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EXPERIMENTAL STUDY ON THE VIBRATION CHARACTERISTICS OF A PREFABRICATED CROSS-LAMINATED TIMBER-STEEL COMPOSITE FLOOR

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ABSTRACT:

Prefabricated mass timber-based floors are lightweight flooring alternatives gaining attention in building applications given their ease of erection, low carbon footprint and structural benefits in reducing the overall seismic mass and foundation requirements in buildings. However, in these floor archetypes, serviceability limit state requirements such as deflection and vibration performance often govern member sizing and layout design. In this paper, the vibration properties of one such flooring system – a prefabricated cross-laminated timber (CLT) -steel hybrid floor, are examined at full-scale via modal and walking tests, considering variations in material properties, geometric configurations, support conditions, walking paths and walking frequencies. The test results indicate that the composite floor is a high-frequency system with a transient response. The study also provides valuable insight into the potential vibration performance of CLT-steel composite floors for residential applications. A prediction of its vibration serviceability via the vibration dose value method indicates that it has a low probability of attracting adverse comments from users in residential applications when a continuous slab is created by connecting its fundamental units using self-tapping screws.

KEYWORDS: Floor vibration, CLT-steel composite floor, prefabricated construction; low-carbon structures

1 INTRODUCTION

1.1 DEVELOPMENT OF STEEL-TIMBER COMPOSITE FLOORS

The use of timber-steel composite decks dates back several decades. One of the earliest applications of this system is in bridge construction, notable among which are some bridge projects in Ontario, Canada. They featured prestressed wood and steel girders connected through shear studs welded to the girders and embedded in the timber via fibre-reinforced grout [1]. More recently, there has been a growing application of mass timber in the construction industry. This can be attributed to its low embodied carbon and constructional efficiency which provide a means of achieving sustainability targets in construction and fast-tracking project completion timelines.

To further optimize the performance of mass timber flooring systems, composite solutions are being developed and mass timber-steel composites are one of the promising solutions. In these flooring systems, steel often provides ductility while mass timber's light weight and low-carbon qualities provide for an environmentally friendly, modular, and demountable system. In building applications, one of the foremost studies on mass timber-steel composite floors examined the feasibility of replacing the conventional composite steel-concrete floor with a CLT-steel solution, focusing on the floor performance under lateral loading action (seismic and wind loads) [2]. More investigations into mass timber-steel composite floors wherein mass timber panels such as CLT or LVL are connected to hot-rolled or cold-formed steel beams to achieve superior structural performance and efficiency have since been carried out [3-6]. These flooring systems have the potential as viable alternatives to mainstream steel-concrete composite floors.

1.2 VIBRATION DESIGN OF LIGHTWEIGHT FLOORS

The design of lightweight flooring systems is often governed by their serviceability limit state requirements – i.e., deflection and vibration, which control their allowable spans. Several guidelines on the vibration design of lightweight floors are available in the literature. These include the American Institute of Steel Construction Design Guide 11 [7], Steel Construction Institute Publication 354 [8], European Guideline on Human-Induced Vibration of Steel Structures [9] and Applied Technology Council Design Guide 1 [10]. Prominent vibration assessment methods contained in these guidelines include the baseline curve culled from ISO 10137 [11], the response factor method and peak acceleration criteria which are derivatives of the baseline

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curve, and the vibration dose value (VDV) method detailed in ISO 10137 [11] and BS 6472 [12].

Many vibration control criteria have also been proposed for timber-joisted floors. These include deflection control requirements [13-15], fundamental frequency benchmarks [14-16], and thresholds on peak velocity and acceleration [14,15]. Recently, a span-limiting vibration control equation for CLT floors was adopted in CSA O86 [17] based on the Canadian CLT handbook [18] which also has a similar requirement for timber-concrete composite floors. However, the literature on the vibration behaviour of timber-steel composite floors and their specific vibration design guidelines is very limited [19,20].

