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FREQUENCY CONTRIBUTIONS TO DYNAMIC RESPONSES OF JOISTED TIMBER FLOORS: A WAVELET TRANSFORM APPROACH

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ABSTRACT: This experimental study investigates the effects of non-uniform live load distribution, represented by different furniture arrangements, on the dynamic characteristics of a joisted timber floor. The modal parameters including fundamental frequency, mode shape, damping ratio, and modal mass participation are estimated for four furniture arrangements. Additionally, floor dynamic responses are evaluated as root mean square accelerations under different walking frequencies for all arrangements. This study aims to assess how different furniture arrangements affect the frequency content of a lightweight timber floor's dynamic responses. The results highlight the significant influence of the non-uniform live load distribution on the floor's modal parameters and dynamic responses. A discrete wavelet transform is applied to analyze frequency contributions in dynamic responses, revealing that lower-frequency components (up to 25 Hz) dominate the responses at mid-span and locations with maximum floor response. However, at higher walking frequencies and the edge points, the responses exhibit increased high-frequency content.

KEYWORDS: Timber joisted floor, modal parameters, furniture arrangement, wavelet transform,

1 – INTRODUCTION

In building structures, floors are the only structural elements in constant contact with occupants. Therefore, vibration-related problems of the floors demand a precise evaluation considering the serviceability limit state, particularly in the context of lightweight floor systems such as timber floors. As a result, many studies have been conducted on the vibration performance of timber floors under human-induced excitation [1–4]. Due to the lightweight properties of the timber floors, particularly joisted timber floors, the presence of live load and its different distributions can influence the floor vibration performance. Some studies have been conducted on the effect of live load on floor dynamic responses implying the important role of live load on the dynamic characteristics and vibration performance of the floors [5, 6]. In design codes such as Eurocode 5, a portion of live load is considered as an uniform distributed load in calculating the vibrational floor mass covering moving equipment such as furniture. Due to light-weight properties of joisted timber floors, it is expected that different live load distributions influence the dynamics and frequency content of floor motion responses. Therefore, this study aims to evaluate the effect of different furniture arrangements on modal parameters and the frequency content of dynamic responses of a timber floor. For this purpose, dynamic characteristics of a floor are obtained considering four different furniture arrangements, then the analysis of dynamic responses is performed using discrete wavelet transform (DWT).

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2 – EXPERIMENTAL TEST

In this study, a series of vibration and walking tests were conducted on a joisted timber floor to determine the modal parameters and dynamic acceleration responses expressed in the form of root mean square (RMS) acceleration. Measurements were taken in the absence and presence of furniture, considering four different arrangements.

2.1 FLOOR MATERIAL AND GEOMETRY

The studied floor is a lightweight timber floor shown in Figure 1. The floor consists of a series of joists enclosed by two end beams on the sides and a particleboard on top. The particleboard with a thickness of 22 mm is attached to the top of the joists by both glue and nails. The joists, and the end beams, are made of "combined" glulam, where the top and bottom lamellae are timber boards graded C40 while the inner lamellae are graded C24. The joists have a centre-to-centre distance of 600 mm, and all joists and end beams cross-sectional dimensions are 48 mm x 300 mm. The two enclosing beams are connected to the joists by means of nails. The floor is simply supported at four corners, not fully representative of an in-situ floor, but it is considered suitable for avoiding any effect of imperfections in boundary conditions. Other properties of the floor are presented in Table 1.

Table 1: Floor properties

Hight (cm)	Width (m)	Length (m)	Weight (kg)
32.2	2.4	4.9	380.3

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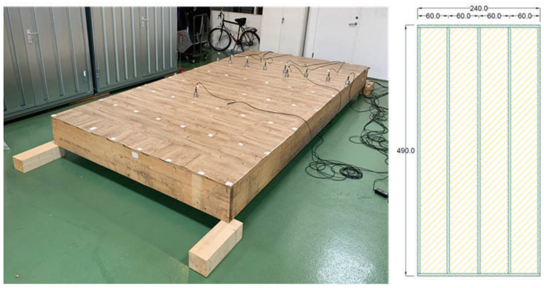

Figure 1: Studied floor

2.2 FURNITURE ARRANGEMENTS

To evaluate the effect of live load distribution on dynamic responses, four different furniture arrangements, named Arr01 to Arr04, are considered as presented in Figure 2, while Arr00 shows the unfurnished case. Notably, the same furniture, with a total weight of 122.7 kg, was used in all four arrangements.

