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VIBRATION SERVICEABILITY OF MASS TIMBER COMPOSITE CLT-GLULAM TIMBER FLOOR WITH MECHANICAL SHEAR PLATES

Sultani Mulk Khan[1], Herry Chen[2], Alana Lund[3], Daniel Lacroix[4]

ABSTRACT: Engineered mass timber products are now a commodity for modern construction due to their improved strength and lightweight characteristics. Mass timber composite (MTC) floor systems have demonstrated potential in large-span floor applications but are currently limited by serviceability factors. Despite significant progress in the development of design guidelines for floor vibrations; challenges, limitations, and knowledge gaps in assessing and modeling the behavior of MTCs still exist. Current guidelines on vibration assessment are based on various parametric criteria such as acceleration, frequency, and deflection but lack a unified approach especially for in-situ application. The present study aims to investigate the gap in design practices by analyzing the dynamic behavior of an MTC floor system subjected to impact hammer, with respect to experimental and numerical methods of vibration serviceability analysis highlighted in current standards. The scope of the current paper is limited to the frequency response analysis of a MTC floor. A 2 m x 4.5 m ribbed panel floor composed of two CLT-glulam T-beams was investigated both at component-level and global system level under impact hammer excitation at 30 different locations. The floor frequency response was recorded at six different locations and a 30 x 6 Frequency Response Function (FRF) matrix was determined. The fundamental frequencies obtained were analyzed and validated using a complex model indicator function (CMIF) and stabilization diagram. Further, the fundamental frequencies were compared both at component level and global system level.

KEYWORDS: Mass timber composites, vibrations serviceability, fundamental frequency, CLT, Glulam.

1 – INTRODUCTION

1.1. BACKGROUND

Modern engineering practices and manufacturing developments have expanded the influence of timber construction, pushing the use of the material in midrise institutional and commercial building. MTC floor systems typically consist of flange(s) elements such as cross-laminated timber (CLT) that are compositely connected to a beam element, such as glued-laminated timber (glulam), using shear connections such as adhesives (e.g., PUR, PRF, commercially available modified silane), mechanical fasteners (e.g., self-tapping screws, shear plates), or a combination thereof. Products such as CLT, mechanically laminated timber (MLT), glued-laminated timber panel (GLT), and laminated veneer lumber (LVL) can be used for the flange(s) while beam-like products such as glulam are commonly used for the webs, thus resulting in a multitude of configurations for application in practice. In application, these systems commonly form ribbed panels with the potential for longer spans that can expand the overall structural capabilities of engineered wood products and push the possible architectural prospects of timber construction.

The high strength-to-weight ratio of engineered wood products in MTCs offers immense benefits in the form of added load bearing capacity, lateral stability, and improved fire resistance. The relatively lower weight of MTC floor systems combined with its use in long spans has contributed to increased floor vibrations that often cause a sense of discomfort to the occupants. In long span floor systems (e.g., spans greater than 4 m), the static and dynamic serviceability criterions can often be the limiting factor in design rather than overall structural capacity [1-3]. For MTC systems, these varying levels of activity can cause amplified vibrations with varying levels of

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acceleration and velocity that are unpredictable [3-5]. These serviceability factors have consequently limited the maximum span length for conventional mass timber flat slab systems to 8 meters [6].

1.2. VIBRATION PERFORMANCE OF MASS TIMBER COMOSITE SYSTEMS

The intended application and basic dynamic parameters, such as fundamental frequency, associated mode shapes, and damping characteristics, can be determined to evaluate and categorize the vibration performance of the timber floor [4]. A critical factor in these classifications is the dynamic response of the floor from human-induced vibrations, which includes low-frequency components that can influence both structural performance and occupancy comfort. As these components usually manifest in higher displacements and receive more energy from human excitations, fatigue and degradation in structural performance can occur. Consequently, various design guidelines and research studies classify floor system based on the fundamental frequency and deflection criteria of the system [7-9]. A threshold of 8 Hz is commonly used for low-frequency floor systems, typically those with a fundamental frequency below 8 Hz, as they present critical challenges in vibration-sensitive applications due to their proximity to the dominant frequencies of human activities, such as walking, jumping, and rhythmic movements which are approximately 1.5–3 Hz. This harmonization between excitation and structural response often leads to resonance, exponentially amplifying vibration amplitudes and causing noticeable human-structure interaction, consequently causing discomfort. From a design standpoint, such resonance-prone behaviour places stringent serviceability demands on low-frequency floors. Even if strength and stiffness requirements are satisfied, failing to meet vibration performance thresholds may render the floor unsuitable for residential or commercial occupancy. Consequently, raising the natural frequency above the resonance-prone zone (typically >8 Hz, as recommended in Eurocode 5) [7] becomes a primary objective in the design of mass timber floor systems to ensure occupant comfort and acceptable dynamic performance. However, other guidelines suggest an alternative frequency range (7-10 Hz) for distinguishing between low and high frequency floors [10] as shown in Table 1. While early design guidelines for timber floor serviceability were initially focused on limiting deflection under a uniformly distributed load, additional research have identified that the fundamental frequency, deflection, and damping are also critical factors that must be considered to design for floor vibrations [11].

