square 6m x 6 m CLT floor composed of two 3m x6m panels and simply supported on two parallel edges, are given in Figure 8. Based on the visual inspection of mode shapes and comparing natural frequency values between floors modeled as monolithic slabs and panels with connections, it is evident that the most significant differences occur in modes where modal coordinates are largest along the connection line.

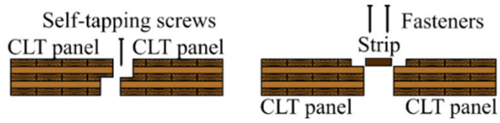


Figure 7. Half-lapped joint (left) and single spline (right) connections of CLT floors

This discrepancy is particularly pronounced when the connection line exhibits dominant movement in relation to the rest of the floor [20]. As the floor is a low frequency floor, vibration response was calculated using Arup's design guideline with walking frequency selected to induce resonant response of the first mode with the third harmonic of the walking force. The response was calculated for two walking paths: walking path 1 in the span direction (parallel to the connection line) and walking path 2 perpendicular to the span direction and connection line. Note that in all calculations the additional mass of concrete topping and non-structural elements including 10% of the live load was 150 kg/m^2. By comparing R factors calculated for floors modeled as monolithic slabs and as panels with connections, it can be concluded that inter-panel connections have a significant impact on the vibration response of CLT floors, Figure 9. Floors with inter-panel connections exhibited larger vibration response, which is especially pronounced for walking path 2. On the other hand, ignoring the inter-panel connections can lead to a notable overestimation of the vibration response. This is because only width of a single panel is accounted for in the vibration response calculation. Given the considerable difference in stiffness between the span and transverse directions, it is justified to employ one-way action in the static analysis of CLT floors. However, such an assumption in dynamic analysis can lead to notable errors. To demonstrate the importance of vibration performance-based approach in the VS assessment of CLT floors, vibration performance of the investigated CLT floor was assessed using the CLT Handbook method. The calculated vibration-controlled span was 5.9 m, which is almost equal to the proposed floor span (6m).

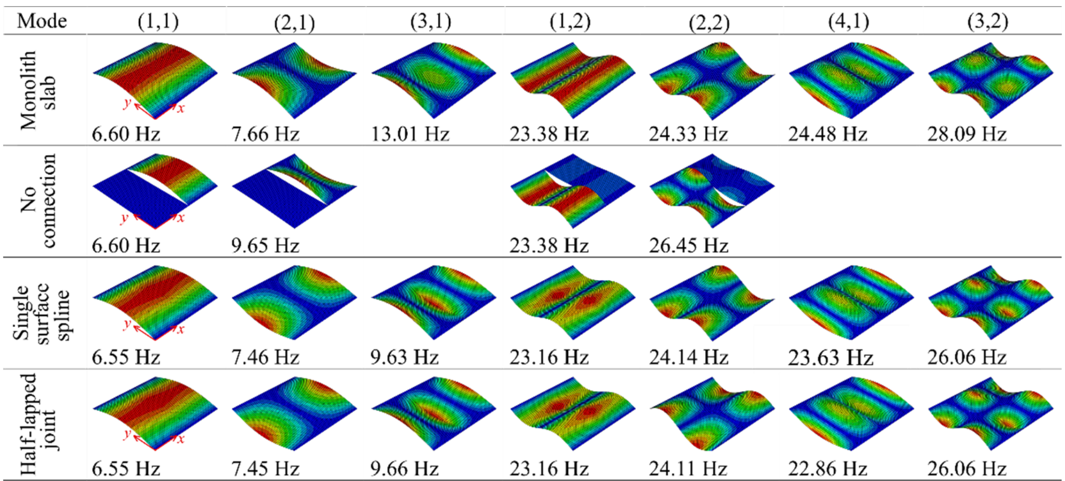


Figure 8. Natural frequencies and corresponding mode shapes of a 6m x 6m square CLT floor considering different inter-panel connections [20]

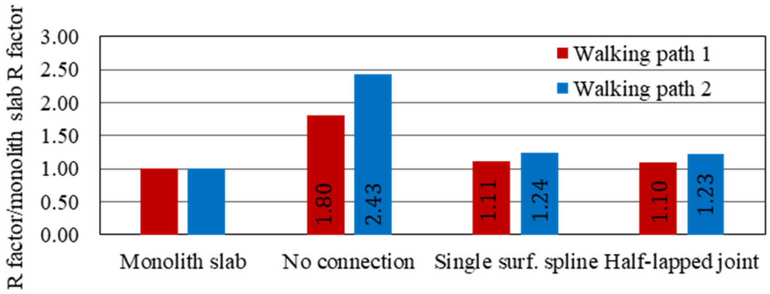


Figure 9. Response factor ratios for different connection models (left) and walking paths (right)