1.3 STUDY OVERVIEW

This paper presents an investigation into the vibration characteristics of a prefabricated modular CLT-steel composite floor via modal tests and walking-induced acceleration measurements on full-scale specimens. The in- and out-of-plane static performance of analogous prototypes of the floor has been previously studied and found to be highly satisfactory [3, 21], but its vibration attributes have been hitherto untested. The study provides insights essential for the development of provisions for the vibration design of CLT-steel composite floors.

2 STUDIED FLOOR CONFIGURATION

The studied composite floor consists of fundamental modules, as shown in Figure 1, connected along their edges via self-tapping screws (STSs). Each fundamental module features a 3-layer CLT panel coupled to twin cold-formed steel beams having omega-shaped profiles. The beams are spaced such that the maximum transverse bending capacity of the CLT panel is not exceeded. Composite action is achieved by the transmission of shear stresses between the beams and panel via STSs.

In regions of high horizontal shear stresses (i.e., close to the beam ends), the STSs are driven in at 30°, guided by steel tubes welded over slots machined in the flange of the beams. In the middle regions of low shear, the STSs are inserted perpendicularly. The CLT panel, which enables two-way loading, is designed to be capacity protected, while the thin-profile steel beams (4.7mm thick) primarily take on plastic deformation. The dry assembly process enables easy production and decommissioning.

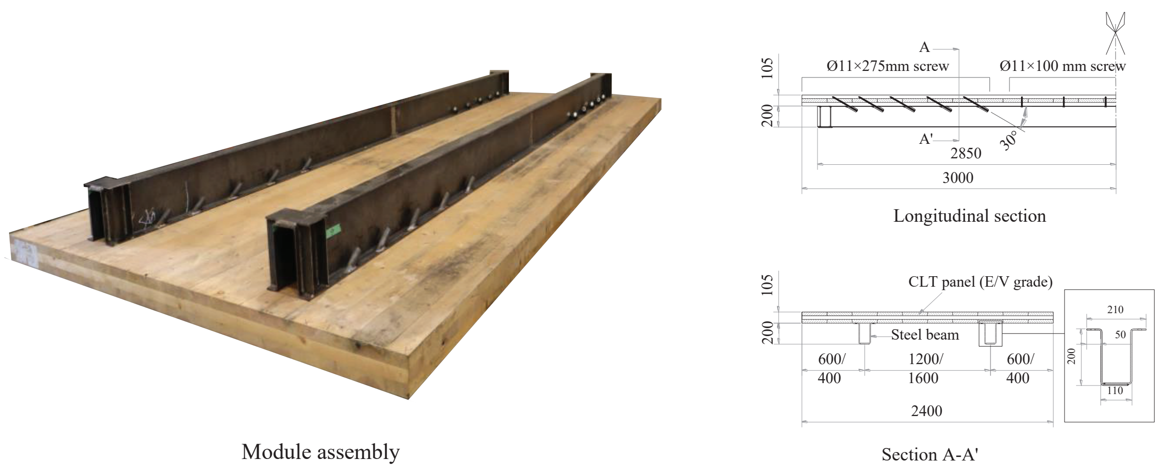

Figure 1: *Fundamental unit of tested composite floor: Module assembly (left) and section details (right)*

3 TESTING METHOD

3.1 PARAMETRIC CONSIDERATIONS

Roving hammer modal tests and walking-induced acceleration measurements were systematically carried out on the floor components, fundamental units, and pairs of connected units. The parametric changes considered during the tests are summarized in Figure 2. These include variations in the Canadian CLT panel grades – E and V grades; beam length – 5.7m and 6m; shear connection – full shear connection and partial connection wherein every other screw is omitted; and spacing of the beams – 1.2m and 1.6m. Regarding the beam spacing, 1.2m was adopted in the original design of the fundamental unit, while 1.6m is the maximum spacing for which a symmetric double T section can be maintained and the transverse bending stress in the CLT panels would remain below the permissible threshold. Also, the longitudinal edge conditions of combined modules were varied, considering free edges, and simply supported edges – to imitate panel continuity. At the supports, a simple support condition was maintained for all specimens throughout the testing.

