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DESIGN OF LONG-SPAN LIGHTWEIGHT TIMBER FLOORS SUBJECT TO WALKING EXCITATIONS: A CASE STUDY

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ABSTRACT: Lightweight timber construction is popular in buildings with two or more storeys in Australia. The floors are made of a floorboard supported on joists or trusses. Recently, the sector is moving towards multi-storey construction of different building classes with different floor usages and shared tenancy. Thus, a need for high performing lightweight floor systems becomes urgent. The current vibration control criteria in the Australian standard recommends limiting static deflection, which is a coarse method and does not necessarily guarantee satisfactory performance. In the current study, vibration performance of a 6m×6m floor system with particleboard flange and truss webs is investigated under single walker excitations and at different walking frequencies. The vibration responses are compared to the predictions and performance criteria recommended in international standards and guidelines. The results show inconsistencies in the calculated levels of acceptance from different sources using simplified expressions and more rigorous methods of analysis. This highlights the significance of the need for further research to develop a harmonised method of analysis that can be used by manufacturers and engineers in Australia to confidently design floors for vibrations.

KEYWORDS: Floor dynamics, Footfall-induced vibration, Lightweight timber floors, Non-destructive testing.

1 INTRODUCTION

There is an increased global focus on using timber structures due to the availability of timber-based and engineered wood products (EWPs) as well as sustainability and lower carbon footprint of timber compared to other conventional construction materials [1]. In Australia, there is a growing trend in lightweight timber floors to enter the multi-storey market [2], mainly due to the increasing surge in land prices in capital cities. A major restriction in current buildings with timber floors is their close column spacing, while most developments require more open space. For spans longer than 6 meters, the design is governed by serviceability not strength; therefore, accurate assessment of the vibration performance of the floor is essential.

The current work aims to investigate the vibration performance of a 6m×6m lightweight timber floor system typically used in Australian buildings. The investigation is comprised of measurement of natural frequencies and accelerations due to walking of the examined floor as well as numerical modal analyses. The vibration responses are calculated and compared to recommendations in existing standards: CSA 086:2019 [3], EN 5:2004 [4], AS 1170.0:2002 [5] and guidelines of CCIP-016 [6], SCI-P354 [7], AISC DG11 [8], HIVOSS [9], and recommended performance criteria in ISO 10137 [10] and BS 6472.1 [11]. The paper is concluded by an analysis of the aforementioned comparison.

2 FLOOR VIBRATION DESIGN IN CURRENT STANDARDS AND GUIDELINES

Canadian standard CSA 086 [3] and Eurocode 5:2004 [4] provide simple methods for vibration design of timber floors. CSA-086 [3] uses simple T-beam equations and gives vibration-controlled span limit of joisted floors. The approach is based on the comprehensive experimental works of Hu and Chui [12, 13] and offers a limit based on the relation between fundamental frequency of the floor system and static deflection under 1 kN at its centre. More rigorous methods that categorise the floor based on the

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fundamental frequency and calculate the response from modal analyses are outlined in [6-8]. However, these methods are developed for steel, concrete or steel-concrete composite floors and their appropriateness for timber floors is disputed.

Prediction of vibration in floor systems requires determination of vibration modes, associated frequencies and damping values. In order to assess the floor systems against serviceability criteria, the floors are categorised into (i) low-frequency floors and (ii) high frequency floors. Low frequency floors are associated with a steady-state resonant response under footfall-induced vibrations, whereas in high-frequency floors, the floor response is transient, and is damped out after each footstep. There is no clear quantitative measure that separates the two categories, and different guidelines [6-8] suggest cut-off frequencies ranging from 7 Hz to 10.5 Hz.

3 EXPERIMENTAL AND NUMERICAL RESULTS

3.1 PHYSICAL TESTS

In the present work footfall-induced vibration (FIV) of the 6 m×6 m lightweight timber floor system (shown in Figure 1) comprised of a floorboard (19 mm particleboard) resting on timber chords MGP12 (softwood), 90 mm × 35 mm in cross-section, and steel braced trusses and supported on 200 PFC steel bearer beams on two sides is studied.

