WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA
Advancing Timber for the Future Built Environment

VIBRATION PERFORMANCE OF A BEAMLESS CROSS LAMINATED TIMBER-CONCRETE COMPOSITE SLAB BAND FLOOR SYSTEM FOR 10-STOREY LIMBERLOST PLACE

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ABSTRACT: Solid cross-laminated timber (CLT) panels are not suitable for long-span floors due to their relatively low density and bending stiffness, which can lead to issues with deflection and vibration. Timber-concrete composite (TCC) floor systems offer enhanced strength and stiffness, improving overall serviceability. Fast + Epp developed an innovative large-span beamless structural system comprising CLT-concrete composite slab bands with perpendicular CLT infill panels. There different shear connectors were explored for composite slab bands and tested in full-scale at the University of Northern British Columbia Wood Innovation Lab. This study examines the vibrational properties of the proposed beamless floor system through both laboratory and field tests. Dynamic characteristics were assessed using experimental modal tests and ambient vibration tests, while subjective evaluations and acceleration responses due to human walking were collected. The results indicate that the different shear connectors have minimal impact on the natural frequencies of the slab bands. Although standalone slab bands exhibited unacceptable vibration performance in laboratory tests, field tests on the fully constructed composite floor system in the Limberlost Place building confirmed its acceptable performance. It was observed that the bending stiffness derived from static bending tests and the gamma method underestimated the fundamental natural frequency by 20%. Numerical models for both the standalone slab band beam and the full-scale floor system were developed and validated with tests, proving to be effective in predicting their natural frequencies with an error of less than 5%. The findings from this study will provide practical insights and guidance for the vibration design of such timber-concrete composite slab band floor system.

KEYWORDS: Floor vibration, Timber-concrete composite floor, composite connector

1 – INTRODUCTION

Mass timber panels such as cross laminated timber (CLT) are becoming increasingly popular in larger and non-residential structures, including institutional and office buildings with expansive open floor areas. A common open floor design consists of a large glulam or steel post-and-beam grid with one-way spanning CLT panels. Other options include point-supported two-way spanning CLT floors using edge moment connections, such as the proprietary TS3 technology [1] or TC FUSION [2], and slim floor structures with CLT slabs and proprietary DELTABEAM® [3] to create open and flat floor plans.

Recently, Fast + Epp has developed an innovative long-span beamless floor system for the newly constructed 10-storey Limberlost Place, serving as Ontario's first tall mass timber institutional building located on George Brown College’s Toronto waterfront campus in Canada [4]. This beamless composite floor system utilizes CLT-concrete composite (TCC) slab bands with perpendicular CLT infill floor panels. The TCC slab bands are supported by wide columns and serve as the supports for perpendicular CLT infill panels as shown in Fig. 1 and 2, which effectively creates a flat exposed wood ceiling. A floating concrete topping is applied to the top surface to meet fire and acoustic requirements. The structural design of the TCC bands is critical to the performance of this composite floor system and requires several key

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https://doi.org/10.52202/080513-0400

considerations, including rolling shear strength and screw reinforcement in the CLT in both major and minor strength directions, and selection of composite shear connections. A structural testing program was conducted to address these design challenges [5,6].