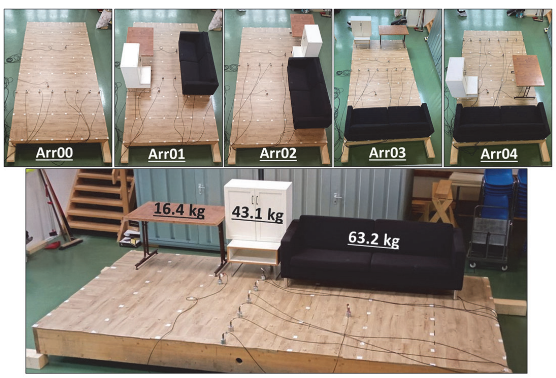

Figure 2: Furniture arrangements

2.3 EXPERIMENTAL SETUP

2.3.1 Vibration test

Using a sensor-roving approach, a dense sensor configuration was adopted to identify the modal parameters of the floor. Two accelerometers were used as references and eight were used as roving sensors. In total, the number of measurement points was 66, as shown in Figure 2 marked with white tapes. The acquisition frequency was 200 Hz with a duration of 120 seconds for each excitation. The excitation was performed by a plastic hammer. The modal parameters have been obtained from the two well-known output-only identification algorithms: the Stochastic Subspace Identification (SSI) and the Enhanced Frequency Domain decomposition (EFDD) using Artemis and PyOMA for mutual validation.

2.3.2 Human-induced excitation

Human-induced excitations were performed under different walking patterns and sensor placements. Figure 3 shows various sensor placements and walking paths, while *W* stands for walking path and *P* presents the sensor placement. All walking tests were conducted with the same individual, weighing 72 kg, at two walking frequencies of 1.5 Hz and 2.0 Hz. A metronome app was used to ensure the accuracy of the walking frequency. In addition, due to the presence of furniture, not all walking paths could be tested for each furniture arrangement. Table 2 shows the walking paths and sensor placements for each furniture arrangement. Each RMS acceleration response is the average of three repeated walking tests.