Table 1. Floors category based on fundamental frequency [10]

Standard/Guideline	Low-Frequency Floor	High-Frequency Floor
ISO 10137 [8]	8 Hz < f_n<10 Hz or smaller	10 Hz < f_n
AISC DG11 [12]	f_n < 9 Hz	9 Hz < f_n
Toratti and Talja [4]	f_n < 10 Hz	10 Hz < f_n
Allen and Murray [13]	f_n < 9 Hz	9 Hz < f_n
BS 6472-1:2008 [9]	7 Hz < f_n < 10 Hz or smaller	10 Hz < f_n

Several empirical methods suggest there is a relationship between the static deflection and fundamental frequency of the floor that can be evaluated [14]. Furthermore, multiple studies [15,16] have reported a strong relationship between the orthogonal stiffness properties of the timber floor and the deflection which can be a substantial indicator of the vibration serviceability performance of the timber floor.

Toratti and Talja [4] presented several criteria for assessing floor vibration serviceability due to human-induced vibrations, emphasizing fundamental frequency, acceleration limits, and point load deflection as key indicators. Hamm et al. [17] proposed a universal vibration assessment method applicable to all timber floor types, distinguishing between higher and lower performance classifications based on vibration control requirements. This approach defines a cut-off frequency threshold and allowable deflections under static loads to evaluate the floor performance. Similarly, various design guidelines, including AISC DG11 [12], ISO 10137:2007 [8], and Eurocode 5 [7], provide criteria for evaluating the vibration serviceability of floors. These guidelines often emphasize the importance of fundamental frequency and peak acceleration in determining occupant comfort. However, discrepancies exist between the evaluation criteria of different guidelines, leading to a lack of consensus in an comprehensive method of analysis that has been validated and an acceptable design criteria for serviceability [18].

Additionally, while various guidelines and standards have established frequency thresholds for vibration control in conventional wood and steel floor systems, a clear gap exists in the applicability of these criteria to MTC floors. The complex interaction between material properties, composite action, boundary conditions, and excitation mechanisms in MTC systems introduces unique dynamic characteristics that are not adequately addressed by existing design frameworks. To evaluate the applicability of these existing guidelines and gain a comprehensive understanding of MTC floor behaviour, it is essential to conduct fundamental dynamic assessments that consider

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key factors such as boundary conditions, excitation type, and the extent of composite interaction between structural elements. Additionally, parameters like damping, mode shape distribution, and load transfer mechanisms must also be incorporated to refine vibration prediction models and enhance serviceability-based design approaches for modern mass timber floor systems.

1.3. OBJECTIVES

The broader aim of this research is to establish a comprehensive understanding of the vibration serviceability of MTC floor system, particularly focusing on the variation of dynamic parameters with boundary conditions and different excitation techniques that can contribute to the development of enhanced vibration assessment methodologies for assessing MTCs. The current study investigates the vibration performance of a CLT-glulam floor with a particular interest in analysing the natural frequencies of the floor system at both component-level and global system-level, which are critical for assessing vibration serviceability performance of a system. Furthermore, the study aims to understand how the mechanical integration of the structural components affects the global dynamic response of the floor.

2 – EXPERIMENTAL PROCEDURE

2.1. CLT-GLULAM FLOOR SETUP

In this study, a ribbed panel floor consisting of two 1 m x 4.5 m CLT-glulam T-beams was assessed for fundamental vibration parameters and characteristics. The web of the T-beam employed was 80 mm x 240 mm x 4.5 m long, 20F-E Spruce-Pine Glulam beam, while the flange of the T-beam was a 1 m wide and 4.5 m long 3-ply V2-grade CLT panel. To compositely connect the CLT slab and glulam web, shear plates were sandwiched between the glulam beam and the CLT panel along the entire length of the beam using self-tapping screws spaced at 152.4 mm to induce a sufficient clamping force to allow for composite action. The properties of the T-beams are shown in Table. 2. To compositely connect the floor, the flanges of the two T-beams were connected using 25 pairs of 140 mm long wide-head self-tapping screws, inclined at an angle of 45˚ from opposite sides. The floor T-beams were simply supported across the major span direction on supporting walls at both ends using metal brackets and screws as shown in Fig.1.

Table 2. T-beam properties

Specimen	EI ($N.m^2$)	Mass (kg/L)
T-beam 01	6.18×10^6	53.54
T-beam 02	6.38×10^6	54.11