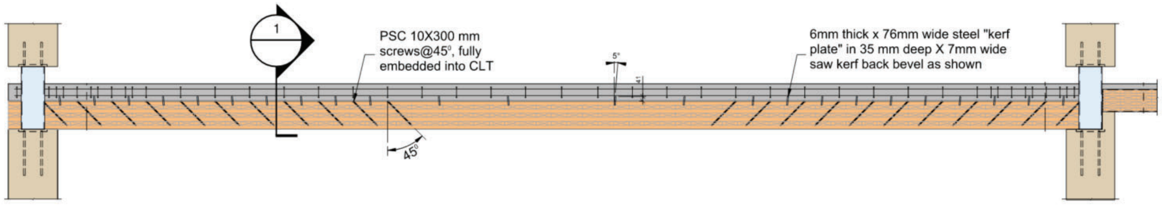

Figure 1. (a) Longitudinal section of TCC slab band beam

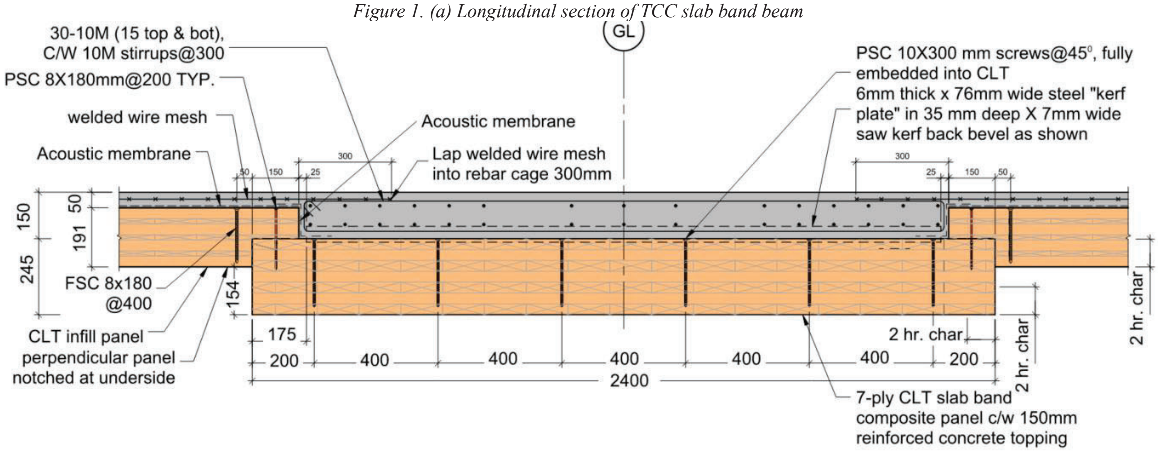

Figure 1. (b) typical cross-section of slab band section [5]

Figure 2. (a) Typical floor plan

Figure 2. (b) exposed ceiling after construction

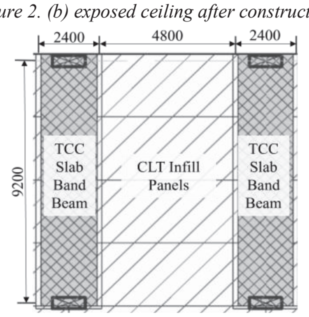

Figure 2. (c) configuration of the floor system (unit: mm)

However, the vibration serviceability design of such a complex composite timber floor system is not currently addressed in existing standards. While steel and concrete floors have established design guides and performance criteria [7,8], guidance for mass timber floors remains limited beyond CSA O86 [9]. The U.S. Mass Timber Floor Vibration Guide [10] provides additional recommendations but requires validation through both laboratory and field testing.

Therefore, vibration testing was conducted on both the TCC slab bands in the laboratory and the fully finished floor system on-site. The dynamic characteristics of the composite standalone slab bands in the laboratory and built floor on-site were assessed using experimental modal testing and ambient vibration testing, respectively. Subjective evaluations of vibration performance were conducted, and acceleration responses under human walking conditions were recorded. Additionally, finite element (FE) models were developed and validated for both the slab band beam and the full-size floor system. The results provide valuable insights into the vibration serviceability and design considerations for the long span mass timber-concrete composite floor systems.

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2 – EXPERIMENTAL TEST PROGRAMS

2.1 MATERIALS

The TCC slab bands were initially tested in the laboratory at the University of Northern British Columbia. Each slab band measured 2.4 m in width and 9.6 m in length, supported by two 430 × 1178 mm glulam columns, connected using Φ 12–16 mm, 250 mm long glued-in threaded rods, as illustrated in Fig. 3. The glulam columns were anchored to the concrete strong floor using angle brackets with anchor bolts.