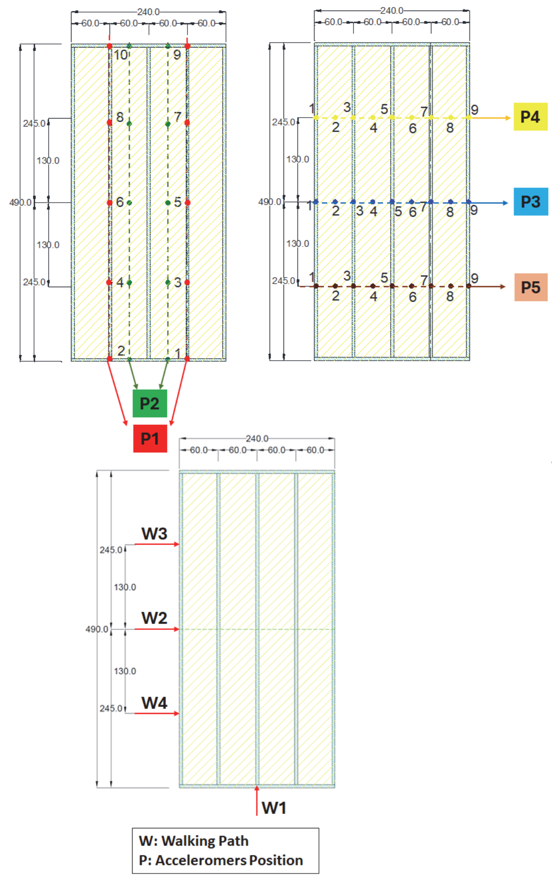

Figure 3: Walking paths and sensor placements

Table 2: Walking paths and sensor placements

Furniture arrangement	Walking path & Sensor placement
Arr00	W1P1 - W1P2 - W1P3 - W2P4 W2P5 - W3P3 - W4P3
Arr01	W1P1 - W1P2 - W1P3
Arr02	W1P1 - W1P2 - W1P3
Arr03	W2P4 - W2P5 - W3P3 - W4P3
Arr04	W2P4 - W2P5 - W3P3 - W4P3

3 – EXPERIMENTAL RESULTS AND DISCUSSION

3.1 MODAL PARAMETERS

3.1.1 Fundamental frequency an damping ratio

Figure 4 illustrates the fundamental frequency of the floor and corresponding damping ratio under various furniture

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arrangements. Notably, the ratio of the furniture's weight to the weight of the bare floor is 32.2%. Despite this fixed weight ratio for all furniture arrangements, the identified fundamental frequencies vary depending on the position of the furniture on the floor. The results demonstrate a significant effect of furniture arrangement on the floor's fundamental frequency. The lowest fundamental frequency was observed for arrangement Arr01 with 14.87 Hz, estimated from the SSI, showing a 16.1% reduction compared to Arr00, whereas only a 3% reduction was observed for arrangement Arr03 compared to Arr00. Table 3 summarizes all identified modal frequencies, including higher modes, and demonstrates that the live load distribution affects not only the fundamental frequency but also the higher modes.

Figure 4 also highlights the influence of furniture on damping ratio with an increase for all cases with furniture, indicating a positive effect of furniture on energy dissipation. In comparison to Arr00, the most significant increase in damping ratio occurs in Arr03 with a 191% rise. Interestingly, despite this substantial increase in the damping ratio, the natural frequency of Arr03 does not exhibit a significant change when compared to Arr00.

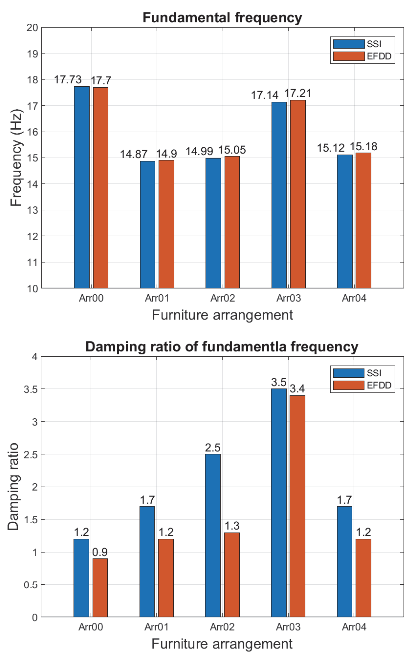

Figure 4: Floor fundamental frequency and corresponding damping ratio

Table 3: Identified modes frequency (Hz)

Mode	Arr00	Arr01	Arr02	Arr03	Arr04
1	17.73	14.87	14.99	17.14	15.12
2	25.82	23.48	23.3	25.01	21.26
3	28.76	33.99	26.94	28.26	28.38
4	32.81	38.88	32.35	33.98	31.02
5	41.02	-	40.91	-	39.11
6	-	-	-	-	43.03

3.1.2 Mode shape

Figure 5 displays the estimated first mode shape. It can be observed that the maximum deformation for Arr01, Arr02, and Arr04 shifts toward areas with greater mass. In contrast, the mode shape for Arr03 remains almost similar to Arr00. It should be mentioned that the smallest reduction in the fundamental frequency was also observed in Arr03 compared to Arr00. This can be due to the location of the furniture that is placed close to the supports, resulting in a small change in the fundamental frequency and mode shape.