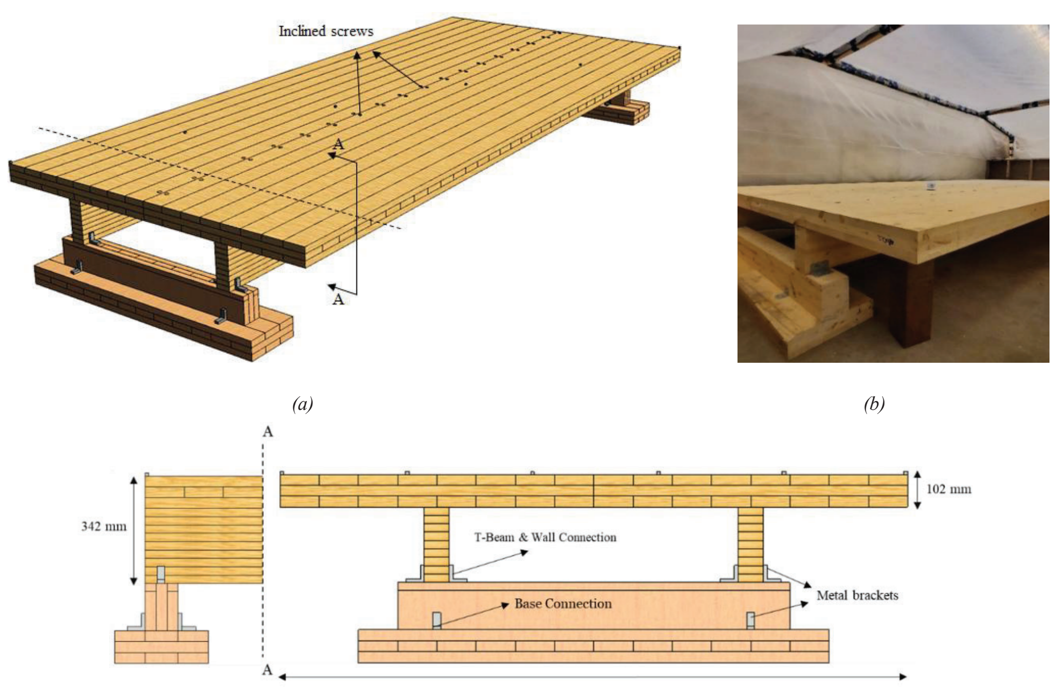

Figure 1. (a) CLT-glulam floor geometry (b) Floor set-up in humidity chamber (c) CLT-glulam floor cross section

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The supporting walls are 102 mm x 342 mm 3-ply V2-grade CLT panels that provided a stable structural base for the floor. Timber blocking was used to support the corners and edges of the ribbed panel for stability. Prior to assembling the floor, a humidity chamber was constructed to house the assembly, assuring a consistent moisture-controlled environment for the CLT-glulam floor. The humidity and temperature data over the period of testing is shown in Fig.2. At the time of the test, an average moisture content of 11.86 % was measured using a pin-probe moisture metre.

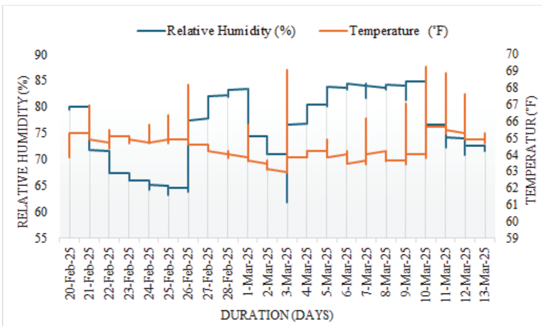
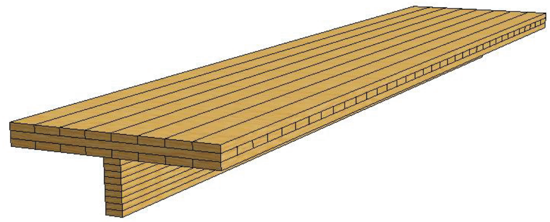


Figure 2. Relative humidity and temperature data

2.2. VIBRATION TEST SETUP AND DATA ANALYSIS

The aim of the modal test was to evaluate the dynamic behaviour of the system both at component and system level. The modal tests on individual T-beam established a base line frequency characteristic of the beams. The T-beams were then compositely assembled into a floor system and evaluated using roving hammer approach in single-input-multi-output (SIMO) configuration, in order to capture the global frequency response of the floor. This approach enabled direct comparison between component level and system level response, highlighting the influence of a composite assembly on the dynamic performance.

Prior to the assembly of the ribbed panel floor, a forced vibration test (FVT) was conducted using a PCB impact hammer (Model 086D05) in a free-free suspended condition for each beam to identify the natural frequency of the individual T-beam, as depicted in Fig.3. Flexible bungee cords were utilized for suspension of the T-beams at nodal points located at 0.22 and 0.78 of the length of T-beam [19,20], ignoring the influence of span and damping characteristics. Before vibration assessment of the floor, the beams were prestressed in four-point bending, and the experimental modulus of elasticities (MOEs) were calculated.



(a)

(b)

Figure 3. (a)T-beam (b) Vibration test setup for CLT-Glulam T-beams

Following the individual analysis of T-beams, the floor was assembled, and the compositely connected floor was evaluated using roving hammer approach in SIMO configuration, depicted in Fig.4. A PCB impact hammer (Model 086D50) weighting 5.5 kg was used to induce excitations and 6 PCB accelerometers (Model 333B40) (e.g., A897, A896, A895, etc) with an average sensitivity of 507.15 Hz were employed to measure acceleration. An impact grid of 900 mm x 400 mm was utilized which produced 30 FRFs per reading and generated a 180 FRFs measurement set. The total duration for each set of measurement was 90 seconds, during which three repeated excitations were performed at each impact location. Data were sampled at 256 Hz, with a frequency resolution of 0.25 Hz. In order to generate a single frequency response spectrum, to characterize the floor assembly and identify outliers, the three data sets obtained per impact were averaged for frequency response analysis. The recorded time domain data was transformed into frequency domain using the fast Fourier transform (FFT) technique. Finaly, the modal parameters were extracted after analysing the generated FRF matrix. The FRF response was then validated against the coherence and phase angle. Additionally, the frequency response was validated with a complex modal indicator function and stabilization diagram.