Figure 3. Lab test photo of the TCC slab band beam

The system consisted of 7-ply, 245 mm thick CLT panels graded as E1M5, in accordance with the manufacturer StructureLam. These panels were manufactured following the PRG320 [11] standard using spruce-pine-fir (SPF) lumber. The laminations in the major strength axis were composed of 2100 Fb-1.8E machine-stress-rated grade lumber, while SPF No.3 grade stock was used for the minor strength axis laminations. A 150 mm reinforced concrete topping with a minimum specified strength of 35 MPa was used. The mix incorporated Type I Portland cement and a maximum aggregate size of 10 mm. A superplasticizer was added to achieve a high-flow consistency with an 80 mm slump.

Three types of shear connectors were designed and utilized between the CLT panel and the concrete topping. Type 1 connectors consisted of fully threaded STS 11× 250 mm screws installed at a 45° angle, with a spacing of 150 mm in the outer one-third spans and 300 mm in the middle span (Fig. 4a). Type 2 connectors were 2100 mm long and 75 mm deep steel kerf plates, spaced at 300 mm in the outer one-third spans and 1000 mm in the middle span (Fig. 4b). Type 3 TCC connectors were proprietary glued-in Holz-Beton-Verbund (HBV) meshes, 90 mm deep, with the spacing and length detailed in Fig. 4c. The estimated stiffness for Type 1, 2, and 3 TCC connectors were 83 kN/mm, 524 kN/mm, and 412 kN/mm, respectively [12].

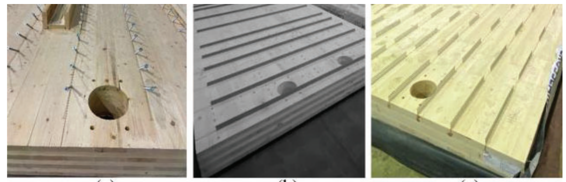
(a) (b) (c)

Figure 4. Photos of three shear connections

In the actual building application, the CLT panels used in the TCC slab band beams were 244 mm thick and manufactured by Nordic. The TCC slab band beams were supported by 422 × 1210 mm glulam columns, connected using Φ 15–16 mm, 400 mm long glued-in threaded rods. The infill CLT panels were sheathed with an acoustic membrane and topped with a 40 mm concrete layer. The configuration of the floor system is shown in Fig. 5, with corresponding dimensions provided in Table 1.

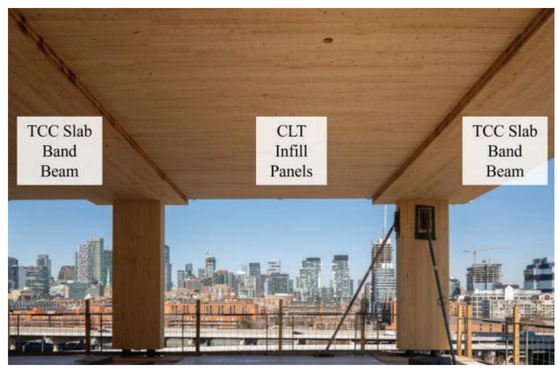

Figure 5. Field test photo of the tested floor system [13]

Table 1. Detailed dimensions of the components in the tested floor system

Component	Material	Thickness (mm)	Span (m)
TCC slab band	CLT	244	9.2
	Concrete	150	
CLT infill panel	CLT	191	4.8
	Concrete topping	40	

2.2 LABORATORY TESTS

The bands with different connectors were first tested for their dynamic properties by experimental modal testing. To determine the modal properties, including natural frequencies, mode shapes, and damping ratios of the specimens, instrumented impact hammer tests were conducted with accelerometers positioned on the concrete surfaces. Five accelerometers, each with a nominal sensitivity of 10 mV/g, were mounted on the test specimens using hot melt glue. Modal analysis was then performed using BK Connect software to evaluate the dynamic properties of each specimen.

Additionally, subjective evaluations were conducted to assess the acceptance level of the specimens for their vibration performance, in accordance with ISO/TR 21136 [14], which ranks floor acceptance on a scale from 1 (definitely unacceptable) to 5 (definitely acceptable).

