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Advancing Timber for the Future Built Environment

DESIGN UNCERTAINTY IN LONG SPAN MASS TIMBER FLOORS: PROPOSED BAND-BEAM SOLUTION

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ABSTRACT: The low relative density of timber compared to other building materials (concrete and steel) increases its sensitivity to low frequency footfall vibrations. Coupled with the scarcity of experimental data on in-situ floor vibration performance, shorter clear spans (~8 m) and excessive panel thicknesses are often prescribed for mass timber floors. This study combines in-situ performance testing of an existing mass timber floor under a conventional 5.5 m span supported by glulam with a conceptual cross-laminated timber band-beam. The existing floor performance met those of a high frequency floor (>10 Hz natural frequency, 2.93% damping ratio). Sensitivity testing indicated damping ratios and floor classifications (low or high frequency) can greatly impact response factor calculations. A conceptual floor design was implemented by replacing the hardwood glulam with thinner, laboratory-tested band-beams. The numerical results indicated a change in the floor classification and an increase in response factor. Further experimental investigations can help determine the optimal band-beam design.

KEYWORDS: Vibration, long-span, deflection, frequency, serviceability.

1 – INTRODUCTION

A recent report released by the Australian Governments' Productivity Commission has uncovered a 53% decline in building productivity over the past 30 years [1]. This finding, coupled with a rising demand for new housing and/or office developments domestically, and the continuing challenges the built environment faces with climate change globally (contributing to 40% of the global greenhouse gas emissions), presents an opportunity for alternative building materials and practices to be considered [2, 3]. Mass timber products (MTPs) such as cross-laminated timber (CLT) present opportunities to compete with conventional building materials through comparable mechanical properties, material stability, cost effective design, and easy installation; all while acting as a natural carbon sink [4-6]. The Council for Tall Buildings and Urban Habitat (CTBUH) reported in 2022 there were 138 buildings containing MTPs (greater than 8 stories) globally [7]. However, increases to this number are impeded by challenges related to the low frequency footfall induced vibrations and the low sound insulation performance of MTPs [8].

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A series of design methods and standards exist globally to address these challenges however they differ on some key performance values, complicating the design process. A recent study by Faircloth *et al.* [9] suggested that much of this stems from the limited research and experimental data on in-situ performance applications of MTPs to then properly inform guide/ standard/ code revision. This has then led to the global mass timber industry imposing overly conservative design practices to account for the information that is considered lacking. One such conservatism is floor spans with many Australian developments limiting clear span lengths at 6 to 8 m. Long spanning floor systems (LSFS's) greater than 8 m were identified through Faircloth *et al.* [9] as one of the key areas of research needing to be expanded on with only 9.2% of reviewed literature focusing on it while the consultation phase of the review echoed industries interest.

This study has sought out to address two areas of lacking experimental information; i) the performance of MTPs during in-situ applications and how this compares with predicted performance values, and ii) potential to consider increased clear spanning to 9 m through alternative product solutions. The study presents the experimental performance of a CLT band-beam (BB) as an alternative to conventional glued laminated timber (glulam) beams currently used in in-situ post-and-beam floor systems. An office floor under construction has then been tested for its vibration serviceability performance to be benchmarked against numerical modal analysis (NMA) and compare measured and predicted performance. The BB design being CLT provides additional flexural stability allowing for a shallower beam size and longer spanning potential. The final stage of the study incorporates the tested BB into the NMA of the tested floor to show performance differences at an increased span of 9 m.

2 – MATERIALS & METHODS

2.1 MATERIALS

2.1.1 Laboratory testing

Five (5) band beams (BB) were provided by XLam Australia (Victoria, Australia), manufactured with Radiata pine (*Pinus radiata*), at the nominal size of 9,600 (L) × 615 (W) × 520 and 12 plies (D) mm. The modulus of elasticity (MOE) was determined using nominal input variables through OSULaminates (Ver. 6.2, Oregon State University) as 9,921 MPa in the major axial direction (MOE_x) with a mean density of 480 kg/m^3.