On the other hand, the maximal calculated value of RMS acceleration response according to Arup's design guideline due to dynamic force with walking frequency equal to 2.18 Hz (selected to induce resonance of the first vibration mode with the third harmonic of walking) was 0.197 m/s^2, resulting in the R factor equal to 39, which is far beyond the maximum acceptable value for floors.

4.3. EXPERIMENTAL IDENTIFICATION OF VIBRATION BEHAVIOR OF CLT FLOORS

The focus of the experimental work we conducted is to evaluate modal properties and pedestrian-induced vibration response of bare CLT floors. For that purpose, an extensive experimental testing was carried out at FCEUB. Several floor layouts were selected as shown in Figure 10. Full-scale CLT floors were composed of one, two or three 5-ply 15 cm thick panels. The panels were connected using half-lap joints.

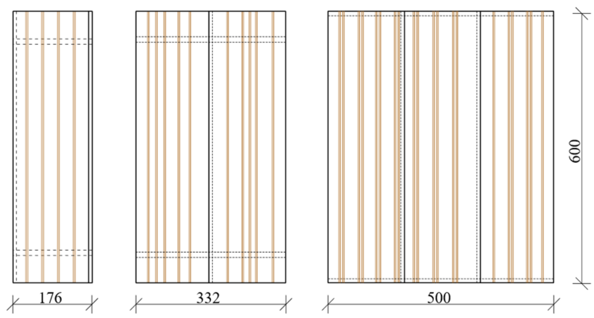


Figure 10. Floor layouts used in experimental testing

4.3.1. MODAL TESTS

First type of experimental testing involves modal tests on single-panel and two-panel CLT plates supported by elastic supports, carried out to define values of the modelling parameters describing the inter-panel connection (elastic properties of the equivalent elastic strip). Random broad-band excitation of panels was generated using rubber impact hammers. Acceleration response was measured using five high-sensitivity accelerometers (Brüel & Kjaer, Naerum, Denmark, type 4508-B, nominal sensitivity 100 mV/g) strategically positioned on the floor specimens. Operational modal analysis was carried out using a commercial platform ARTeMIS Modal Pro [21] to extract modal properties of the investigated floor specimens.

Applying a finite element model updating technique, the initial numerical models were calibrated based on the experimentally identified modal properties (natural frequencies and mode shapes). Timber material properties were then obtained from the single-panel configuration, while elastic properties of the half-lap joint connection were extracted from the two-panel configuration. Finally, verification of the updated parameters was carried out through an experimental testing of three-panel CLT floor simply supported on two parallel edges (SFSF). Comparison of the experimentally extracted modal properties and the modal properties obtained from numerical simulations using the updated parameters is given in Table 4 and Figure 11. The presented procedure can be used as a benchmark for assessment of modelling parameters of inter-panel connection described using an elastic strip from experimental data.

Table 4. Natural frequencies and MAC values of the three-panel CLT floor

Mode	Experiment	Initial numerical model		Updated numerical model	
	f_e (Hz)	f_i (Hz)	Diff (%)	f_u (Hz)	Diff (%)
1	8.4	8.33	-0.82	8.42	0.24
2	10.2	9.96	-2.39	10.10	-1.03
3	14.6	14.91	2.12	14.67	0.50
4	19.6	20.60	5.11	18.94	-3.36