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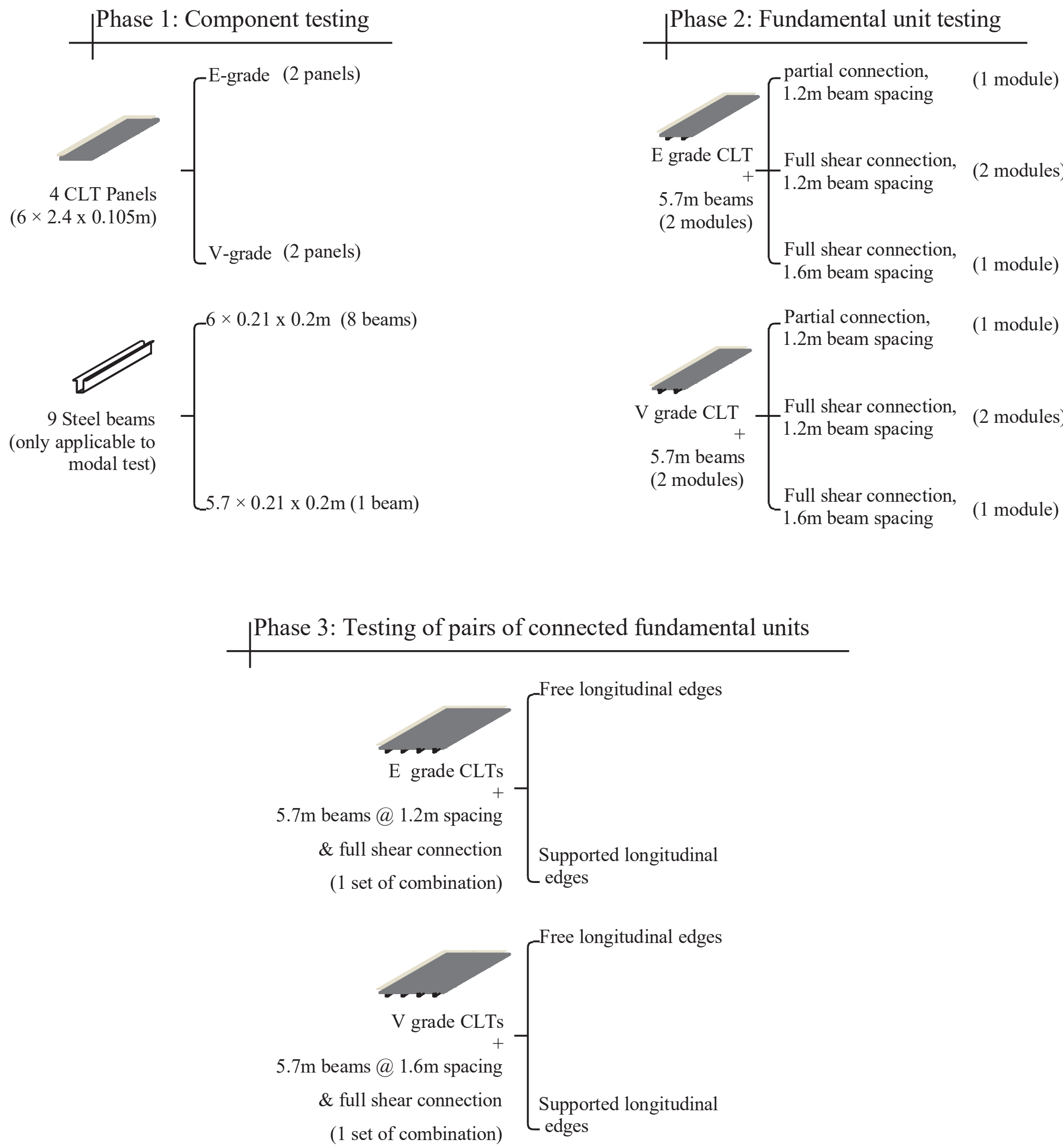

Figure 2: *Parametric variations considered during modal and acceleration measurements in the three testing phases*

3.2 MODAL TESTING AND ANALYSIS

Roving hammer modal tests were carried out in line with ISO 18324 [22] and BS EN 16929 [23]. The testing process and instrumentation are shown in Figure 3. In each tested CLT panel, fundamental unit and combined units, the experiment involved 49 impact locations and five accelerometers placed along the panel diagonal. In testing the beams, seven impact locations were set up along the base of each beam and three accelerometers were installed. The accelerometers employed in the modal test had an average sensitivity of 1mV/m/s^2. A six-channel data acquisition hardware with an input range of DC – 50kHz was used to record the data over eight seconds. Three averages were taken at each impact location of the beams, while two averages were taken for the CLT panels, fundamental units, and combined units, given their greater number of impact points compared to the beams.