2.1.2 In-situ floor systems

The floor system tested was a 5-layer, 220 mm thick CLT panel sourced from XLam Australia, manufactured with Radiata pine, a nominal density of 480 kg/m^3, and layered with a layer of nominal 10,000 MPa MOE_x boards on each face and three layers of nominal 6,000 MPa MOE_x boards in the core [10]. The tested bay was located on the south-west corner of the structure with two sides of the bay made up of the building façade (image of floor shown in Figure 1).

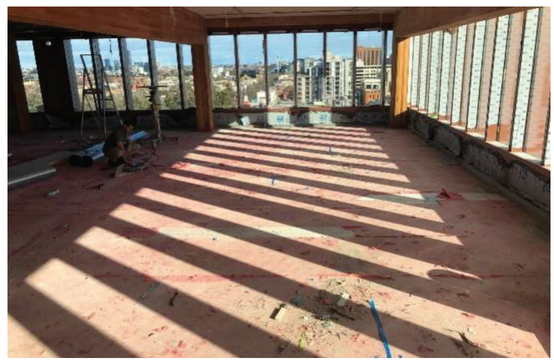

Figure 1: Exemplar floor bay tested showing exposed CLT, building façades, columns and supporting beams.

The building design used a post-and-beam configuration with a 9,675 (length - L) × 5,500 (width – W) mm span between columns in the x and y axial directions, respectively. The column and beam end cross-section at the tested bay location were 480 (depth - D) × 380 (W) mm and 840 (depth - D) × 380 (W) mm, respectively. The column and beam products were supplied by Australian Sustainable Hardwoods (ASH, Victoria) with a nominal density of 650 kg/m^3 and MOE_x of nominal 18,500 MPa. The floor configuration showing column and beam locations are shown in the experimental sections of the article.

2.2 EXPERIMENTAL APPROACH

Vibration analysis of the in-situ CLT floor and laboratory tested BBs was performed with a series of (3) single-axis accelerometers (100mV/g, IEPE type, National Instruments) and an electronic impact hammer (2.25 mV/N, 2kN capacity, IEPE type, Brüel & Kjær). Data collection and initial processing was performed using a NI 9234 sound and vibration module, LabVIEW (Ver. 2017, NI), and post-processing conducted through MATLAB (Ver. 2021, MathWorks).

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2.2.1 Laboratory testing

The BBs were first simply supported for static deflection experiments (performed by XLam Australia, Wodonga Victoria), then freely supported for vibration testing (performed by Griffith University, Gold Coast Campus, Queensland) to measure properties such as natural frequencies, damping ratios, and mode shapes.

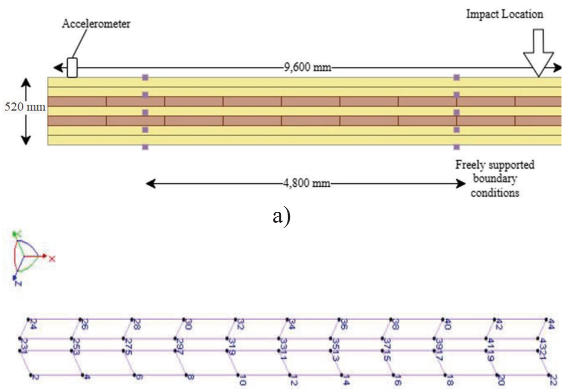

Figure 2: a) experimental setup in laboratory for vibration analysis, and b) impact point grid.

For the vibration testing performed, the BBs were freely supported at quarter points as shown in Figure 2a and tested using a multiple input single output (MISO) roving excitation method with 44 points tested. From these tests the natural frequencies associated with key bending modes were recorded, and damping ratios (ς) calculated from Eq 3 [11]:

$$\varsigma = \frac{1}{2Q}, \qquad Q = \frac{f_n}{f_2 - f_1} \qquad \text{Eq 3}$$

where Q is the quality factor of a single frequency peak (f_n) and the peak bandwidth is represented by the difference between f_2 and f_1.