Full-scale static bending tests were subsequently conducted using a four-point bending configuration, as detailed in [6]. The load increase from 10 to 40% of maximum force (F_{max}), ΔF_{10-40}, and the corresponding increase in deflection, Δd_{F10-40}, allowed calculating the apparent bending stiffness EI_{app} using Equation (3):

$$EI_{app} = \frac{\Delta F}{48\Delta d}(3L^2a - 4a^3) \qquad (1)$$

where ΔF is the change in forces between 10 and 40% of F_{max}, Δd is the corresponding change in deflection, L is the span, and a is the distance between the support and loading points, which was 3.07 m in this test.

2.3 FIELD TESTS

An ambient vibration test (AVT) was conducted to determine the dynamic properties of the tested floor area in the field. For the AVT protocol, a 24-channel SEIMENS SCADAS dynamic data analyzer was used, along with 10 uniaxial PCB accelerometers, each with a sensitivity of 100 mV/g and a sampling frequency of 200 Hz for data collection. The accelerometers served as both reference and measurement points. In total, four test setups were performed, with one of the setups shown in Fig. 6. The accelerometers were mounted on the floor using hot melt glue. Each setup lasted for a duration of 180 seconds.

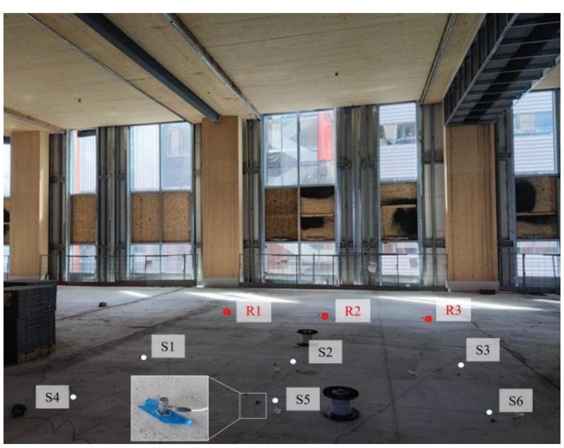

Figure 6. Ambient vibration test setup

Post-processing of the collected data was performed through operational modal analysis (OMA) using Simcenter Testlab, with the PolyMAX OMA add-in. The floor's natural frequencies, mode shapes, and damping ratios were then obtained. Additionally, the acceleration signals from the AVT were processed according to ISO 2631 [15] to derive the acceleration values from the frequency-weighted floor acceleration-time response.

3 – ANALYTICAL ANALYSIS

For the design of TCC systems, the equations in EN 1995–1-1 can be used [16], which is based on the gamma (γ) method. In this method, the composite action is quantified by estimating γ, ranging from 0.0 (no composite action) to 1.0 (full composite action or full rigid connection), as shown in Equation (2). The γ-value, along with the cross-sectional properties of timber and concrete, allows for the estimation of the effective bending stiffness EI_{eff}, of TCC system, as given in Equation (3).

$$\gamma_t = \frac{1}{1 + \frac{\pi^2 (EA)_t s}{kL^2}} \qquad (2)$$

$$EI_{eff} = (EI)_c + (EI)_t + \gamma_c (EA)_c a_c^2 + \gamma_t (EA)_t a_t^2 \qquad (3)$$

where E_c, E_t, I_c, I_t and A_c, A_t are the moduli of elasticity, second moment of inertia, and cross-section area for concrete and timber components, L is the floor span, k is the slip modulus of the connector, s is the connector spacing, and a_c and a_t are the distances from the neutral axis of the composite section to the neutral axis of the concrete and timber layers, respectively.

The calculation of the fundamental natural frequency is often the first step in most floor vibration design methods [7-10]. It is often estimated based the assumption of a simple-supported beam model, as shown in equation (4).

$$f_1 = \frac{\pi}{2l^2}\sqrt{\frac{EI}{m}} \qquad (4)$$

where l is the span, m; EI is the bending stiffness, N·m^2; and m is the mass over unit length, kg/m.

Based on the static bending test results of the TCC slab band beams, the apparent bending stiffness EI_{app} can be calculated based on Eq. (1). Additionally, the effective bending stiffness EI_{eff} can be estimated based on Eq. (2) and Eq. (3), in consideration of the connection stiffness. The detailed static bending test results and connection

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stiffness values are provided in [5] and [6]. Both values were used to calculate the slab band's fundamental natural frequency based on Eq. (4), and the results will be discussed in the following section.