Frequency response functions (FRFs) were generated from the excitation forces and frequency-domain accelerations obtained by fast Fourier transformation (FFT). The FRFs were used in the identification of modal parameters (i.e., mode shapes, natural frequencies, and damping ratios) via the rational fraction polynomial method.

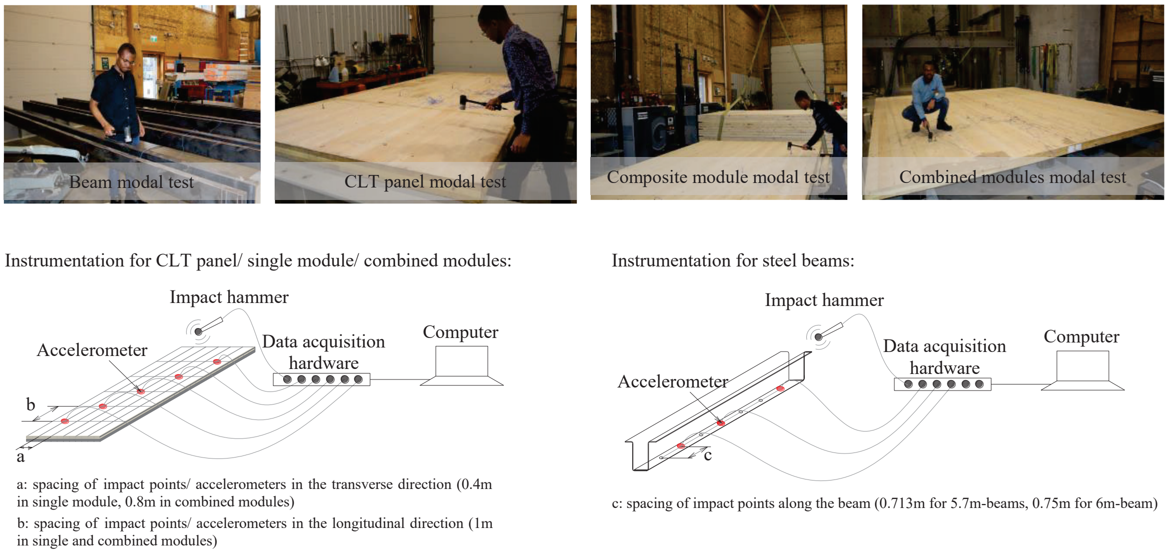

Figure 3: Modal experiment and instrumentation

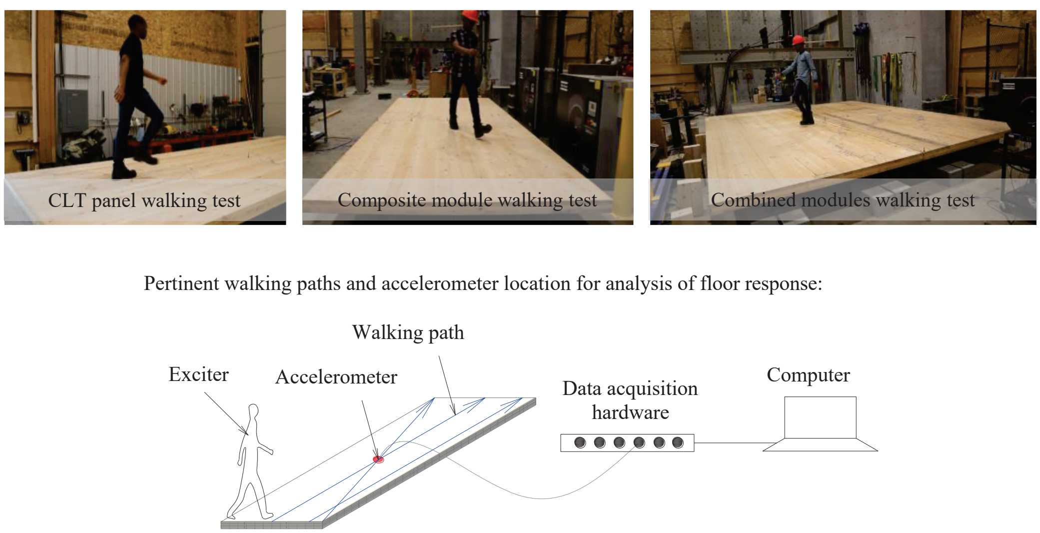

***Figure 4**: Walking-induced acceleration measurement*

3.3 WALKING-INDUCED ACCELERATION MEASUREMENT AND POST-PROCESSING

In this test, a 58kg human exciter aided by a metronome, walked over the specimens at different frequencies (1.2 Hz, 1.6 Hz, 2.0 Hz and 2.4 Hz) in line with ISO 10137-suggested range of forcing frequencies [11]. The acceleration data were obtained through the same set of accelerometers and data acquisition hardware used in the modal test. The pertinent walking events considered in analyzing the response of the specimens were those carried out along the longitudinal edge, diagonal and longitudinally along the middle of the specimens (Figure 4). Also, the acceleration data used in the analysis were those recorded at the centre of the specimens.

The root mean square values of the recorded vertical accelerations (A_{rms}) were computed, and the frequency-weighted acceleration data were obtained following guidance in ISO 2631-1 [24]. These were then used in calculating VDVs – see Equation (1), for predicting the probability of adverse comments by users based on BS 6472 [12].

$$VDV = \left(\sum_{n=1}^{N} \int_0^T a_n^4(t)dt \right)^{0.25} \quad (1)$$

where a_n is the frequency-weighted acceleration for vibration episode "n" and T is the total duration of the vibration event.

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The VDV approach was chosen given its suitability for interpreting intermittent vibration events expected in residential settings. In obtaining the VDVs, a 16-hour day setting was adopted, with the assumption of a 10-minute interval between walking events. The worst value (highest value) of VDV obtained for each tested configuration was selected for drawing inferences about their vibration serviceability.