2.2.2 In-situ floor systems

The in-situ experimental modal analysis (EMA) tests were performed at a 1 × 1 m spaced grid over the floor bay (60 points). A roving impactor method was adopted for the testing with sensor placement and impact locations shown in Figure 3. Each point was tested three times and the average of these impulses analysed as the response. Similar to the method detailed in 2.2.1, the first four natural frequencies were recorded and ς calculated from Eq 3.

Additionally, footfall induced vibration testing was performed on the in-situ floor using the path indicated in Figure 3 with sensor placement remaining the same as it was for EMA testing. The acceleration over time was recorded for the duration of walking for a 1.8 Hz walking rate conducted by an 80 kg test subject.

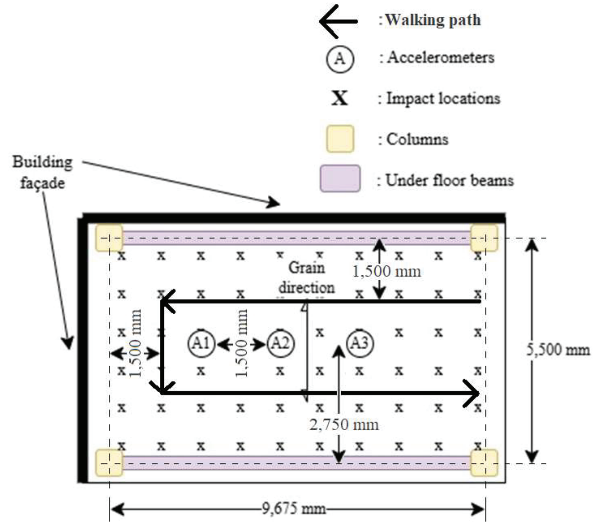

Figure 3: Schematic of impact positions for modal testing.

The measured values from EMA and footfall experiments relate to those parameters required for the CCIP-016 [12]. The CCIP-016 [12] method is used to predict the response factor (R_f) in floors subjected to walking excitations, where the R_f is related to the floor's acceptability by occupants [9, 12].

2.3 NUMERICAL APPROACH

2.3.1 Band-beam performance

Using the same properties noted in Section 2.1.1 and poisson's ratio values of 0.33 for μ_{xz}, 0.29 for μ_{xy}, and 0.38 for μ_{yz} [13], a BB was modelled in ANSYS (Ver. 2024 [14]) workbench using a layered shell model. This will be compared against experimental results for the BB and used to integrate the BB into the in-situ floor model.

2.3.2 In-situ floor systems

ANSYS Parametric Design Language (APDL, Ver. 2024) [14] was used to model the bays expected performance characteristics as shown in Figure 4. The supporting column's between floors were modelled as half-length above and below the floor. For this model, the CLT floor is modelled using a 5-layer shell with the two outer face layers assigned 10,000 MPa MOE_x while the three inner layers were assigned 6,000 MPa MOE_x. The glulam columns and two edge beams are modelled using beam elements with a modulus of 18,500 MPa MOE_x.

Using symmetry, the columns are modelled in half-length on either side of the floor. The edge beams are offset from the CLT mid-surface (by 420 mm) and are connected to the adjacent nodes of the CLT shell elements using multi-point constraints in ANSYS [14]. The shell and beam elements are discretised with a mesh size of 0.1 m and the density of CLT and glulam in the NMA is taken as 518 kg/m^3 and 650 kg/m^3, respectively.