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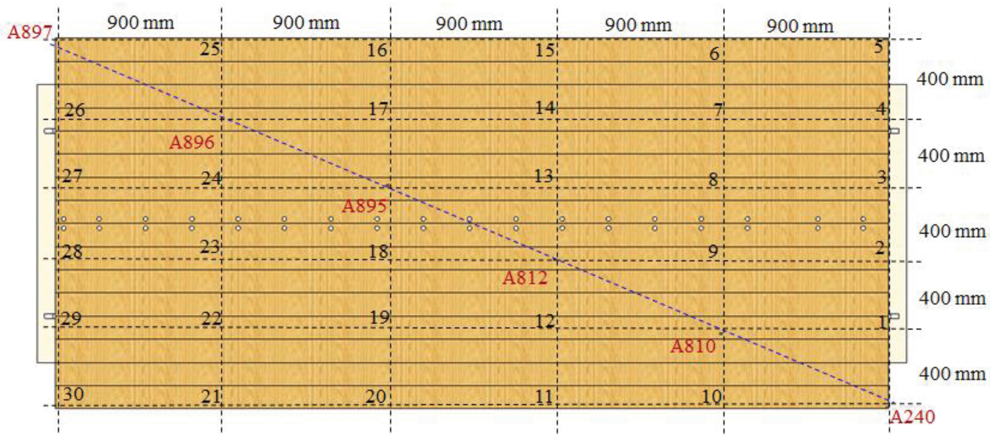


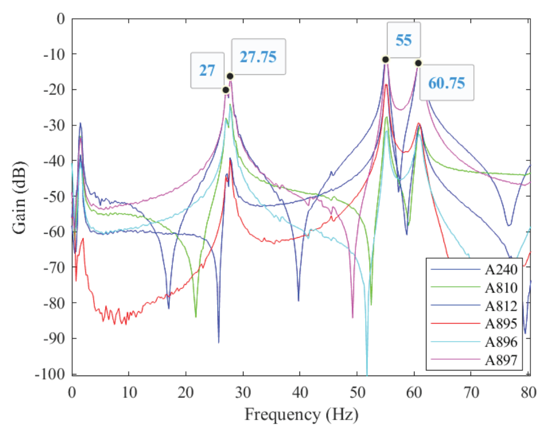
Figure 4. Vibration test setup for CLT-Glulam floor (Top view) (Accelerometers location, A897, A896, A895, A812, A810, A240)

3 – ANALYSIS OF RESULTS

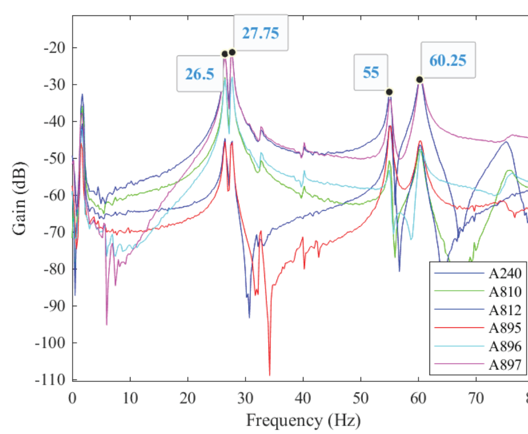
3.1. SIGNAL ACQUISITION AND SPECTRAL ANALYSIS

A frequency analysis for each individual T-beam was performed using an FVT. The frequency response function at a single point for both T-beams is shown in Fig.5. It is observed that both T-beams followed a complex response in the initial frequency zone. The initial four frequencies obtained are highlighted in the FRF responses for both T-beams. Focusing on the low frequency zone, the natural frequency for each T-beam was determined to be 27 Hz, and 26.5 Hz respectively. The initial peak around 4 Hz in both T-beam FRFs is attributed to the influence of the free-free boundary condition applied during testing of the beams [21]. The floor vibration setup had 30 impact points. Prior to the generation of the overall FRF matrix, time domain data for each impact point was converted into the frequency domain using the FFT technique. The data acquisition, preprocessing, and validation process for data generated at impact location 11 are demonstrated. This process is representative of the processing performed at all impact locations. The impulsive force applied to the floor by the impact hammer and the corresponding vibration response recorded at the six fixed locations are shown in Fig.6. The acquired signal was pre-processed to eliminate transient artifacts and align the time-domain with the output response. The input frequency content of the hammer was analysed using the input power spectrum that quantified the energy distribution across various frequencies in the excitation signal, ensuring the hammer impact adequately excited the target band of frequency. Based on the input spectrum, a roll-off of 6 dB was considered, accurately exciting a frequency band of around 140 Hz.

In addition, the output power spectra and cross power spectra were analysed to ensure a linear relationship which resulted in consistent phase and amplitude for detected peaks across repeated measurements between the input force and the output response of the floor, as illustrated in Fig.7.



