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DYNAMIC PERFORMANCE ASSESSMENT OF FULL-SCALE CLT AND CLT-CONCRETE COMPOSITE FLOORS

Yitu Chen [1], Ulrike Dackermann [2], and Hamid Valipour [3]

ABSTRACT: Cross-laminated timber (CLT) is increasingly used in multi-storey construction, but its low mass can lead to vibration serviceability concerns in long-span floors. CLT-concrete composite floor systems offer a potential solution, yet the effects on dynamic performance require further investigation. This study investigates the dynamic behaviour of full-scale CLT and CLT-concrete composite floors using experimental modal analysis (EMA). Two 8-meter-long floor systems, fabricated from 3-ply and 5-ply CLT panels, were tested under simply supported conditions. Modal properties, i.e. natural frequencies, mode shapes and damping ratios, of the first four flexural modes were extracted using hammer impact. The results showed that the additional concrete layer generally increased damping ratios, with some damping values more than doubling in the higher modes. The 3-ply floor exhibited increases in natural frequencies across all modes, while the frequencies of the 5-ply floor showed reductions, attributed to the combined effects of added mass and stiffness changes. The findings support the use of CLT-concrete composites for enhanced vibration serviceability. However, observed frequency reductions in the 5-ply configuration suggest caution when assuming universal improvements.

KEYWORDS Cross-laminated timber (CLT), CLT-concrete composite floor, vibration performance, experimental modal analysis, serviceability design

1 – INTRODUCTION

Cross-laminated timber (CLT), developed in the 1990s in Austria and Germany, has emerged as a highly sustainable and structurally efficient construction material. Its high strength-to-weight ratio, excellent fire performance, carbon-negative characteristics, and ease of prefabrication have driven widespread adoption, particularly in mid-to high-rise timber buildings. Despite these advantages, CLT floor systems often face serviceability challenges related to human-induced vibrations due to their low mass and inherent flexibility. These issues are critical to occupant comfort, particularly for long-span applications.

Serviceability design guidelines, such as those outlined in the European standard [1], recommend that the fundamental frequency of floor systems should exceed 8 Hz to prevent resonances induced by human activities. Meeting these requirements can be challenging for lightweight CLT systems, prompting ongoing efforts to enhance their dynamic performance.

One promising approach has been the development of CLT-concrete composite floor systems. These systems combine the benefits of timber and concrete by adding a reinforced concrete topping to the CLT panel, improving durability and stiffness while retaining some of the material and environmental advantages of timber. Initially developed in the early 2000s, these hybrid systems offer improved load-bearing capacity and longer span capabilities. However, their vibration performance remains a key consideration, as the additional mass introduced by the concrete layer can produce variable effects on natural frequencies and damping.

Prior research has shown that the dynamic response of composite timber-concrete floors depends on the relationship between added stiffness and added mass [2].

[1] Centre for Infrastructure Engineering and Safety (CIES), School of Civil and Environmental Engineering, The University of New South Wales (UNSW), Sydney Australia, yitu.chen@unsw.edu.au

[2] Centre for Infrastructure Engineering and Safety (CIES), School of Civil and Environmental Engineering, The University of New South Wales (UNSW), Sydney Australia, u.dackermann@unsw.edu.au

[3] Centre for Infrastructure Engineering and Safety (CIES), School of Civil and Environmental Engineering, The University of New South Wales (UNSW), Sydney Australia, h.valipour@unsw.edu.au

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The effect of an additional concrete layer can be categorised into three scenarios:

- Increase in fundamental frequency: In some cases, the added concrete layer substantially increases floor stiffness, leading to higher natural frequencies. For example, Van Thai [3] reported 15–28% increases in fundamental frequency for 175 mm CLT floors with 80 mm concrete topping over an 8.7 m span. Similarly, Mai et al. [4] observed increases of 31–37% for a 150 mm CLT floor topped with 100 mm of concrete over a 5.8 m span. Kozarić et al. [5] further demonstrated that lightweight aggregate concrete could enhance stiffness while minimising the increase in mass.
- Marginal change in fundamental frequency: In other instances, the increased mass of the concrete offsets the stiffness gain, resulting in negligible frequency shifts. Casagrande et al. [6], for instance, observed a slight reduction in natural frequency from 13.3 Hz to 13.1 Hz when comparing plain CLT and composite systems.
- Decrease in fundamental frequency: When the increase in mass outweighs the increase in stiffness, the fundamental frequency can decrease. As demonstrated by Santos et al. [7], the fundamental frequency of a 3.4 m × 3.5 m timber floor dropped noticeably from 31.0 Hz to 17.4 Hz after the addition of a 50 mm concrete layer.