4 – NUMERICAL MODELLING

Two FE models were developed for the TCC slab band and the full-scale floor system, as tested in laboratory and field tests, respectively. The accuracy of these models was validated against the experimental data obtained in this study. The purpose of model development and validation was twofold: first, to provide an additional point of reference for predicting the dynamic characteristics of this floor system, and second, to conduct modal response analysis if there is a need for more comprehensive vibration serviceability assessment.

The FE models were created using the commercial FE software Dlubal RFEM 5.30 [17]. In the TCC slab band beam model, as shown in Fig. 7, the CLT panel was modeled using the RF-Laminate module, with the properties of each layer specified according to the manufacturer's data. For simplicity, the reinforcement for the rolling shear strength of the CLT panels was not included in the model. The concrete layer was then incorporated into the model. Openings in the bands were also modeled, and the boundary conditions were represented by line supports over the corresponding area, as used in the laboratory tests. The shear connections were modeled by surface releases in RFEM, with spring constants derived from the tested connection stiffness. The mesh size was set to 0.5 m.

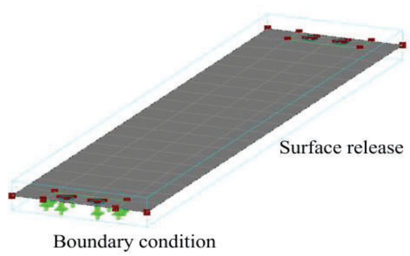

Figure 7. FE model of the TCC slab band beam component

Dynamic analysis was performed in RFEM by the add-on module RF-DYNAM pro to extract mode shapes and natural frequencies. The default Lanczos eigenvalue solution method was used to extract the modal characteristics for the range of frequencies of interest up to approximately 100 Hz.

After validating the TCC slab band beam model with the experimental test results, a full-size model, as shown in Fig. 8, was created to represent the test floor area from the field test. The CLT infill panels with the 40 mm concrete topping were modeled using the same surface release function with the spring constant value from [18] to account for the accidental composite action. The connections between the CLT infill panels and the slab bands were assumed to be rigid for as the concrete topping is continuous.

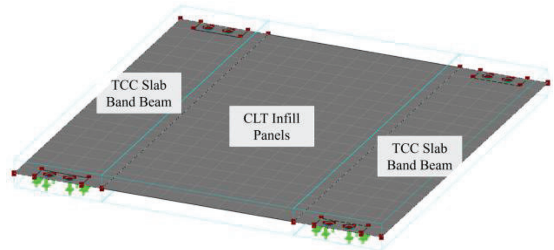

Figure 8. FE model of the full-scale floor system

5 – RESULTS AND DISCUSSION

5.1 LABORATORY TEST RESULTS

5.1.1 Dynamic Properties and Vibration Performance

The dynamic properties of the TCC slab band beams with different shear connectors were obtained, and the results are summarized in Table 2, along with their vibration performance. The corresponding mode shapes are shown in Fig. 9.

From the table, the TCC slab band beam had a fundamental natural frequency ranging from 7.5 to 7.9 Hz, with the different connectors having a slight effect on the frequency even though they showed different load capacities in the static bending test [6]. For the first three modes, the beam exhibited the first bending mode along the span, followed by the torsional mode, and then the second bending mode along the span.

Due to the 150 mm concrete topping, the floor exhibited a damping ratio of 3.5%, which is typically higher than that of a pure mass timber floor. From the subjective evaluation, the single TCC slab band beam displayed unacceptable vibration performance under laboratory conditions, which the occupants felt excessive vibration while others were walking. However, it is important to note that the vibration response of this isolated slab band beam does not fully represent the performance of the complete floor system in actual construction. The presence of infill panels and interaction with other slab band beams on-site could significantly influence the system's overall vibration behavior, which will be discussed in the next section.