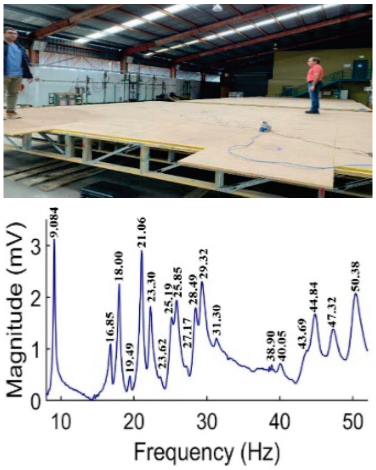

Figure 1: *The tested 6m×6m floor system and the frequency response function (FRF) showing frequency-domain response.*

The floor was excited using a digital hammer at a location close to the accelerometer 'A' shown in Figure 2. The impulsive excitation was repeated 10 times. Using Fast Fourier Transform (FFT) of the acceleration time-history, Frequency Response Functions (FRF) were developed and natural frequencies were calculated as shown in Figure 1. Natural frequencies, f_i measured at accelerometer A, and corresponding critical modal damping values ζ_i, showing average and CoVs are represented in Table 1. Damping values are calculated from the half-bandwidth method according to AS ISO 2631.2 [14]. The deflection of the floor under a static 1 kN load applied at the centre was found to be 1.54 mm.

Table 1: *Measured frequencies and critical damping.*

	Accelerometer A (centre of the floor)		Damping	
Mode, i	$f_{i\,(avg)}$ (Hz)	CoV	ζ	CoV
1	9.08	0.59%	0.90%	0.14%
2	17.05	3.77%	1.08%	0.66%
3	17.84	0.01%	1.03%	0.17%
4	19.41	0.01%	0.84%	0.55%
5	20.98	0.01%	0.91%	0.14%
6	22.01	0.26%	0.89%	0.14%
7	24.86	0.01%	0.95%	0.21%

Then, the floor was excited to dynamic walking forces, and accelerations were measured at three different locations (A, B, and C) on the slab.

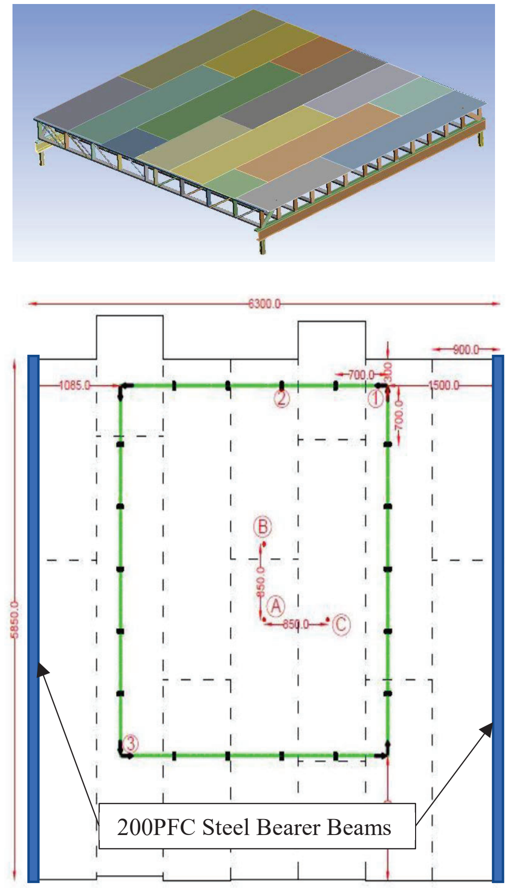

Figure 2: *The floor layout and walking path (in Green).*

Two walking scenarios, with single walker (80kg) in two different walking frequencies f_w of 1.80 Hz (brisk walking) and 2.25 Hz (fast walking), of W1 and W2, respectively, were selected to examine footfall-induced vibration of the floor. The 4th harmonics of walking frequency of 2.25 Hz and the 5th harmonics of walking frequency of 1.80 Hz, correspond to the fundamental natural frequency (9.08 Hz) of the floor system.

The acceleration time-histories were calculated from each accelerometer and were filtered using the weighting factors outlined in AS 2670.1 (ISO 2631-1) [15]. The vibration responses of each walking scenario were calculated in terms of root-mean-square (rms) and Vibration Dose Value (VDV) defined in Equations (1 & 2):

$$a_w(t_0)=\sqrt{\frac{1}{\tau}\int_{t_0-\tau}^{t_0}[a_w(t)]^2\,dt} \qquad (1)$$

$$VDV=\left\{\int_0^{\tau}[a_w(t)]^4\,dt\right\}^{\frac{1}{4}} \qquad (2)$$

where τ is the time (integration variable) recommended to be equal to 1 second. The raw and ISO weighted acceleration time histories of W1 and W2 walking configuration tests are plotted in Figure 3. There were some differences between accelerometer results at A, B and C. However, for the sake of comparison against standards and guideline only results of accelerometer, A which is located at the centre of the floor are presented herein.