(a)



(b)

Figure 5. (a) FRF response T-beam 01 (b) FRF response T-beam 02

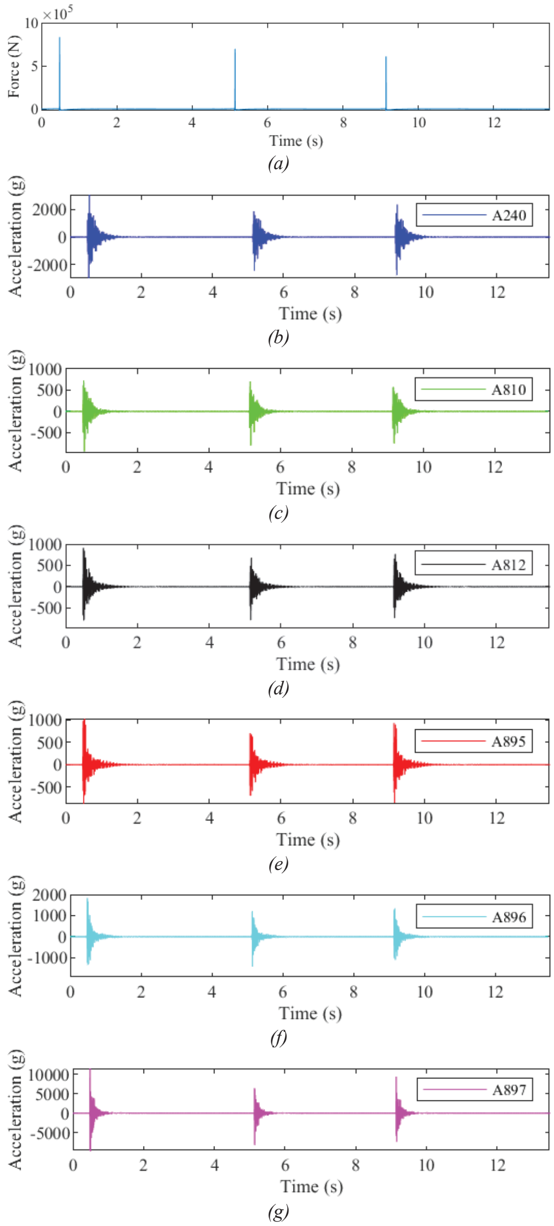
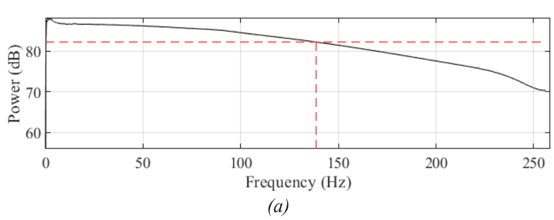


Figure 6. (a) Impact force input (b-g) transient responses at various accelerometer locations.



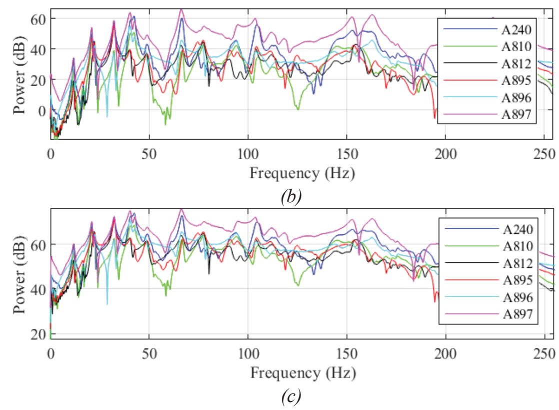


Figure 7. (a) Input power spectrum, (b) Output power spectrum and (c) Cross-power spectrum

3.2. FREQUENCY RESPONSE FUNCTION ANALYSIS

After preprocessing the recorded signals, FRF responses were plotted for all impact points individually. The first five peaks in the FRF response for impact point 11 are shown in Fig.8. A highly complex response can be observed in the low frequency zone, showing a fundamental frequency peak of 11.75 Hz, followed by 16 Hz, 21 Hz, 22.25 Hz and 32.25 Hz for the CLT-glulam floor. The peaks at 21 Hz and 22.25 Hz were observed to be very close and validation of these values as genuine peaks was confirmed after close observation of the coherence and phase angle. The coherence plot showed two separate drops in anti-resonance zones confirming two different modes at 21 Hz and 22.25 Hz. Additionally, the complex variation in the phase angle at these frequencies highlights the presence of two modes. The coherence and phase angle plots for each accelerometer are presented in Fig.9. Based on frequency analysis of the floor, which is a basic step in obtaining the dynamic response of a system. It was observed that the MTC systems provide effective stiffness at component level. However, to reach the maximum potential of the MTC systems at system level it is important to ensure effective mechanical system providing effective composite action and uniform energy distribution between the components of the overall system, minimizing joint slip and flexibility.