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Table 2. Dynamic properties of the tested TCC slab band beam

Specimen	f_1 (Hz)	f_2 (Hz)	f_3 (Hz)	Damping of 1st mode (%)
TCC-STS	7.5	15.8	21.5	3.7
TCC-Steel	7.9	16.0	24.6	3.5
TCC-HBV	7.7	16.2	24.2	3.6

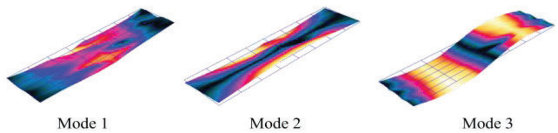

Figure 9. First three mode shapes of the tested TCC slab band beam

5.1.2 Prediction of Fundamental Natural Frequencies

As detailed in the analytical analysis, both apparent bending stiffness EI_{app} and the effective bending stiffness EI_{eff} were used to estimate the beam's fundamental natural frequency using equation (4). The results are shown in Table 3, compared with the results from the dynamic tests.

Table 3. Comparison of the fundamental natural frequencies calculated from different bending stiffness

Specimen	EI_{app} ($kN\,m^2$)	$f_{1,\,app}$ (Hz)	EI_{eff} ($kN\,m^2$)	$f_{1,\,eff}$ (Hz)	$f_{1,\,test}$ (Hz)
TCC-STS	120942	6.0	116102	5.9	7.5
TCC-Steel	141718	6.5	144533	6.6	7.9
TCC-HBV	150976	6.7	149603	6.7	7.7

From the table, it can be observed that in the static bending test, using the gamma method with the connection stiffness allows for a good estimation of the beam's stiffness, with the EI_{app} and EI_{eff} values of the three beams being very close. However, for the prediction of the beam's fundamental natural frequency, using both stiffnesses seem to have underestimated the values, with an error of approximately 20%.

This difference can be explained by that the equation for the fundamental natural frequency is based on the assumption of a simply supported beam, while the TCC slab band was not fully supported at both ends. Additionally, the composite floor system may exhibit different composite behavior under low-amplitude vibration compared to static bending tests, as observed in some studies [19], which could result in a higher frequency in the test compared to the estimated values. To accurately estimate the beam's fundamental natural frequency, a more complex method, such as numerical modeling, is necessary.

5.2 FIELD TEST RESULTS

In the field test, the dynamic properties and mode shapes of the floor were collected and are presented in Table 4 and Fig. 10. The floor exhibited a fundamental natural frequency of 6.1 Hz, which is typically recognized as a low-frequency floor in current design standards [7,10]. The damping ratios for this floor system in the field ranged from 2.0% to 4.9% across different modes. According to the corresponding mode shapes, the floor's first vibration mode occurred more along the direction of the TCC slab band beam.

Table 4. Dynamic properties of the tested floor in field

Mode	Frequency (Hz)	Damping (%)
1	6.1	2.0
2	10.6	3.5
3	15.6	4.9

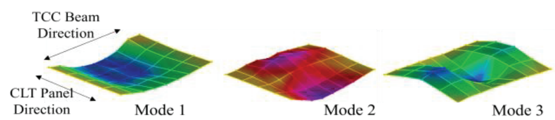

Figure 10. First three mode shapes of the tested floor

From the recorded ambient vibration test data as shown in Fig. 11, the floor's acceleration response to normal human walking was also determined, which may include some noise due to the construction activities. The floor had a maximum weighted RMS acceleration of 0.003 m/s^2 and a peak acceleration of 0.103 m/s^2, values commonly used as design parameters in current response-based floor vibration design methods [7,8]. In contrast to the unacceptable TCC slab band beam tested in the lab, the tested floor area in the field demonstrated acceptable vibration performance, with occupants not perceiving any noticeable vibrations during their walking or when others walked on the floor.