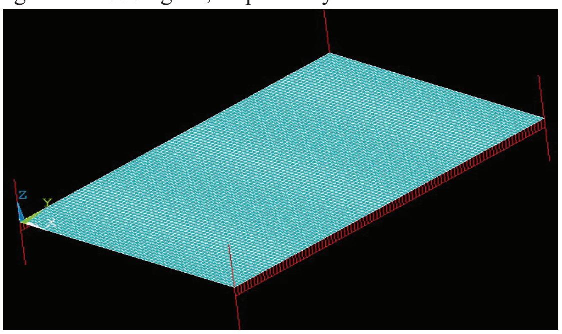

Figure 4: ANSYS [14] mesh and geometry of modelled floor bay based on dimensions noted in Section 2.2.2.

CCIP-016 [12] provides a simple method used by many engineers to predict the acceptability of a floor, known as the R_f. Using Eq 6 and 7 the R_f for a low and high frequency floor can been calculated, respectively [12, 17]:

$$R_{f,L} = \frac{a_{w,RMS}}{5.0 \times 10^{-4}} \quad \text{Eq 6}$$

$$R_{f,H} = \frac{v_{RMS}}{1.0 \times 10^{-4}} \quad \text{Eq 7}$$

where $a_{w,RMS}$ is the root-mean square (RMS) value of the weighted acceleration response (m/s^2), and v_{RMS} is the RMS value of the velocity response (m/s).

2.3.3 Integration of laboratory results

After exploring the difference between the NMA and experimental results for the in-situ CLT floor bay, conceptually the glue laminated timber beams in the in-situ floor model are replaced with the BB support beams. In the FEA, mechanical properties of the BB are taken from the laboratory tests discussed in Section 2.3.1. The R_f for the alternate designs are then reported. Using the same numerical approach as explained in Section 2.3.2, the glulam beams are replaced with BB's in a conceptual floor design scenario. The response factors from Eq 6 or 7 are then re-calculated and presented.

3 – RESULTS & DISCUSSION

3.1 EXPERIMENTAL TESTING

3.1.1 Laboratory testing

Table 1 presents the summarised frequency results from the tested BBs using experimental modal analysis (EMA).

Table 1: Summary results of BB characterisation using EMA.

Method	f_1	f_2	f_3
		(Hz)	
EMA	16.6	45.3	67.0

The frequency values show no major change between measurements on the individual BBs or between mean measurements and the experimental numerical analysis (NMA) response. The first three major bending mode shapes are depicted in Figure 4. There were some differences between EMA and NMA frequencies due to the estimations in modelling the boundary conditions in the FE model. However, the deflection calculated from the FEA matched the experimental measurements with good accuracy.

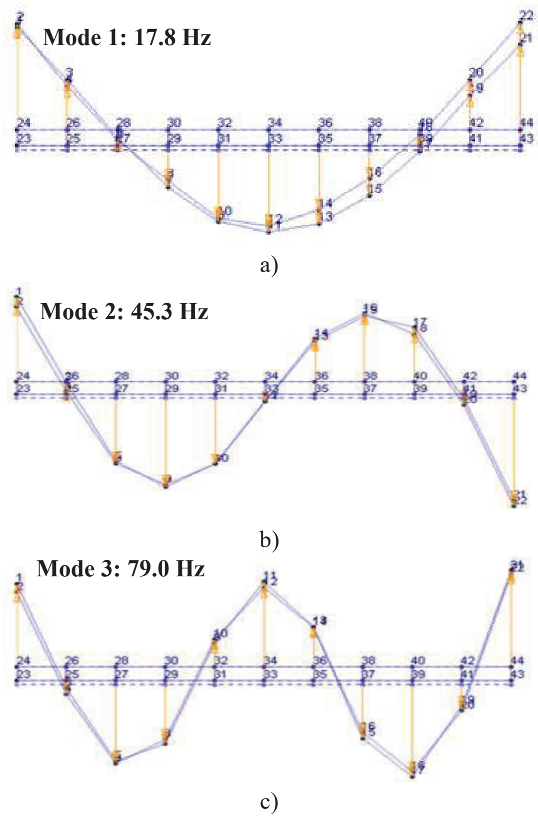

Figure 5: Mode shapes of BB showing the major bending mode shapes (Mode 1: a, Mode 2: b, Mode 3: c) with corresponding frequencies in Table 1.