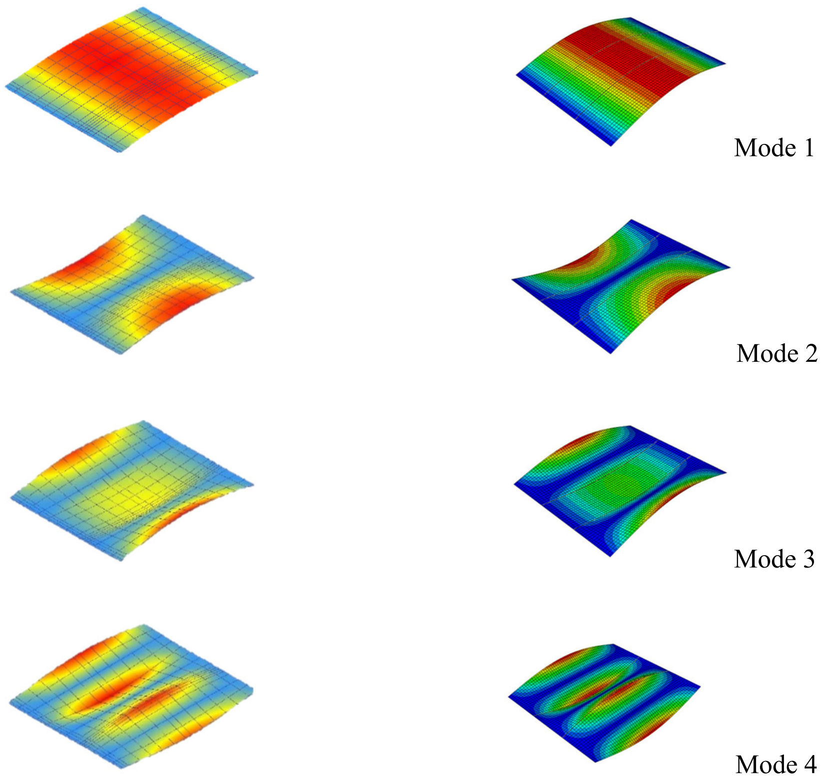


Figure 11. First four mode shapes of a three-panel CLT floor (SFSF) obtained from experimental testing (left) and numerical modeling (right)

4.3.2. WALKING TESTS

Another experimental study we conducted involves the evaluation of the vibration response induced by pedestrians walking on CLT floors. For that purpose, several test subjects were selected to walk with different walking frequencies and along straight walking paths. Walking frequency was controlled by a metronome. Figure 12 illustrates acceleration response and Fourier spectra of the floor layouts given in Figure 10 due to pedestrian walking at frequency of 1.8 Hz. In addition, RMS value of acceleration response is calculated as well over T = 1s averaging time. Although the tested floors have almost identical fundamental frequency (see Table 5), they exhibit different vibration responses. Contribution of vibration modes other than the fundamental in the case of two-panel and three panel floor is evident. Consequently, these modes cannot be neglected in the VS assessment.

As the fundamental frequency of the three-panel floor is 8.3 Hz, walking frequency of a test subject was set to 2.08 Hz to induce resonance with the fourth harmonic of walking force. Resonant response of the floor was calculated using Arup's design guideline as well. The results of both experimental and numerical simulations are given in Figure 13. The floor showed near-resonant response. While the measured and simulated peak acceleration values closely match, there is a notable difference in their corresponding RMS values – equal to 0.39 and 0.67, respectively. Note that the numerically simulated vibration response was calculated assuming 1.5% of modal damping. Increase of modal damping to 2% would result in a decrease of vibration response for even 20%.

4.4. DEVELOPMENT OF HYBRID FRP-CLT FLOORS

The most important aspect of our research study is the development of hybrid CLT floor solutions by applying a novel strengthening technique which includes strategic positioning of fiber reinforced polymer (FRP) reinforcement within the CLT panel to achieve higher strength and stiffness. FRP bars were placed in the grooves in both upper and bottom layers of the panel and bonded by using epoxy adhesive, as illustrated in Figure 14 (left). To identify stiffness and strength of the proposed hybrid solution, static tests were carried out first, as shown in Figure 14 (right). The preliminary analysis of the collected experimental data has shown that FRP reinforcement can significantly improve static performance of CLT panels. The findings report a 28% increase in the ultimate load and an 18% increase in stiffness for the applied reinforcement scheme and reinforcement percentage of 0.87%. In the next phase, vibration simulations were foreseen to identify vibration performance of a full-scale hybrid FRP-CLT floor when subjected to pedestrian footfall loading. Figure 15 (left) illustrates the modal testing of a single hybrid panel with reinforcement percentage of 0.7%. The panel was supported on elastic supports to eliminate any potential influence of boundary conditions on the modal properties. Results of the modal testing were elaborated in Table 6. They demonstrate an increase of natural frequencies of the hybrid panel in comparison to the bare CLT counterpart. The most prominent increase of 22% and 11% was detected for bending modes 2 and 4, respectively.