These varying effects on the fundamental frequency highlight the importance of considering the stiffness-to-mass ratio when designing timber-concrete composite floor systems. Achieving optimal vibration performance requires careful selection of material dimensions and span lengths to ensure serviceability limits are met without compromising other performance criteria.

This study investigates the influence of a concrete topping on the vibration performance of CLT floor systems through full-scale dynamic testing. Two 8-meter-long floor specimens were constructed using 3-ply and 5-ply CLT panels. Both panels were tested in their original plain form and as part of a CLT-concrete composite system, achieved by adding a reinforced concrete topping.

Experimental modal analysis (EMA) was employed to extract the modal parameters, including natural frequencies, damping ratios, and mode shapes. The floors were excited using instrumented hammer impacts, and their vibrational responses were captured using an array of accelerometers. The modal parameters were then identified using the Rational Fraction Polynomial in the z-domain (RFP-z) method, implemented in the ARTeMIS Modal Pro software.

The results of this work contribute to a better understanding of the dynamic effects of concrete toppings in CLT-concrete composite floors and support the development of more refined vibration-based serviceability design approaches for mass timber construction.

3 – CLT-CONCRETE COMPOSITE FLOOR DESIGN

Two full-scale floor specimens, each measuring 8 m in length and 1 m in width, were constructed using C24-grade spruce CLT panels in both 3-ply (90 mm thick) and 5-ply (150 mm thick) configurations. For the composite systems, an 80 mm-thick concrete topping was added using N32 commercial concrete (slump: 190 mm), reinforced with N12 × N10 steel mesh. Composite action was facilitated by circular notch-screw connections, achieved by driving Rothoblass VGZ 5 × 80 screws through precision-cut circular notches in the CLT panels. To protect the timber from moisture during curing, a waterproofing system was applied: Rothoblass VA260 was used for surface treatment, and Rothoblass BYTUM PRIMER paste was applied to the notches.

The fabrication process of the CLT-concrete composite floors consisted of five main stages: (1) cutting circular notches into the CLT soffit; (2) applying waterproofing treatments and installing notch screws; (3) placing and securing the reinforcement mesh; (4) casting the concrete topping; and (5) curing the assembly for 28 days. To avoid mid-span deflection during concrete placement, temporary props were installed and later removed once the concrete reached sufficient initial strength.

Each floor specimen was tested as a simply supported system with a clear span length of 5.4 meters and 1.3-meter overhangs at each end. Figure 1 shows the 3-ply and 5-ply CLT-concrete composite floor specimens, including indications of the span length.

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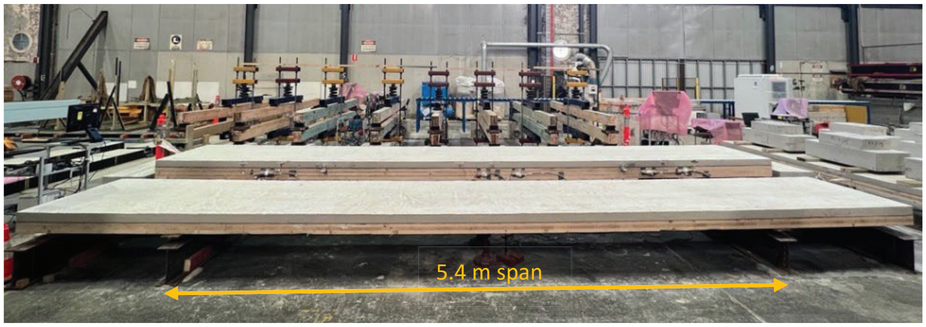
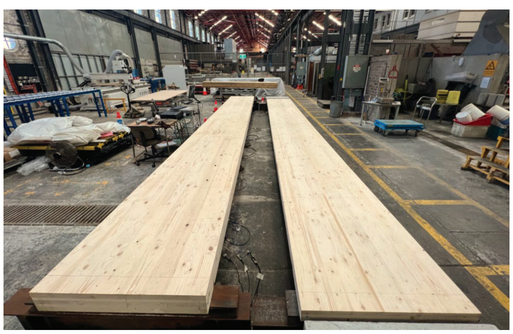