Following the individual analysis of all the impact points, the FRF matrix was generated through synthesis of the FRF matrix. The 2D and 3D plot for the overall system FRF matrix are presented in Fig.10. An additional analysis was performed using the Complex Modal Indicator Function (CMIF), which confirms the number of modes by analysing the singular values in the FRF

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matrix, with results shown in Fig.11. This analysis validated the first four modes in the system and provided additional evidence for the separate peaks at 21 Hz and 22.25 Hz. Since the CMIF is a non-parametric analysis method that does not consider any model for the analysis, the stabilization diagram was plotted for the FRF matrix, which is a parametric modal identification technique. The stabilization diagram identified multiple modal orders, considering up to a modal order of 42, with a frequency and damping tolerance of 0.5 Hz and 0.01 respectively. The stabilization diagram confirmed the occurrence of two modes at 21 Hz and 22.25 Hz once again as shown in Fig.12. It can be observed that beyond the modal order of 35, the stability in the 2nd closest peak becomes more prominent which can be attributed to the fact that the lower modal-order fits may lack sufficient polynomial degrees of freedom to separate the two peaks. At the lower modal order fits, the solver merged both resonances into one approximate pole but gained sufficient model flexibility in higher modal orders to resolve the individual peaks. The collective assessment of these analysis strategies suggests the validity of the closely spaced modes at 21 Hz and 22.5 Hz.

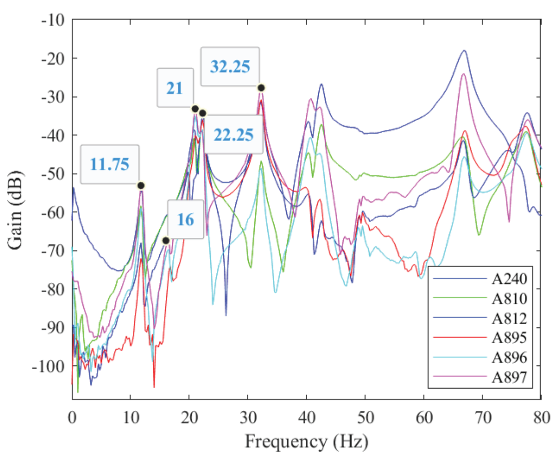
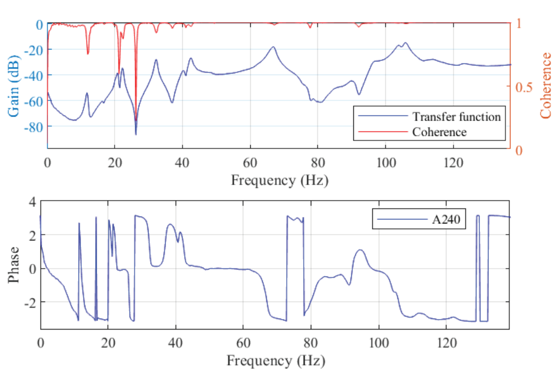
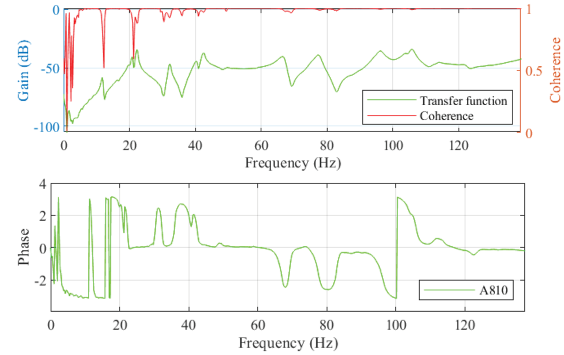


Figure 8. Frequency response spectrum for impact location 11



(a)



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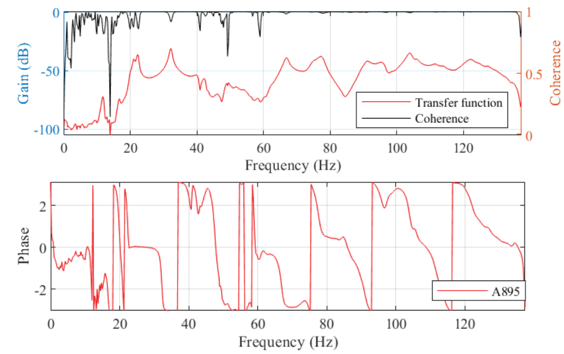

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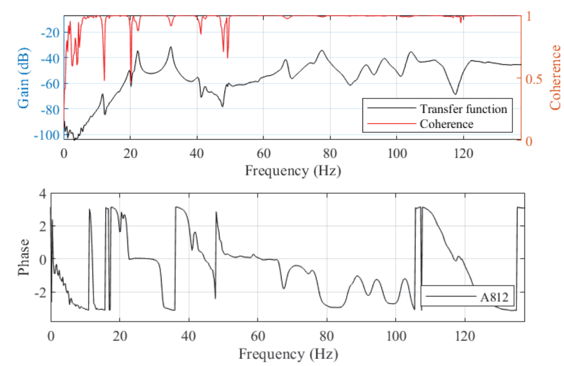

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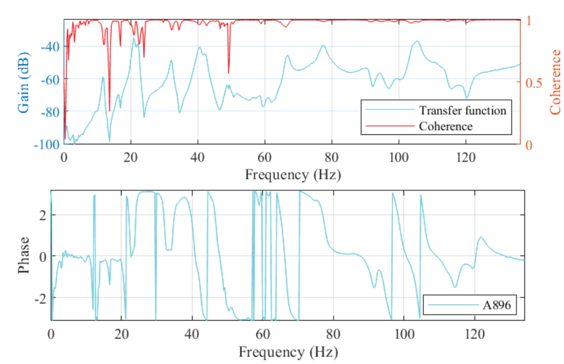