The acceleration time histories show a steady-state response much more significant than the transient response in both walking configurations, distinguished with a clear resonant excitation in W2.

The frequency content (FFT) of W2 walking test is also shown in Figure 3, and indicates that the fundamental frequency (9.08 Hz), as well as modes with frequencies of 21 Hz and 18 Hz are significantly excited. These frequencies were also shown to have the largest amplitude as displayed in the frequency domain results of Figure 1.

The measured vibration response parameters are represented in Table 2. Following recommendations of ISO 2631-1 [15], the running r.m.s. acceleration, a_w, is calculated using an integration time constant of 1 second. The maximum acceleration, $a_{w,max}$ corresponds to the peak in the time-history.

Table 2: *Measured vibration responses of the floor system.*

	a_w (m/s^2)	$a_{w,max}$ (m/s^2)	VDV (m/s$^{1.75}$)
T1	0.75	1.75	0.92
T2	0.91	2.05	1.10

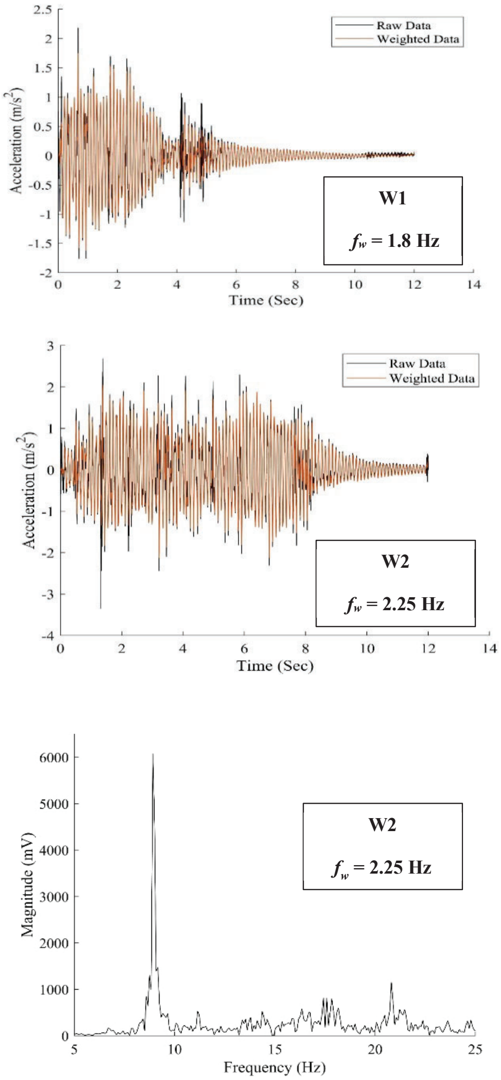

Figure 3: *The raw (black) and weighted (orange) acceleration time-histories of a single person walker, 80 kg at walking frequencies of 1.8 Hz (W1) and 2.25 Hz (W2). The frequency content of W2 is shown in the bottom of the figure.*

3.2 FINITE ELEMENT ANALYSIS (FEA)

Modal analysis of the floor system was carried out in the commercial package, Ansys [16]. Mechanical properties of sawn timber boards (orthotropic) and steel beams were taken from AS 1720.1:2010 [17] and AS 4100:2020 [18], respectively. Particleboard was assumed to be isotropic [19]. In the FEA model (see Figure 4) MGP boards, particleboard, PFCs and the supporting short columns were meshed using 8-noded Shell-181 elements with 5 integration points, and the metal webs were modelled with 2-noded beam elements [16]. The connection between the bearer beam and the PFC, and that between the PFC and the short column was defined a Mohr-Coulomb frictional contact with a coefficient of friction of 0.45 (calculated from a simple sliding test). From a mesh sensitivity analysis (not shown here for the sake of brevity), a mesh with a total of 182,550 nodes was selected, which has mid-span deflection and fundamental frequency of less than 5% difference from an FEA model with 303,015 nodes. Mid-span deflection of the floor system from the FEA is 1.99 mm and the mode shapes and associated frequencies are shown in Figure 4.