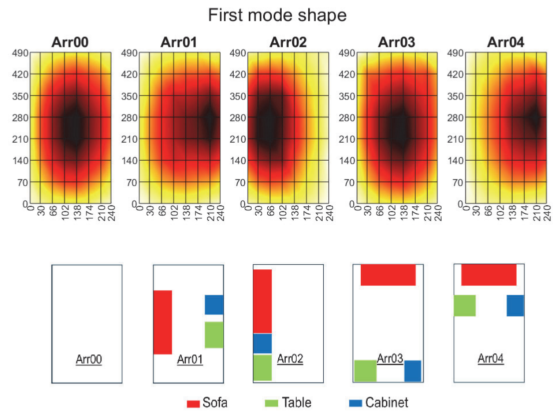

Figure 5: The first identified mode shape

3.1.3 Modal mass participation

The modal mass participation for the first mode is calculated for all arrangements and presented in Figure 6. The participation varies significantly depending on the furniture arrangement, ranging from the lowest at 66.8% for Arr04 to the highest at 80.5% for Arr01. No clear relationship was observed between the modal mass participation and the identified fundamental frequency shown in Figure 4. For example, the modal mass participation of Arr03 is 68.6%, slightly higher than that of Arr02 (67.1%). However, the fundamental frequency of Arr03 is 14.2% higher than that of Arr02.

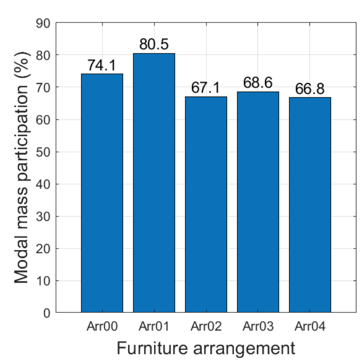

Figure 6: Modal mass participation of the first mode

3.2 ANALYSIS OF HUMAN-INDUCED DYNAMIC RESPONSES

The analysis of the walking excitation responses showed a reduction range of 15% to 50% in responses in the presence of furniture due to higher mass compared to the unfurnished floor responses. The maximum floor responses and the corresponding measurement points are presented in Figure 7. It can be observed that for Arr00, the location of the maximum response at both walking frequencies is at the mid-span of the floor. However, considering the furnished cases, the location of the maximum response shifted toward edges, particularly for Arr03 and Arr04 at a walking frequency of 2.0 Hz. The lowest response was observed under the walking frequency of 1.5 Hz for Arr03 while this arrangement has the lowest reduction in the fundamental frequency but the highest damping ratio.

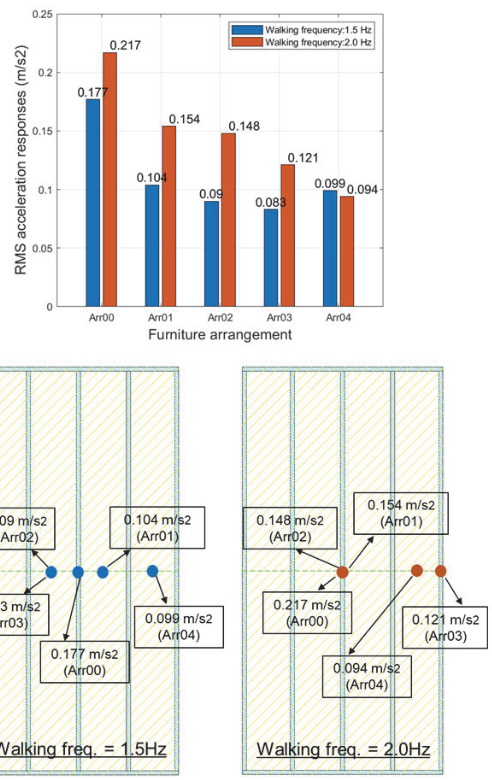

Figure 7: Maximum dynamic responses of the floor and their measurement location

3.3 ANALYSIS OF DYNAMIC RESPONSES USING DISCRETE WAVELET TRANSFORM (DWT)

Wavelet transform is a mathematical tool for signal processing. Wavelet analysis breaks down a signal into shifted and scaled versions of a wavelet. Unlike a sine wave, a wavelet is a rapidly decaying, wave-like oscillation, making it suitable for capturing both time and frequency information. This unique property allows wavelets to represent data across multiple scales effectively. Depending on the application, various types of wavelets can be used to achieve the desired analysis. Wavelet transforms can be classified into two broad classes: the continuous wavelet transform (CWT) and the discrete wavelet transform (DWT).