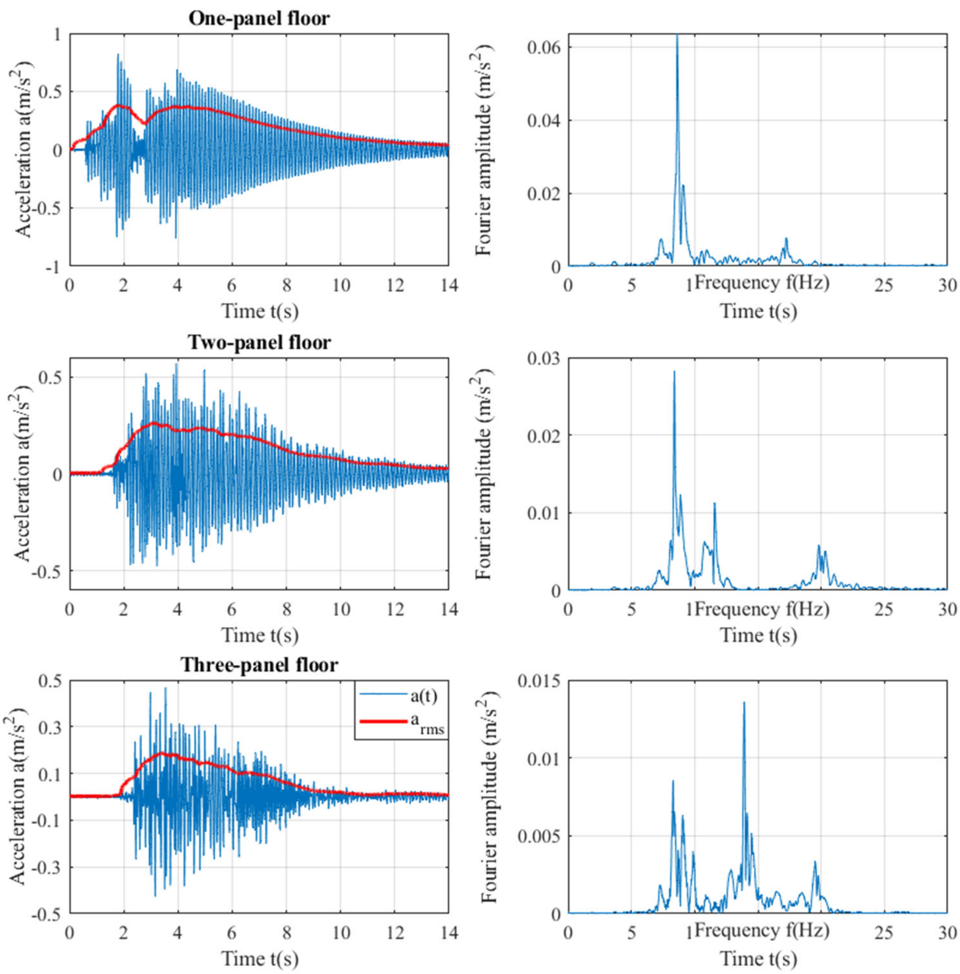
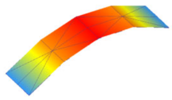
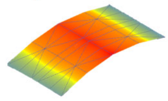
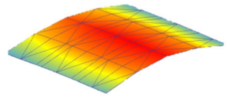
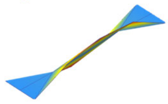
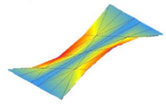
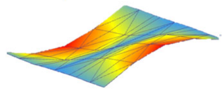
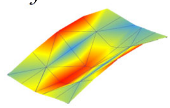
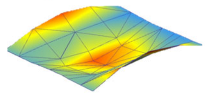
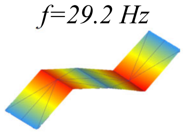
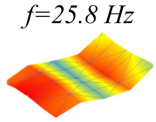
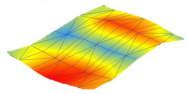
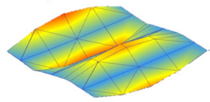


Figure 12. Acceleration time history and Fourier spectra for walking frequency 1.8Hz

Table 5. Natural frequencies and mode shapes of experimentally tested floors

Mode	One-panel floor	Two-panel floor	Three-panel floor
(1,1)	*f=8.6 Hz* 	*f=8.4 Hz* 	*f=8.3 Hz* 
(2,1)	*f=17.6 Hz* 	*f=11.6 Hz* 	*f=9.9 Hz* 
(3,1)		*f=20.3 Hz* 	*f=15.1 Hz* 
(1,2)	*f=29.2 Hz* 	*f=25.8 Hz* 	*f=25.6 Hz* 
(4,1)			*f=19.6 Hz* 