3.1.2 In-situ floor systems

Table 2 summarises the first four natural frequencies as well as associated damping ratios from EMA impact testing performed. These have been compared against NMA frequency values for the same first four modes with modal mass contribution values also reported from NMA only.

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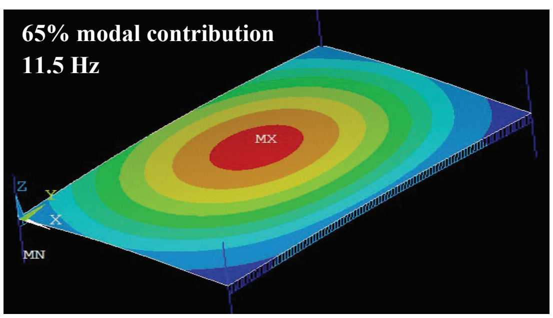
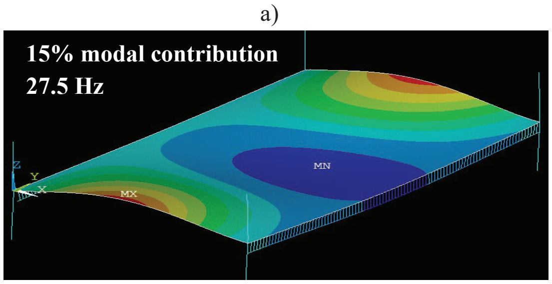
Table 2: EMA and NMA of the in-situ floor (CoV percentage presented in the parenthesis).

Mode	*f* EMA (Hz)	ζ (%)	*f* NMA (Hz)	Modal mass (%)
1	11.6 (7.54%)	2.93 (1.25%)	11.5	65%
2	18.4 (6.12%)	2.22 (6.37%)	18.2	0.0%
3	23.2 (11.1%)	1.76 (13.5%)	22.8	0.3%
4	30.7 (6.43%)	1.38 (4.61%)	27.5	15%

The results of Table 2 show a close agreement between frequency values for all natural frequencies with a 3.33%, 2.72%, 4.31%, and 10.5% variation between EMA and NMA. This variation being below 5% and the CoV values below 8% suggests the NMA is representative of the EMA values. The modal mass contributions reported in Table 2 indicate that while up to 4 modes have been accurately detected for both EMA and NMA, only modes 1 and 4 contribute significantly to vertical displacement. The NMA mode shapes with significant mass contribution are shown in Figure 6. These modes equate to 80% of the modal mass contribution percentages. It is worth noting that the accumulative mass contribution of the first 50 modes (up to a frequency of 168 Hz) sums up to 85% of the total mass.



a)

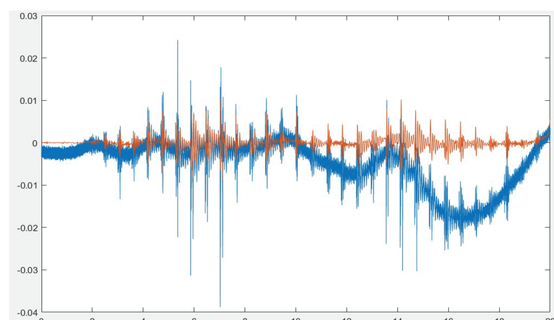


b)

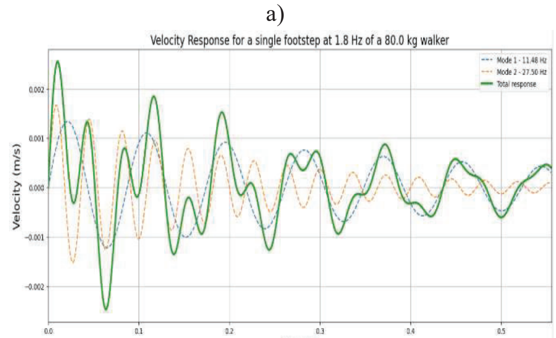
Figure 6: NMA shapes showing significant z-axis bending modes for a) 11.5 Hz, and b) 27.5 Hz mode shapes.