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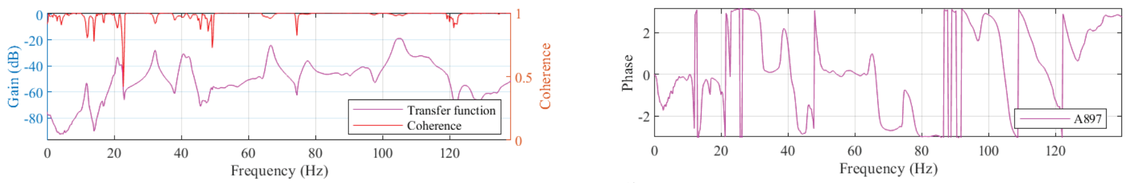
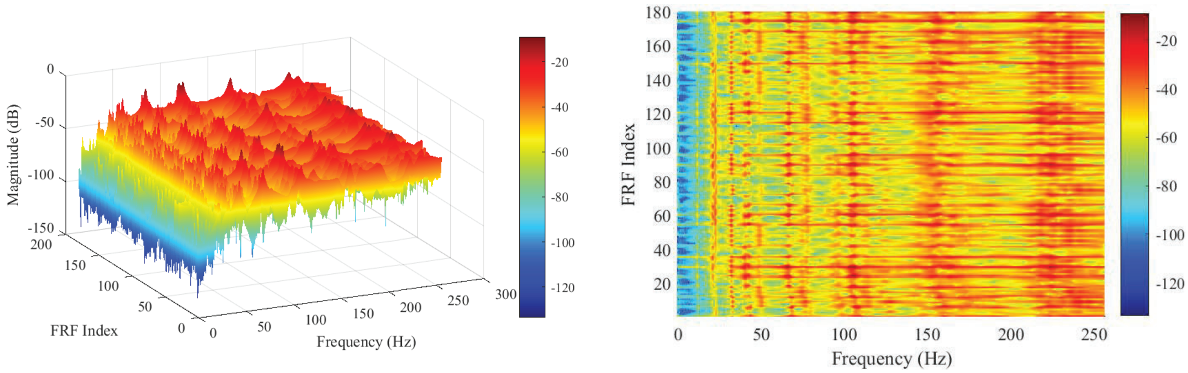


(f)

Figure 9. Coherence and phase angle for impact point 11 with respect to each accelerometer (a-f)



(a) *(b)*

Figure 10. Frequency response spectrum 3D and 2D plot for the FRF Matrix

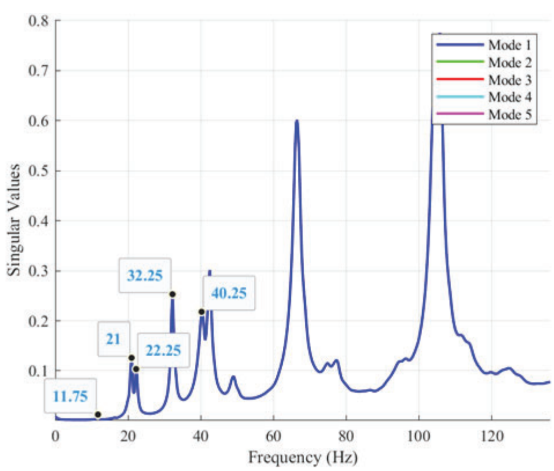


Figure 11. Complex Modal indicator function for the FRF Matrix

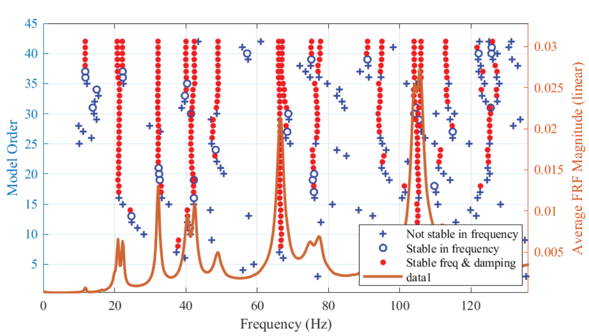


Figure 12. Stabilization diagram for the FRF Matrix

4 – CONCLUSIONS

The results presented are based on the investigation of dynamic behaviour of the CLT-Glulam T-beams and floor with impact hammer excitations, particularly focusing on the frequency response of the floor. The floor was mainly constructed from joining two T-beams with CLT flanges and glulam beams with mechanical shear plates sandwiched in between the CLT and glulam beam. The T-beam flanges were joined together with wide-head self-tapping screws of 6 mm in diameter. The floor was tested in a humidity and temperature-controlled environment maintaining moisture content. For vibration analysis the T-beams and floor were excited with impact hammer and the response was recorded at six different locations along the surface of the floor at a diagonal, corner to corner. The frequency response at each impact location was obtained by plotting the FRF using the FFT technique. Additionally, the FRF plots were validated using the coherence and phase angle.