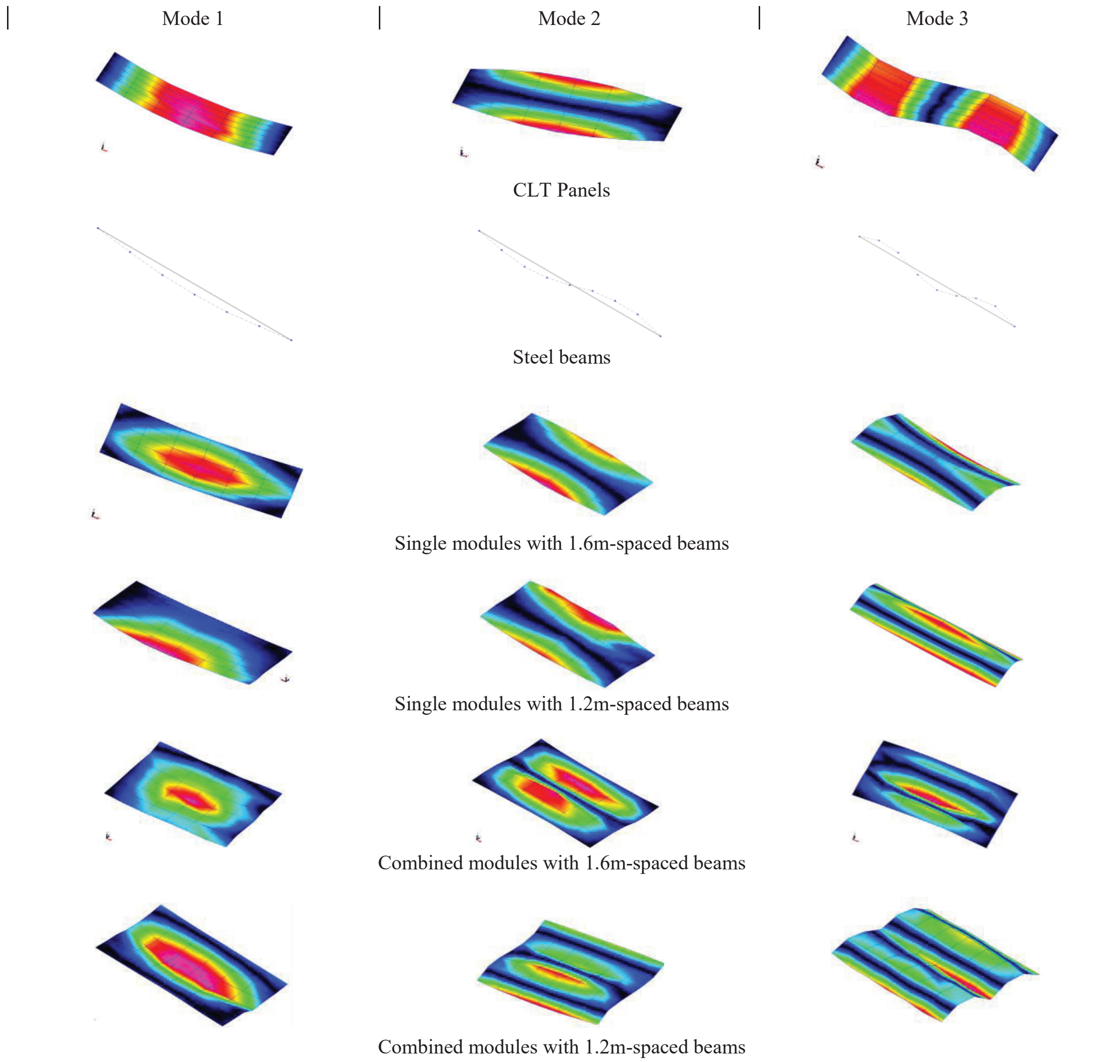

Figure 5*: First three mode shapes of floor modules and their components*

4 RESULTS AND DISCUSSION

4.1 MODE SHAPES OF FLOOR MODULES AND THEIR COMPONENTS

Figure 5 shows the first three vibration modes of the tested specimens. The observed modes shapes of the steel beams were in conformity with the sinusoidal modes of an ideal simply supported beam. For the CLT panels, the first and third modes were bending modes while the second was torsional as anticipated. The spacing between beams was found to be the main influencer of mode shape discrepancies in the composite modules. As such, the vibration modes for composite modules in Figure 5 have been grouped based on beam spacing. In the fundamental modules, the first bending mode of specimens with 1.2m -spaced beams was partial longitudinal bending, while that of their counterparts with 1.6m-spaced beams was domed-shaped bending. However, their second (torsional) and third (transverse bending) vibration modes were similar. The combined modules had similar domed-shaped fundamental modes, but those with 1.2m-spaced beams experienced transverse bending in their second and third modes while the corresponding modes in specimens with 1.6m-spaced beams were akin to mirrored domes.

4.2 NATURAL FREQUENCIES AND DAMPING RATIOS OF FLOOR MODULES AND THEIR COMPONENTS

Table 1 summarizes the natural frequencies and damping ratios of the tested components and modules. Regardless of material grade, the CLT panels had similar natural frequencies and damping ratios (less than a 10% difference in the observed range of fundamental frequencies and damping values). The same is true of the steel beams where the discrepancy is less than 20%. The fundamental frequencies of the composite floors were heavily influenced by the beams, leading to high fundamental frequency values (greater than 15 Hz) which classified them as high-frequency floors. Other parametric changes did not significantly influence the fundamental frequencies. Also, their fundamental damping ratios (1.8% – 3.2%) were consistent with values suggested in ISO 10137 [11] for bare floors (1.3% – 2%).