Figure 1: CLT-concrete composite floor specimens with 3-ply and 5-ply CLT panels.

4 – EXPERIMENTAL MODAL ANALYSIS

Dynamic testing of the floor systems was conducted in two phases. Initially, the plain CLT panels were tested to establish baseline vibration characteristics. Subsequently, the same panels were retested after the addition of the concrete topping, allowing direct comparison of the dynamic performance before and after composite action. Figure 2 illustrates the 3-ply and 5-ply floor specimens in both the CLT-only and CLT-concrete composite configurations.



(a)

(b)

Figure 2: Configurations of the two testing phases: (a) CLT floors, and (b) CLT-concrete composite floors.

To extract the modal properties of each configuration, experimental modal analysis (EMA) was conducted using hammer impact testing. The structures were excited using an instrumented impact hammer, while a dense network of accelerometers captured the vibrational responses. The sensor network comprised of 21 accelerometers (Model: PCB 352C34) that were uniformly distributed along the underside of each CLT panel. Each sensor was securely attached using rare-earth neodymium magnets mounted to steel plates that were screwed into the panel surface, ensuring consistent coupling and signal quality. The sensors were connected to a National Instruments PXIe-1073 data acquisition system, controlled via LabVIEW 2016. Data was sampled at a rate of 1 kHz to capture detailed modal information.

To ensure comprehensive excitation of the structure's dynamic modes, six hammer impact locations (termed H1 through H6) were selected. At each impact point, five consecutive hammer strikes were delivered, ensuring sufficient averaging of the frequency response. Each test ran for 21 seconds, including a 1-second pre-trigger. The subsequent impact was applied only after the oscillations from the previous strike had fully decayed. In total, 120 hammer impacts were performed across the full test campaign (2 CLT thicknesses × 2 floor systems (with and without concrete topping) × 6 impact locations × 5 replicates).

Post-processing and modal identification were conducted using ARTeMIS Modal Pro with the embedded Rational Fraction Polynomial in the z-domain (RFP-z) algorithm. This method supports multi-input and multi-output (MIMO) analysis, allowing simultaneous processing of the six input excitations and 21 output responses. The testing setup enabled identification of the first to fourth flexural modes in each configuration. Based on preliminary analysis, these modes fell within the 0–150 Hz range. To ensure full spectral coverage, the analysis bandwidth was set to 0–200 Hz. A modal order of 50 was selected, typically 3–6 times the number of expected modes, to ensure robust estimation. The Modal Assurance Criterion (MAC) was used to verify the validity of the extracted mode shapes.

Five independent MIMO analyses were conducted for each configuration to determine natural frequencies, mode shapes, and damping ratios. The results were averaged, and the coefficient of variation (CoV) was calculated to quantify variability and support reliability assessment.

The workflow of EMA for modal property extraction, encompassing specimen setup, instrumentation, excitation, data acquisition, and modal analysis, is summarised in Figure 3.