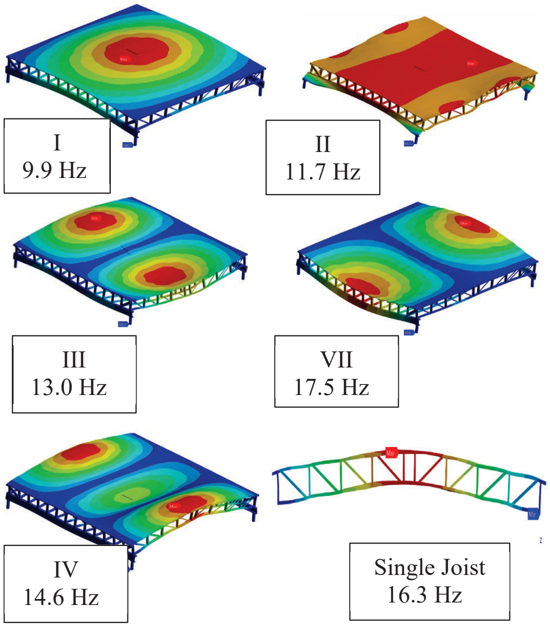

Figure 4: *Mode shapes and frequencies from the FEA ranked based on ascending frequencies.*

There is a relatively reasonable agreement between experimental and numerical frequencies. The fundamental FEA frequency of 9.9 Hz corresponds to a plate-type mode shape. The next frequency (11.7 Hz) is due to minor-axis bending of the PFC (steel) beams. Flexural modes along unsupported edges occur at frequencies below 15 Hz. Bending mode along the supported edge is at 17.5 Hz from FEA, and probably corresponds to the 18 Hz peak in the experimental FFT results of Figure 1.

The fundamental frequency of the floor system can be approximated from deflection under self-weight, δ:

$$f_1 = \frac{17.8}{\sqrt{\delta}} \tag{3}$$

Knowing δ is equal to 4.72 mm (from FEA), a fundamental frequency of 8.2 Hz is calculated using Equation 3, which is 10% lower than the measured frequency.

The other method normally used to calculate fundamental frequency of composite floor systems supported by primary beams and secondary beams of frequencies f_b, and f_j, respectively, is the Dunkerly's modal decomposition method [20] in Equation 4:

$$\frac{1}{f_1^2} = \frac{1}{f_b^2} + \frac{1}{f_j^2} \tag{4}$$

where the frequencies f_b, and f_j in Equation 4 shall be associated with the same mode shape as the fundamental mode shape of the floor system. The major axis flexural mode shape and frequency of the joist (16.3 Hz) is shown in Figure 4. Frequency of the PFC beam in the minor bending mode is 8 Hz (from FEA). Using Equation 4 and knowing the floor system has 2×PFC beams and 14×joists, a fundamental frequency of 15.9 Hz is calculated, which is 75% greater than the measured frequency. If the number of PFC beams and joists are reduced to one in Equation 4, a frequency 7.2 Hz is derived.

4 COMPARISON AGAINST EXISTING STANDARDS AND GUIDELINES

Several methods are available that provide insight into floor vibration. These methods vary from simple rules to more sophisticated methods. Simple methods require less design effort, modelling and analysis, whereas more complicated methods have more room for flexibility, engineering judgement and innovation. Vibration performance of the investigated floor system is discussed from a code-compliancy point of view, here forth.

4.1 AUSTRALIAN STANDARD

Most commonly accepted simple rule to minimise the annoying vibration is a limit on deflection based on the design live load. In the Australian standard AS 1170.1 [21] the design live load is 1.5 kPa for residential buildings and 3 kPa for commercial ones (excluding shopping areas, public assembly areas, dance halls, etc.). The ripple/sag serviceability limit state criterion in AS 1170.0 [5] is $L/300$ for dead load plus 40% live load combination. Moreover, for vibration serviceability, a static mid-span deflection under a 1 kN vertical load, (d_{1kN}) of less than 1 to 2 mm is recommended. The measured and FEA deflections of the floor system are both under 2 mm, which can be interpreted as satisfactory vibration performance according to the Australian standard. Under a self-weight plus 40% live load combination with 1.5 kPa (residential) and 3 kPa (commercial) distributed live loads, floor centre deflections are 13.9 mm and 23.1 mm (from FEA), respectively, compared to the 20 mm limit ($L/300$). Thus, in deflection serviceability, the floor is acceptable for residential usage, but misses the acceptance tolerance of commercial buildings by a margin of 15.5%.