The damping ratios of the combined modules were at least a fifth higher than those of the single modules. Also combined modules with supported longitudinal edges (introduced for simulating floor continuity) had about 21% higher damping values than their unsupported counterparts on average. This is suggestive of better vibration performance in on-site settings where there will be floor continuity.

Table 1: *Modal properties, A_{rms} and VDVs of floor modules and their components*

Component	$f_{1\ mean}$ (Hz)	$\xi_{1\ mean}$ (%)	$A_{rms,\ max}$ (m/s^2)	VDV_{max} (m/s$^{-1.75}$)	P (Adverse comment) [a]
Steel beam	18.1 (16.8 – 19.9)	1.5 (1.4 – 1.6)	-	-	-
CLT panels	6.6 (6.4 – 6.8)	4.4 (4.1 – 4.5)	1.3 (0.5 – 1.3)	4.3 (1.6 – 4.3)	Very likely
Single modules (1.2m-spaced beams)	17.9 (17.0 – 19.1)	1.9 (1.8 – 2.1)	0.4 (0.1 – 0.4)	2 (0.4 – 2.0)	Very likely
Single modules (1.6m-spaced beams)	16.8 (15.4 – 18.1)	1.9 (1.8 – 2.0)	0.6 (0.4 – 0.6)	2.8 (1.6 – 2.8)	Very likely
Combined modules (1.2m-spaced beams, free edges)	16.9	2.5	0.1	0.4	Low
Combined modules (1.2m-spaced beams, supported edges)	16.9	3.2	0.1	0.4	Low
Combined modules (1.6m-spaced beams, free edges)	17.4	2.8	0.1	0.4	Low
Combined modules (1.6m-spaced beams, supported edges)	17.9	3.2	0.1	0.4	Low

Note: Values in parentheses are the range of values obtained for the specimens in each category. Entries without values in parentheses have the same values for all tested replicates.

[a] P (adverse comment): the probability of adverse comment. 0.2 to 0.4 – low probability of adverse comment, 0.4 to 0.8 – adverse comment possible, 0.8-1.6 – adverse comment probable, >1.6 – adverse comment very likely [12]

4.3 RESPONSE OF COMPOSITE MODULES AND CLT PANELS TO WALKING

The VDVs and A_{rms} values of the tested specimens are presented in Table 1. Specifically, the values obtained for the CLT panels and fundamental units varied significantly in each category and their VDVs were unsatisfactory for residential applications as implied by the predicted high probability of adverse comments. On the contrary, the results for the combined modules – the form in which the floor system will be installed in practice – were less varied and favourable. Their VDVs translated to a low likelihood of adverse comments by residential building occupants per BS 6472 [12] provisions. Further details on the vibration response of the floor system and its serviceability performance are presented in the paper titled: "Vibration properties and serviceability performance of a modular cross-laminated timber -steel composite floor system" which is currently under review.

5 CONCLUSIONS

The vibration characteristics of a modular CLT-steel composite flooring solution have been examined in this paper. The modal properties, acceleration responses and prediction of its vibration serviceability have been elucidated. The main deductions of the study are as follows:

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- The studied composite flooring solution is a high-frequency floor largely due to its beam components
- The floor's damping ratios are in agreement with the provisions in ISO 10137 [11] for the precursory design of bare floors
- The modal properties and acceleration response of the floor were mainly influenced by beam spacing, module combination and edge condition while other parameters – CLT panel grades, and shear connection – were less significant
- The combined floor modules were found to have consistent A_{rms} and VDVs. The VDVs of the combined modules also indicated favourable vibration serviceability. Nonetheless, evaluations involving real humans are required to ascertain the veracity of the vibration serviceability prediction

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REFERENCES

[1] Krisciunas R.: Ontario's experience with Composite Wood/Steel Bridges. In: National Conference on Wood Transportation Structures, US Forest Service, Forest Products Laboratory; Federal Highway Administration, No. FPL-GTR-94, 1996.

[2] Asiz A., Smith I.: Demands placed on steel frameworks of tall buildings having reinforced concrete or massive wood horizontal slabs. Structural Engineering International, 19(4):395-403, 2009.