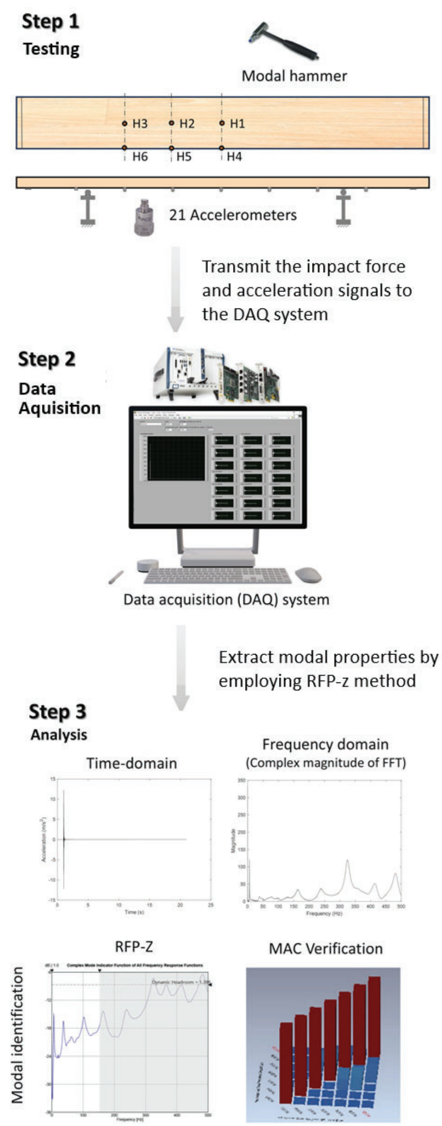


Figure 3: Workflow of EMA for modal property extraction.

5 – EMA RESULTS

The EMA results of the CLT floors and the CLT-concrete composite floors are summarised in Tables 1-3. These results include the natural frequencies and damping ratios of the 3-ply and 5-ply floors, both before and after the addition of the concrete topping.

5.1 MODAL PROPERTIES OF CLT FLOORS

Table 1 presents the baseline modal properties of the plain CLT floors, including the natural frequencies and damping ratios of the first to fourth flexural modes and corresponding coefficients of variation (CoV).

Table 1: Natural frequencies and damping ratios of 3-ply and 5-ply CLT floors.

Modes	3-ply CLT floor 5.4 m span		5-ply CLT floor 5.4 m span	
	Freq.(Hz) (CoV (%))	*ζ (%) (CoV (%))*	*Freq.(Hz) (CoV (%))*	*ζ (%) (CoV (%))*
1st	6.79 (0.01)	2.72 (0.02)	11.06 (1.95)	2.19 (9.86)
2nd	36.70 (0.29)	1.87 (5.60)	51.26 (0.04)	3.02 (0.72)
3rd	57.94 (0.04)	1.10 (2.06)	87.01 (0.04)	3.17 (1.22)
4th	84.40 (0.14)	1.78 (6.63)	117.94 (0.08)	2.29 (3.91)

The mode shapes of the first four flexural modes for the 7.8 m span 5-ply CLT floor are exemplarily illustrated in Figure 4.

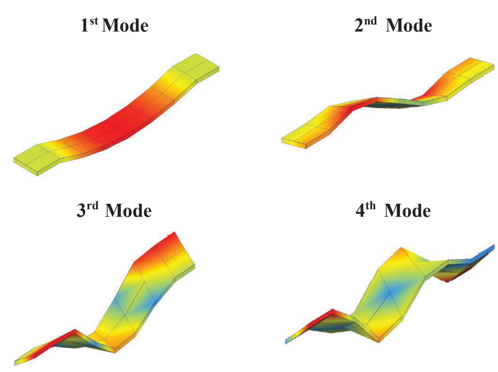


Figure 4: Mode shapes of 1st to 4th flexural modes.

As shown in Table 1, and as expected, the 5-ply floor exhibited significantly higher natural frequencies across all four modes compared to its 3-ply counterpart, due to increased stiffness and mass. The fundamental frequency of the 5-ply floor increased from 6.79 Hz to 11.06 Hz, representing a 63% rise. Similarly, the second mode frequency rose from 36.70 Hz to 51.26 Hz, marking a 40% increase.

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Damping ratios for the plain CLT floors were generally low (<5%), which is typical for timber structures. Notably, the 3-ply floor exhibited higher damping in the first mode (2.72%) compared to the 5-ply floor (2.19%). This may be attributed to its greater flexibility, which can enhance energy dissipation mechanisms such as internal friction or joint movement.

5.2 MODAL PROPERTIES OF CLT-CONCRETE COMPOSITE FLOORS

The dynamic properties of the 3-ply and 5-ply CLT concrete composite floors following the application of the concrete topping are presented in Table 2. Table 3 summarises the corresponding changes in natural frequencies (Δ Freq.) and damping ratios (Δ ζ) relative to the plain CLT floors.