4.2 ISO/TR 21136 [22]

The ISO/TR 21136 method [22] proposes a relation between fundamental frequency and static deflection of the floor as indicated in Equation (5), which is developed from a logistic regression on the database of field light

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frame timber floors in across Canada occupants' survey and testing.

$$d_{1kN} \le \frac{f^{2.56}}{1090.31} \qquad (5)$$

Knowing the fundamental frequency, *f*, is equal to 9.08 Hz, Equation 5 gives a deflection limit of 0.6 mm, which is 61% smaller than the measured deflection. The floor is "unacceptable" to ISO/TR 21136 [22].

4.3 Eurocode 5:2004 [4]

Eurocode 5:2004 [4] divides the floors into better performance and poorer performance using three criteria for controlling vibration in residential floors: (i) frequency limit, (ii) deflection limit, and (iii) impulse velocity control. These conditions are outlined in Equation 6.

$$(i) f > 8Hz \ ; \ \text{(ii)} \frac{d}{F_s} \le a \ ; \ \text{(iii)} v \le b^{(f\xi^{-1})} \qquad (6)$$

where v, is the unit impulse velocity response, calculated as the maximum initial vertical velocity (m/s) caused by an ideal unit impulse (1 Ns) applied at a location on the floor that gives the maximum response. The first condition in Equation 6 is satisfied since the fundamental frequency is larger than 8 Hz. The force (F_s)-defection (a) criterion is also satisfied and places the floor within the better performance region of the curve in EN 5:2004 [4]. However, assuming 1% damping, the calculated unit impulse velocity response is v=23 mm/Ns^2, which is 42% larger than the recommended value of 16.2 mm/Ns^2 calculated using Equation 6.

4.4 CANADIAN STANDARD [3]

CSA 086:2019 [3] has a vibration-controlled span approach for single-span wood joisted floor systems with prefabricated wood I-joists and wood structural panel subfloor. The maximum recommended span l_v (m) is

$$l_v = \frac{0.122(EI_{eff})^{0.284}}{k_{tss}^{0.14} m_L} \qquad (5)$$

$$k_{tss} = 0.0294 + 0.536k_1^2 + 0.516k_1^{0.5} + 0.31k_1^{0.75}$$

where EI_{eff} (Nm^2) is the effective flexural stiffness of the floor system in the span direction, k_{tss} is a factor that accounts for the flexural stiffness in the transverse direction, and m_L is the mass per unit length (kg/m) of the composite floor system. Using FEA and calculating k_1 and K_{tss} of 0.15, and 0.49, respectively, and EI_{eff} of 2.35×10^6 Nm^2, a maximum recommended span, l_v of 5.3 m is calculated, which suggests that the floor system is 13% longer than recommended.

4.5 CCIP-016 [6]

In floors with low-frequency (<10 Hz) the guideline [6] recommends prediction of vibration response based on the first four harmonics of the footfall forces for a range of walking frequencies. That requires calculation of the response in all modes to each of these harmonics and then combining them. The method in CCIP-16 [6] is valid for floors with natural frequencies less than 4.2 times the maximum footfall frequency (i.e. about 15 Hz). The calculation method is comprised of several steps to find mode shapes, frequencies, mode shape amplitudes at excitation and response locations, and eventually calculating the response factor by dividing calculated accelerations by the base accelerations in BS 6472-1 [11].

Response factors at the centre of the floor in a range of walking frequencies (1-2.8 Hz) based on CCIP-016 [6] are displayed in Figure 5. Response factors from the measurements are calculated by dividing a_w in Table 2 by the base acceleration of 0.05 m/s^2 recommended in ISO 2631.2 [14]. It should be noted that the CCIP-016 [6] response factors in Figure 5 are based on 3% damping (in all modes) recommended in the guideline, whereas the experimental response factors are based on the measured damping of 1% (see Table 1).

Using the CCIP-016 method, a maximum R of 479 is calculated at walking frequency of 2.48 Hz (the 4th harmonic of the FEA fundamental frequency), which is much greater than R=18.2, from walking measurements at walking frequency equal to the 4th harmonic of the measured fundamental frequency.

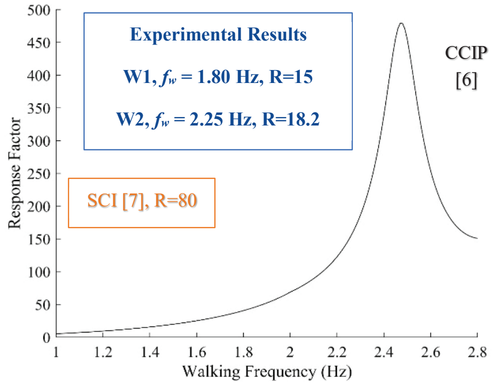

Figure 5: *Response factors from CCIP-016 [6] and SCI-P354 [7] modal approaches and those calculated from the experimental measurements.*

Acceptable response factors for residential and commercial floors are typically below 8. Therefore, assessment based on CCIP-016 [6] indicates that the floor is not acceptable.