Figure 7a presents a measured acceleration time history response of the floor under a walking excitation of 1.8 Hz with static weight of 80 kg. The time history is filtered to the weighing factors in ISO 2631 [19]. Once weighted, the measured time domain response clearly shows a transient response recognised through a peak, heel-drop, and decayed component until the next footfall event. In this response, a peak velocity of 0.00255 m/s and a v_{rms} of 0.0008 m/s is measured, which yields $R_f = 8.0$ using $R_{f,H}$, as per Eq 7. The response factor is also calculated using the method described in CCIP-016 [12] where two critical damping scenarios are assumed. The first scenario being an assumed ζ of 3% across all major bending modes and the second scenario with ζ assigned based on the measured values in Table 2. The velocity response is shown in Figure 7b.

The calculated $R_{f,H}$ are 8 and 10.3 for scenario 1 and scenario 2, respectively. This 22.3% difference in $R_{f,H}$ shows the influence difference between assumed and measured ζ values. It is also worth noting that a $R_{f,L}$ of 2 can be obtained using the same values introduced above if a low-frequency method is used from Eq 6 [12, 17]. However, in CCIP-016 [12] the low-frequency method is not recommended in floors with fundamental frequency less than 10 Hz.



a)

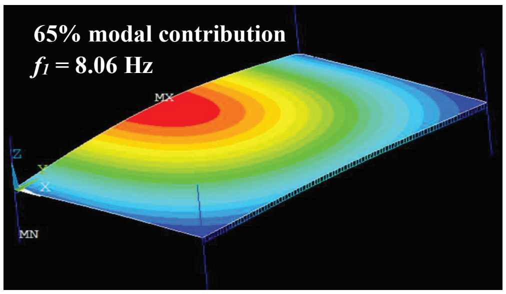


b)

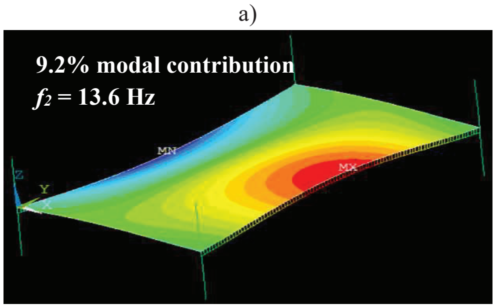
Figure 7: In-situ floor response: (a) The experimental acceleration measurements (raw and ISO 2631 [19] weighted), and (b) the numerical predictions using the CCIP-016 [12] method.

3.2 INTEGRATION OF LABORATORY RESULTS

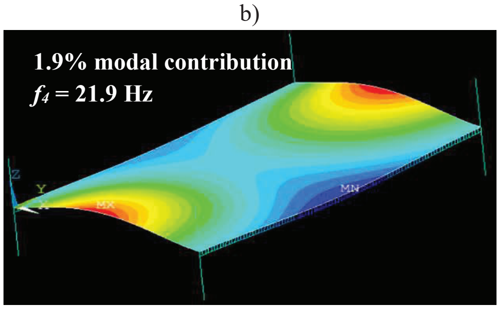
The mode shapes from the FEA model of the BB integrated floor response with significant vertical modal mass contribution are presented in Figure 8 (modes 1, 2, 4, and 7). Seeing as that the first fundamental natural frequency is below 10 Hz, the low frequency method detailed in Eq 6 was used to find the $R_{f,L}$ [12, 15, 20].