Table 2: Natural frequencies and damping ratios of 3-ply and 5-ply CLT concrete composite floors.

Modes	3-ply CLT-concrete composite floor		5-ply CLT-concrete composite floor	
	5.4 m span		5.4 m span	
	Freq.(Hz) (CoV (%))	*ζ (%) (CoV (%))*	*Freq.(Hz) (CoV (%))*	*ζ (%) (CoV (%))*
1st	7.77 (0.00)	2.62 (0.00)	11.01 (0.00)	2.20 (0.00)
2nd	-	-	-	-
3rd	63.78 (0.00)	3.46 (0.00)	72.52 (0.00)	5.15 (0.00)
4th	87.24 (0.00)	3.46 (0.03)	99.13 (0.00)	5.25 (0.00)

Table 3: Changes in natural frequencies (Δ Freq.) and damping ratios (Δ ζ) of 3-ply and 5-ply CLT floors due to added concrete layer.

Modes	3-ply CLT vs. CLT-concrete composite floors		5-ply CLT vs. CLT-concrete composite floors	
	5.4 m span		5.4 m span	
	Δ Freq.(Hz) (Change %)	*Δ ζ (%)*	*Δ Freq.(Hz) (Change %)*	*Δ ζ (%)*
1st	0.98 (14.43)	-0.1	-0.05 (-0.45)	0.01
2nd	-	-	-	-
3rd	5.84 (10.08)	2.36	-14.49 (-16.65)	1.98
4th	2.84 (3.36)	1.68	-18.81 (-15.95)	2.96

As shown in the tables, the natural frequencies either increased moderately for the 3-ply floor or decreased slightly to moderately for the 5-ply floor. For the 3-ply system, the fundamental frequency rose from 6.79 Hz to 7.77 Hz (+14.43%). In contrast, the 5-ply system exhibited a slight reduction in the first mode, from 11.06 Hz to 11.01 Hz (–0.45%). In higher modes, the 3-ply floor showed frequency gains of up to 10.08%, while the 5-ply floor experienced reductions of up to –16.65%. These results suggest that the concrete topping has a more pronounced stiffening effect on thinner panels, whereas for thicker panels, the added mass may partially offset stiffness gains.

Damping ratios increased across the higher modes, in some cases more than doubling. The largest increase was observed in the fourth mode of the 5-ply floor (Δζ = +2.96%). For the first mode, damping remained essentially unchanged for both floor systems. These enhancements in damping are beneficial for vibration serviceability, particularly in mid-to-high frequency ranges where perceptible vibrations are a critical design concern.

6 – CONCLUSIONS

This study investigated the dynamic performance of full-scale CLT and CLT-concrete composite floors through experimental modal analysis (EMA). The main objectives were to evaluate the influence of concrete topping and CLT panel thickness on modal properties, namely, natural frequencies and damping ratios, and to assess how these parameters affect vibration behaviour and serviceability performance in mass timber floor systems. The following summarises the main findings:

- The addition of a concrete layer had contrasting effects on the natural frequencies depending on CLT panel thickness. The 3-ply floor exhibited frequency increases across all modes, reflecting improved stiffness. In contrast, the 5-ply floor showed frequency reductions in most modes, attributed to the added mass outweighing stiffness gains.
- With the addition of the concrete topping, damping ratios increased significantly in the higher modes for both CLT thicknesses, while remaining largely unchanged in the fundamental mode. In several cases, damping values more than doubled, indicating enhanced energy dissipation.
- Increasing the CLT panel thickness from 3-ply to 5-ply had a marked, positive impact on the modal properties. The 5-ply floors consistently exhibited higher natural frequencies and greater damping ratios than their 3-ply counterparts in both plain and concrete-composite configurations.

These results support the use of CLT-concrete composite systems for improved vibration performance in long-span timber floor applications. However, the findings also highlight that assumptions of increased frequencies due to concrete topping may not hold for thicker CLT panels, particularly in higher modes. Therefore, configuration-specific analysis is recommended in the vibration design of mass timber floor systems.

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