The Discrete Wavelet Transform (DWT) acts as a filtering mechanism that breaks down an input signal into approximation (A) and detail coefficients (D) using two types of filters: a low-pass filter for low-frequency content and a high-pass filter for high-frequency content. Essentially, the signal is separated into two components: one containing high-frequency details and the other capturing low-frequency trends. Through a process known as multilevel decomposition, the DWT allows signals to be analyzed at various levels of resolution. This hierarchical approach progressively narrows the frequency bands, enabling a comprehensive analysis of both high- and low-frequency components. Figure 8 illustrates this decomposition process schematically.

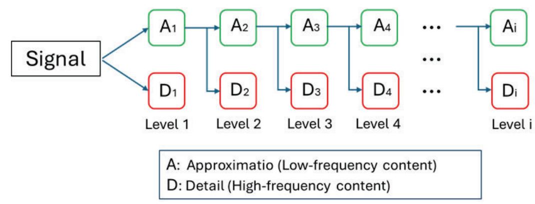

Figure 8: Schematic decomposition process of a signal using DWT

In order to analyze the dynamic acceleration response using DWT, this study employs the Daubechies wavelet of order 10 (db10) to decompose the floor responses and calculate the energy percentage within each frequency band. The db10 wavelet was chosen due to its minimal overlap between adjacent frequency bands, ensuring more precise analysis. In contrast, lower-order Daubechies wavelets exhibited considerable overlap between frequency bands, which could compromise the accuracy of energy distribution calculations. By selecting five levels of decomposition, the frequency bands are divided according to Table 4. All identified modes, presented in Table 3, are categorized into levels 2 and 3.

Table 4: Frequency bands using db10

	Frequency range (Hz)
Level 1	50 - 100
Level 2	24.9 - 50.1
Level 3	12.5 - 25.1
Level 4	6.23 - 12.5
Level 5	3.12 - 6.27
Approx.	0 - 3.12

Figure 9 displays the cumulative energy of the responses within the frequency bands at the mid-span and at measurement points with the maximum responses. For the 1.5 Hz walking frequency, it can be observed that at the mid span, the energy percentage exceeds 90% for all arrangements when considering frequencies below 25.1 Hz, highlighting the limited contribution of higher modes to the floor responses. According to Table 3, the first and second modes

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are below 25.1 Hz for all furnished cases. This energy percentage drops below 90% in Arr03 and Arr04 for 2.0 Hz walking frequency, while the other cases exhibit contributions above 90%.

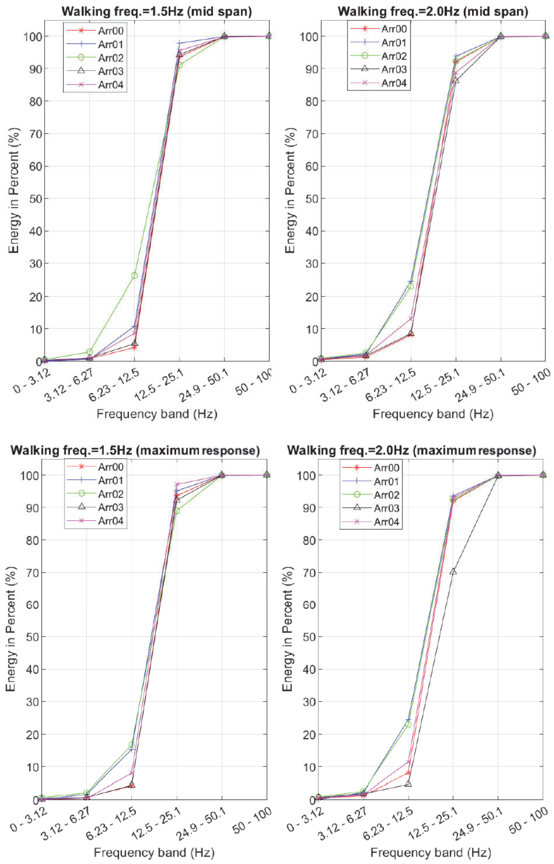

Figure 9: Cumulative energy percentage of floor responses at mid span and maximum response