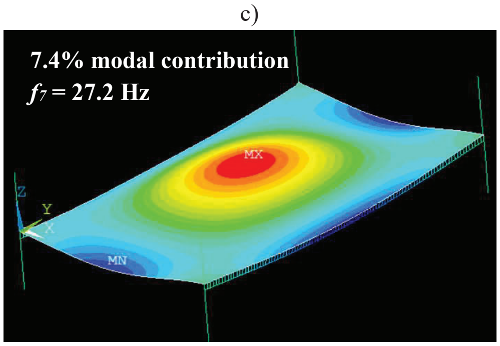
a)



b)



c)



d)

Figure 8: NMA modes shapes of BB supporting beams instead of glulam (Mode 1: a, Mode 2: b, Mode 4: c, Mode 7: d).

Comparing the FEA results for the two most dominant bending mode shapes (Figure 6a and 8a), a shift in the displacement maxima towards the building façade can be seen in Figure 8a. Figure 6a however shows a near central displacement maxima point.

Considering the same f_w as for the glulam supported FEA model of 1.8 Hz, the concept BB floor $R_{f,L}$ value is 13. The $R_{f,L}$ at walking frequencies between 1.6 Hz to 2 Hz is shown in Figure 9. It can be seen that the largest contribution in the response is from the 4th harmonic of the walking excitation shown with the Fourier expression in Eq 8 [17].

$$F(t) = Q\left\{1 + \sum_{n=1}^{k} \alpha_n \sin(2\pi n f_w t + \emptyset_n)\right\} \qquad \text{Eq 8}$$

where Q is the static load of the walker of 80kg (noted above), α_n and $\emptyset_n$ are the Fourier coefficient and phase angles, respectively, corresponding to the n^{th} harmonic, and k is the number of harmonics. It should be noted that the CCIP-016 [12] specifies an α_n of $0.41f_w - 0.3895 < 0.56$ for an f_w of 1.0 to 2.8 Hz. ISO 10137 [20] suggests that for harmonics below resonance, consider a $\emptyset_n$ of 90°.

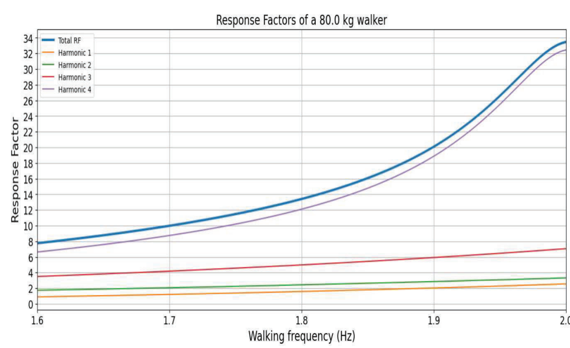


Figure 9: Response factors at different walking frequencies of the conceptual floor with band-beams.

4 – CONCLUSION

This paper summarises the results from a study proposing a solution for mass timber, long spanning floor systems. The study first evaluates the EMA in-situ performance of a mass timber floor before comparing the accuracy of a developed NMA model. The comparison between EMA and NMA is shown through natural frequency comparisons with less than 5% variation for first 4 modes, and corresponding NMA modal mass contribution percentages summing to 80%. Classifying the in-situ floor as high frequency with the first mode occurring >10 Hz, the response factors range from 8 to 10.3 depending on use of predicted (3% for all modes) or measured (2.93% for mode 1 and 1.38% for mode 4) critical damping values, respectively. These comparisons between CCIP-016 and

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in-situ measurements show good agreement at the tested walking frequency of 1.8 Hz. The response factor of the conceptual floor design in Section 3.2 increases to 13 (20.8% increase) with the floor now classified as low frequency (8.06 Hz). Additional work is needed to fully realise the potential of a BB floor system under various experimental sensitivity parameters to understand limitations (span, floor build up, and CLT thickness). Further experiments are planned to address some of the unknowns raised through this study.

5 – ACKNOWLEDGEMENTS

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