4.6 SCI-P354 [7]

The method described in SCI P354 [7] is based on finding peak response (acceleration or VDV) from range of walking frequencies and floor frequencies. The cut-off

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frequency (distinction between low- and high-frequency floors) for general floors is 10 Hz in SCI-P354 [7]. In low-frequency floors, both steady-state response and transient responses need to be checked. All modes of vibration with natural frequencies up to 2 Hz higher than the cut-off frequency shall be considered. Initially, the weighted root mean square (RMS) acceleration response of each force harmonic at every mode of the response at the centre of the floor from excitation at designated point on the floor is calculated. Then, the total acceleration response function is found by summing up RMS of each mode of vibration at each harmonic of the forcing function.

Using 1.1% damping for joisted timber floors suggested in [7], an r.m.s. acceleration of 0.4 m/s^2, and a response factor of 80 is calculated and is presented on Figure 5. The calculated response factor is larger than the recommended values (4-8) for residential and office floors, for continuous and intermittent vibrations in BS 6472-1 [11]. However, assuming impulsive vibration, response factors of 60-128 can be acceptable for office and school floors [11].

4.7 HIVOSS [9]

The method is developed by ArcelorMittal (Steel manufacturer) in their design for vibration of timber floors and is based on the statistical distribution of walking frequencies [9]. A design value OS-RMS$_{90}$ called the "*one step root mean square 90*", is developed which covers the response velocity of the floor filtered using the weighting functions for a significant step with the intensity of 90% of people's walking normally. In this method, the fundamental frequency and corresponding modal mass are calculated from FEA or simple equations. A critical damping value is chosen and from the provided design diagrams, a classification of the floor is derived.

Using a damping of 3% (recommended in [9] for joist timber floors) the floor is classified as 'E' in HIVOSS, which means it is critical for residential and office buildings. However, if used in industrial and sport facilities the floor will have vibration performance at an acceptable level.

5 CONCLUSIONS AND RECOMMENDATIONS

Dynamic properties and vibration response parameters of a lightweight timber floor was studied experimentally. The experimental results were compared to the predictions from simple methods and modal superposition methods, by implementing modal analysis in FEA.

Simplified methods of vibration design, provide a rigid "Yes" or "No" acceptance criterion. The acceptance criterion is based on frequency-deflection equations in which the frequency appears in powers of 2 and larger. Hence, finding the accurate frequency of the floor system is critical. It was understood that a modal analysis in FEA can provide a reasonable approximation of the measured fundamental frequency of the floor system. However, simplified equations fail to provide accurate predictions of natural frequencies. It should be noted that in future work, study of effects of edge supports (4-edge supported floors) on the floor dynamics and vibration performance will be implemented.

The other issue in using simplified methods is calculation of the deflection. The deflection of the floor system under a 1 kN concentrated load is normally smaller than 2 mm and its measurement is a delicate task.

An engineer may decide to use modal superposition methods. The vibration performance in these methods is based on the frequency cut-offs, modal mass, mode shapes and damping. This will provide the engineer more flexibility to make a judgement on the vibration performance of the floor. However, the current study shows that the response factors predicted by modal superposition methods considerably outweigh the experimental observations. The conservative design approach causes oversizing of the floor systems and their structural elements and may result in forsaking a timber design.

Based on the findings of the current study, the following future research directions may be pursued to promote implementation of timber floors in longer spans in buildings of different usages:

- Measure and formulate load functions of continuous and impulsive excitations as well as rhythmic activities, tailored for long-span timber floors.
- Characterise the dynamic properties (natural frequencies, modal mass, mode shape and damping) and response to vibration of floor slabs (i) in the laboratory environment, and (ii) floor systems in selected constructed or completed buildings. This will help understand the difference between a slab design analogy and the actual performance of the floor within the structural system.
- To develop experimentally validated analytical models that can reliably predict the dynamic properties and vibration response of the floor systems.
- To assess occupant comfort with different floor usage and identify acceptance criteria for the investigated floor systems.

In order to establish design criterion in Australia, subjective evaluation of occupants' perception of level of comfort needs to be conducted. There will be enormous benefit in gathering the data from field tests and occupant surveys to establish an international database for researchers and practitioners worldwide for vibration design of long-span floor systems.

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