[3] Loss C., Davison B.: Innovative composite steel-timber floors with prefabricated modular components. Engineering Structures, 132:695-713, 2017.

[4] Hassanieh A., Valipour H. R., Bradford M.A.: Experimental and numerical investigation of short-term behaviour of CLT-steel composite beams. Engineering Structures, 144:43-57, 2017.

[5] Hassanieh A., Valipour H.R., Bradford M.A.: Experimental and numerical study of steel-timber composite (STC) beams. Journal of Constructional Steel Research, 122:367-78, 2016.

[6] Owolabi D.O., Loss C.: Experimental and numerical study on the bending response of a prefabricated composite CLT-steel floor module. Engineering Structures, 260:114278, 2022.

[7] Murray T.M., Allen D.E., Ungar E.E., Davis B.D.: AISC design guide 11: Vibrations of steel-framed structural systems due to human activity. 2nd ed. American Institute of Steel Construction, Chicago, 2016.

[8] Smith A.L., Hick S.J., Devine P.J.: Design of floors for vibration: A new approach. Ascot: The Steel Construction Institute, 2009.

[9] Feldmann M., Heinemeyer C., Lukic M., Caetano E., Cunha Á., Goldack A., et al. Human-induced vibration of steel structures (HiVoSS). European Commission, Brussels, 2007.

[10] Allen DE, Onysko DM, Murray TM. ATC design guide 1: Minimizing floor vibration. California: Applied Technology Council; 1999.

[11] International Organization for Standardization. ISO 10137: Bases for design of structures – Serviceability of buildings and walkways against vibrations. International Organisation for Standardization, Geneva, 2007.

[12] British Standards Institution. BS 6472-1: Guide to evaluation of human exposure to vibration in buildings. Part 1: Vibration sources other than blasting. BSI Standards Limited, London, 2008.

[13] Canadian Commission on Building and Fire Codes, National Research Council of Canada. User's guide-NBC 2010 structural commentaries (Part 4 of Division B). Canadian Commission on Building and Fire Codes, Canada, 2011.

[14] European Committee for Standardization. EN 1995-1-1: Design of timber structures - Part 1-1: General rules and rules for buildings. European Committee for Standardization, Brussels, 2004.

[15] Hamm P., Richter A., Winter S.: Floor vibrations – New results. In: 2010 World Conference of Timber Engineering Italy, 2010.

[16] Dolan J.D., Murray T.M., Johnson J.R., Runte D., Shue B.C. Preventing annoying wood floor vibrations. Journal of Structural Engineering, 125 (1):19-24, 1999.

[17] Canadian Standard Association (CSA): CSA-O86-19: Engineering design in wood. CSA Group, Toronto, Canada, 2019.

[18] Karacabeyli E., Gagnon S.: CLT handbook 2nd Canadian edition. FPInnovaitons Special Publication SP-532E, Pointe-Claire, Canada, 2019.

[19] Chiniforush, A. A., Makki A.M., Dackermann U., Valipour H. R., and Akbarnezhad A.: Vibration behaviour of steel-timber composite floors, part (1): Experimental & numerical investigation. Journal of Constructional Steel Research 161: 244-257, 2019.

[20] Hassanieh A., Chiniforush A. A., Valipour H. R., & Bradford M. A.: Vibration behaviour of steel-timber composite floors, part (2): Evaluation of human-

induced vibrations. Journal of Constructional Steel Research, 158: 156-170, 2019.

[21] Loss C., Frangi A. Experimental investigation on in-plane stiffness and strength of innovative steel-timber hybrid floor diaphragms. Engineering Structures, 138:229-44, 2017.

[22] International Organization for Standardization. ISO 18324: Timber structures – Test methods – Floor vibration performance. International Organisation for Standardization, Geneva, 2016.

[23] British Standards Institution. BS EN 16929: Test methods – Timber floors – Determination of vibration properties. BSI Standards Limited, London, 2019.

[24] International Organization for Standardization. ISO 2631-1 – Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1: General requirements. International Organization for Standardization, Geneva, 1997.

https://doi.org/10.52202/069179-0248