Analyzing the maximum responses, under 1.5 Hz walking frequency, shows that only in Arr02 the contribution of frequencies below 25.1 Hz drops slightly less than 90%, at 88.9%. But for the maximum responses at 2.0 Hz walking frequency, a significant drop can be observed in the contribution of frequencies below 25.1 Hz for Arr03, with a value of 70.1%. As seen in Figure 7 the corresponding location of the maximum response for Arr03 is in the middle of the right edge of the floor.

To analyze the responses at the edge points more effectively, Figures 10 and 11 compare the frequency content of responses at four measurement points along the four edges for Arr00, Arr01, Arr02. In Arr00, the floor response at point C has the lowest contribution to the low frequencies (below 25.1 Hz) at 52% for both walking frequencies, while in Arr01 and Arr02 this contribution increases by approximately 10% as a result of the added mass of the furniture.

For the furnished floor, the lowest contribution to the low-frequency component was observed at point D in Arr02 at 76% and 71% for 1.5 Hz and 2.0 Hz walking frequencies, respectively. Interestingly, in Arr02, no furniture was placed near point D, which may explain why the

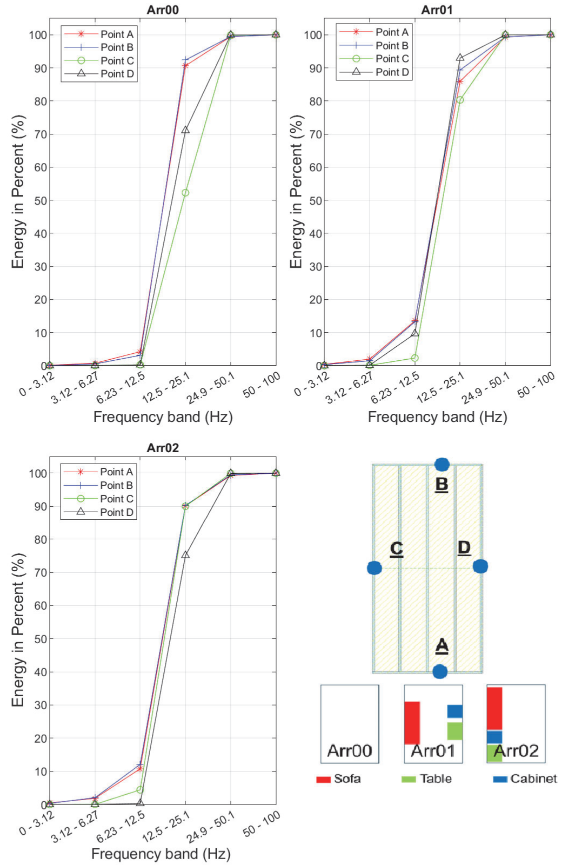

Figure 10: Cumulative energy percentage of floor responses at the edge points (Walking frequency=1.5 Hz)

low-frequency contribution of the responses at this point remains relatively low.

4 – CONCLUSION

This study investigated the influence of non-uniform live load distribution represented by different furniture arrangements, on the dynamic response of a joisted timber floor. Experimental tests, including vibration and walking excitation tests, were conducted to analyze the modal parameters and acceleration responses of the floor under various conditions. With a furniture-to-bare-floor weight ratio of 32.2%, the results demonstrated that furniture arrangements significantly affect the dynamic characteristics of the floor. The analysis of modal parameters revealed a notable reduction in the floor fundamental frequency with certain furniture arrangements, with the lowest value occurring in Arr01, where it was reduced by 16.1% compared to the bare floor (Arr00). Additionally, damping ratios increased in all furnished cases, indicating enhanced energy dissipation.