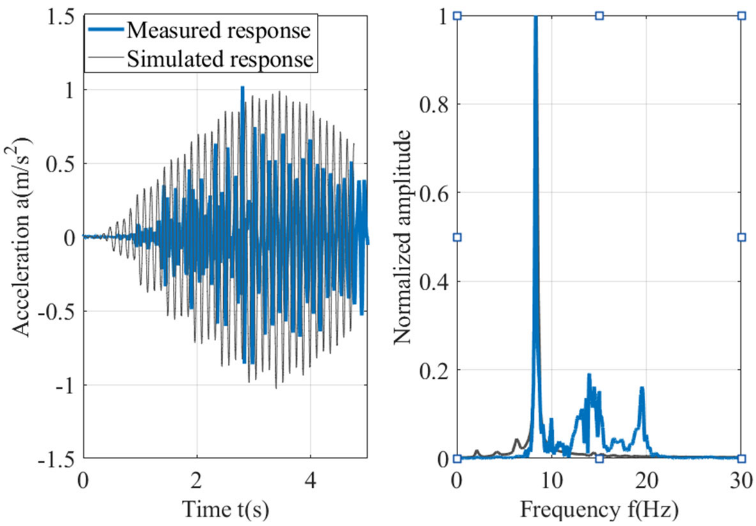
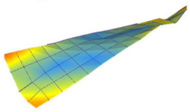
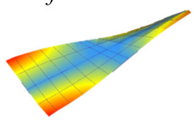
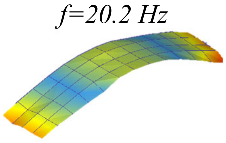
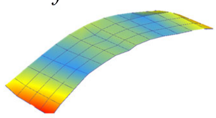
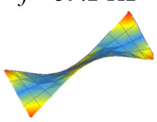
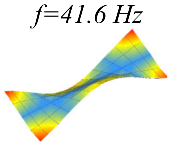
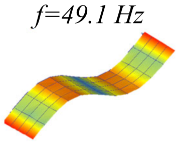
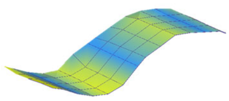


Figure 13. Measured and simulated resonant response of a three-panel floor (f_p = 2.08 Hz)

Figure 14. Hybrid FRP-CLT panel (left), static experimental setup (right)

Figure 15. Modal testing of hybrid FRP-CLT panel

Table 6. Comparison of modal properties of bare CLT and hybrid FRP-CLT panel supported on elastic supports

Mode	CLT	FRP-CLT
1	*f=19.7 Hz* 	*f=21.1 Hz* 
2	*f=20.2 Hz* 	*f=24.6 Hz* 
3	*f= 39.2 Hz* 	*f=41.6 Hz* 
4	*f=49.1 Hz* 	*f=54.5 Hz* 

5. CONCLUDING REMARKS

To meet net-zero carbon emission, contemporary design solutions require minimal use of structural materials. Given that zero-carbon buildings represent one of the key challenges in the 21st century, it is evident that CLT is emerging as a construction material of the future. Although lightweight, CLT floors possess enough stiffness to bridge relatively long spans. However, they often exhibit excessive vibrations when excited by human activities. Consequently, their design is often dictated by vibration serviceability limit state.

The traditional approach for VS assessment of CLT floors based on empirical recommendations is conservative and outdated, resulting in unreliable assessment of vibration performance of CLT floors. On contrary, vibration performance-based approach is a more comprehensive approach, based on fundamental principles of structural dynamics. It enables taking into consideration all pertinent design parameters in the VS assessment of CLT floors such as inter-panel connections, walking path and vibration acceleration or velocity response due to pedestrian-induced dynamic loading amongst others.

Improvements in the computational methods for vibration response calculation of CLT floors subjected to pedestrian-induced loading developed through the ongoing research would help engineers to apply more reliable and efficient procedures in design practice. In addition, novel hybrid floor solution designed as a combination of CLT and FRP reinforcement is promising, offering improved vibration performance of CLT floors.

Future research challenges are related to the application of more sophisticated models of pedestrian-induced dynamic loading, including human-structure interaction and probabilistic-based approach in the VS assessment of CLT floors. In addition, due to many sources of uncertainty in vibration response predictions at design stage (damping being one of the most uncertain among them), a novel approach would involve addressing potential vibration serviceability issues after the floors have been constructed.

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