The experimental frequency analysis results of the individual CLT-glulam T-beam were compared against the CLT-glulam floor system. Further the frequency response was validated with CMIF and Stabilization diagram confirming the initial modal responses at these frequencies. The comparison revealed substantial variation in the natural frequency response at component-level and system-level. The natural frequency for each T-beam were experimentally determined to be 27 Hz and 26.5 Hz, respectively. However, the experimental modal

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testing of the floor configuration yielded a much lower estimated fundamental natural frequency of 11.75 Hz. The observed decrease in fundamental frequency highlights that the joined floor system has introduced additional mass and connection flexibility to the system, which may outweigh the contribution of any increase in global stiffness of the floor.

5 – REFERENCES

[1] J. Dolan, T. Murray, J. Johnson, D. Runte, and B. Shue, "Preventing annoying wood floor vibrations," *J. Struct. Eng.*, vol. 125, no. 1, pp. 19–24, 1999.

[2] S. Ohlsson and L. J. Gruber, "Springiness and human-induced floor vibrations: a design guide," *No Title*, 1988.

[3] J. Weckendorf, T. Toratti, I. Smith, and T. Tannert, "Vibration serviceability performance of timber floors," *Eur. J. Wood Wood Prod.*, vol. 74, pp. 353–367, 2016.

[4] T. Toratti and A. Talja, "Classification of Human Induced Floor Vibrations," *Build. Acoust.*, vol. 13, no. 3, pp. 211–221, Sep. 2006, doi: 10.1260/135101006778605370.

[5] S. V. Ohlsson, *Floor vibrations and human discomfort*. Chalmers University of Technology, Division of Steel and Timber Structures, 1982.

[6] K. Lewis, B. Basaglia, R. Shrestha, and K. Crews, "The use of cross laminated timber for long span flooring in commercial buildings," in *WCTE 2016-World Conference on Timber Engineering*, 2016.

[7] B. EN, *1-1: 2004 Eurocode 5: Design of timber structures—General—Common rules and rules for buildings*. NA to BS EN, 1995.

[8] International Organization for Standardization, *ISO 10137: Bases for Design of Structures – Serviceability of Buildings and Walkways Against Vibrations*, ISO 10137, Geneva, Switzerland., 2007. [Online]. Available: https://www.iso.org/standard/37070.html

[9] British Standards Institution (BSI), *BS 6472-1: Guide to Evaluation of Human Exposure to Vibration in Buildings*, BS 6472-1, 2008. [Online]. Available: https://knowledge.bsigroup.com/products/guide-to-evaluation-of-human-exposure-to-vibration-in-buildings-vibration-sources-other-than-blasting

[10] H. Karampour, F. Piran, A. Faircloth, N. Talebian, and D. Miller, "Vibration of Timber and Hybrid Floors: A Review of Methods of Measurement, Analysis, and Design," *Buildings*, vol. 13, no. 7, p. 1756, Jul. 2023, doi: 10.3390/buildings13071756.

[11] L. J. Hu, Y. H. Chui, and D. M. Onysko, "Vibration serviceability of timber floors in residential construction," *Prog. Struct. Eng. Mater.*, vol. 3, no. 3, pp. 228–237, 2001.

[12] T. M. Murray, D. E. Allen, E. E. Ungar, and D. B. Davis, *Vibrations of steel-framed structural systems due to human activity*. American Institute of Steel Construction, 2016.

[13] D. E. Allen and T. M. Murray, "Design Criterion for Vibrations Due to Walking," *Eng. J.*, vol. 30, no. 4, pp. 117–129, Dec. 1993, doi: 10.62913/engj.v30i4.1281.

[14] I. Smith and Y. H. Chui, "Design of lightweight wooden floors to avoid human discomfort," *Can. J. Civ. Eng.*, vol. 15, no. 2, pp. 254–262, 1988, doi: 10.1139/l88-033.

[15] L. J. Hu, "Serviceability design criteria for commercial and multi-family floors," *Can. For. Serv. Rep. Forintek Can. Corp. Sainte-Foy QC Can.*, 2000.

[16] D. Onysko, *Serviceability criteria for residential floors based on a field study of consumer response*. 1986.

[17] P. Hamm, A. Richter, and S. Winter, "Floor vibrations–new results," in *Proceedings of 11th World Conference on Timber Engineerig (WCTE2010), Riva del Garda*, 2010.

[18] L. Wang, G. Gong, and J. Xia, "Comparison of evaluations of human-induced floor vibration based on different design guidelines," *Structures*, vol. 68, p. 107114, Oct. 2024, doi: 10.1016/j.istruc.2024.107114.

[19] R. Brincker and C. Ventura, *Introduction to operational modal analysis*. John Wiley & Sons, 2015.

[20] M. M. Ebadi, G. Doudak, and I. Smith, "Vibration responses of glulam beam-and-deck floors," *Eng. Struct.*, vol. 156, pp. 235–242, Feb. 2018, doi: 10.1016/j.engstruct.2017.11.051.

[21] D. J. Ewins, *Modal testing: theory, practice and application*, 2nd edition revised. in Mechanical engineering research studies. Engineering dynamics series, no. 10. Hertfordshire: Wiley-Blackwell, 2009.