The study also analyzed human-induced dynamic responses, highlighting a reduction in acceleration responses due to the increased vibration mass from the added furniture. In some cases with furniture arrangement, the location of maximum response shifted from mid-span toward the floor edge, particularly at a walking frequency of 2.0 Hz. The frequency content of the responses was

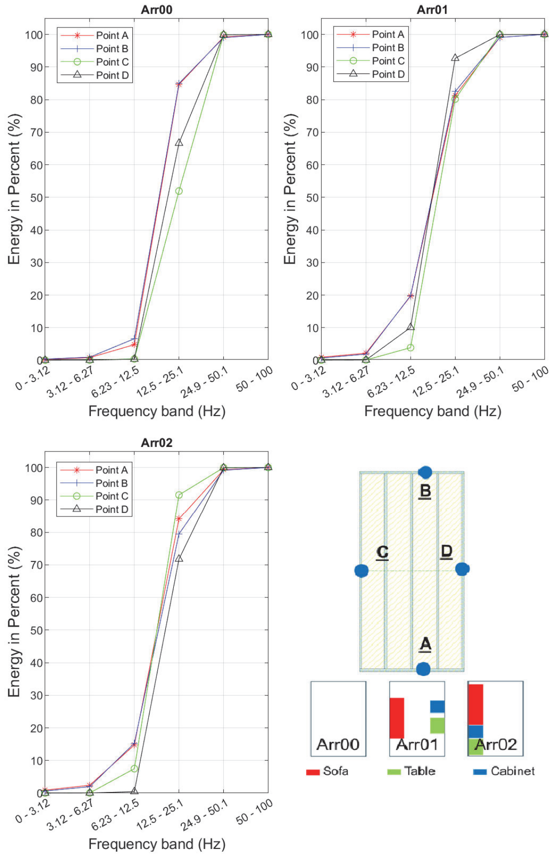

Figure 11: Cumulative energy percentage of floor responses at the edge points (Walking frequency=2.0 Hz)

analyzed using Discrete Wavelet Transform (DWT). The DWT analysis indicated that low-frequency components, up to 25.1 Hz, dominated the responses at mid-span and at the measurement points with a maximum response. However, at the edge points, the responses contain higher-frequency components. Additionally, an increase in walking frequency contributed to a higher proportion of high-frequency components in the responses.

Overall, the results emphasize the importance of considering furniture arrangements in vibration assessments of lightweight timber floors. The findings can contribute to a better understanding of serviceability performance in timber floor design, supporting the use of timber as a reliable building material.

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REFERENCES

[1] A. Aloisio, D. P. Pasca, D. Owolabi, and C. Loss. "Vibration serviceability of hybrid CLT-steel composite floors based on experimental and numerical investigations using random walk models." In: *Engineering Structures* 304 (2024), p. 117600.

[2] E. Ussher, A. Aloisio, D. P. Pasca, S. L. Hansen, and R. Tomasi. "Effect of partition walls on the vibration serviceability of cross-laminated timber floors." In: *Journal of Building Engineering* 95 (2024), p. 110001.

[3] E. Ussher, K. Arjomandi, and I. Smith. "Status of vibration serviceability design methods for lightweight timber floors." In: *Journal of Building Engineering* 50 (2022), p. 104111.

[4] J. Weckendorf, E. Ussher, and I. Smith. "Dynamic response of CLT plate systems in the context of timber and hybrid construction." In: *Composite Structures* 157 (2016), pp. 412–423.

[5] S. ZHANG, N. YANG, Y. WANG, and C. DONG. "Numerical Analysis of Long-span Floor Vibration Due to Crowd Synchronized Walking." In: ().

[6] G. Zhou and J. Chen. "Floor live load survey by forced vibration test using human-induced excitation." In: *Engineering Structures* 272 (2022), p. 114961.

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