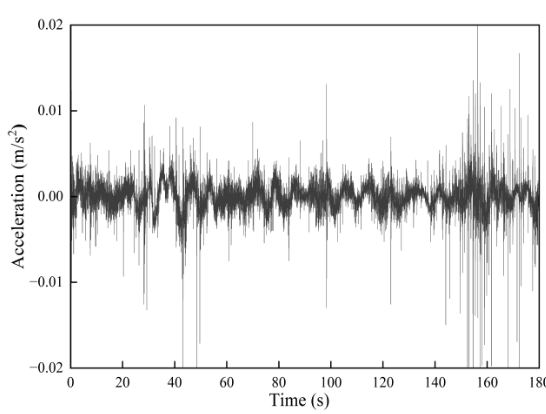

Figure 11. Acceleration history data of the floor

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5.3 FE MODELLING RESULTS

5.3.1 Lab Test Results

The dynamic properties of the TCC slab band beam were obtained with the corresponding mode shapes from FE modelling. The models were compared against the lab test results and verified. The results are summarized in Fig. 12 and 13.

The results show that, with accurate boundary conditions and connection stiffness in the FE model, the prediction accuracy for the first three frequencies is quite good, with an error of approximately 5%. Additionally, the mode shapes matched those observed in the experimental tests.

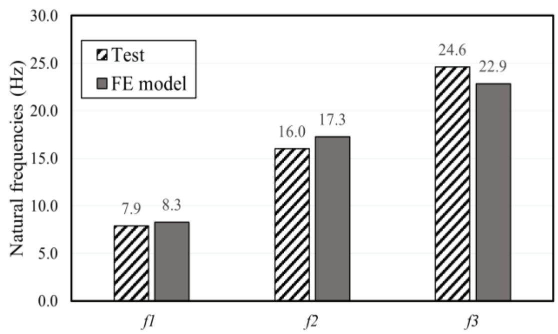

Figure 12. Comparison of the natural frequencies from the modelling and lab tests

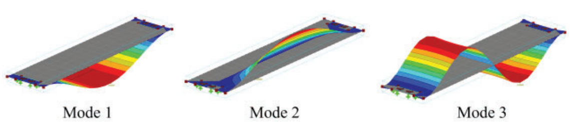

Figure 13. First three mode shapes of the TCC slab band beam from modelling

5.3.2 Field Test Results

After validating the TCC slab band beam component, the full-scale floor system was created in the FE program with the results summarized in Fig. 14 and 15.

The results indicate that the proposed full-scale FE model accurately predicted the floor's fundamental natural frequency, as well as the higher frequencies. The corresponding mode shapes were also in good agreement with the test results. According to the US mass timber floor vibration design guide [10], a modal response analysis is recommended for complex floor systems using the FE modeling approach. Therefore, it is essential to create and validate the model for further vibration analysis.

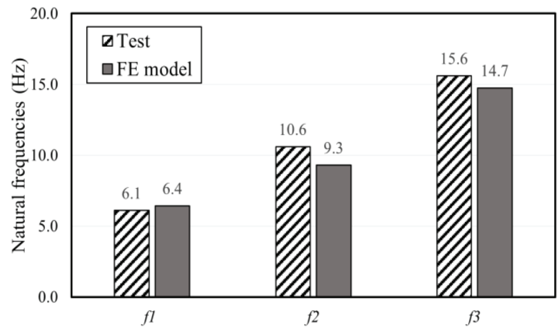

Figure 14. Comparison of the natural frequencies from the modelling and field tests

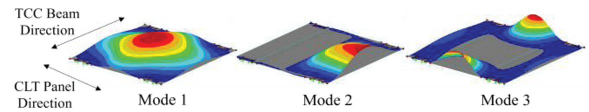

Figure 15. First three mode shapes of the floor from modelling

6 – CONCLUSION

In this study, the TCC slab band beams were tested in the laboratory to evaluate its vibrational performance with different shear connectors. Additionally, the innovative beamless floor system was tested in the field for its vibration performance. Using the experimental data, both analytical and numerical analyses were conducted to predict the floor's fundamental natural frequency. The following conclusions can be drawn from the findings:

1. In the lab tests, the TCC slab band beam with three shear connectors exhibited similar fundamental natural frequencies and damping ratios. Although different shear connectors significantly influenced its load-carrying capacity in static bending tests, they had no noticeable effect on its dynamic properties.
2. In the field test, the tested floor area with the floating concrete topping exhibited acceptable vibration performance, despite the supporting slab band beam demonstrating unacceptable vibration performance in the laboratory.
3. For predicting the floor's fundamental natural frequency, using the bending stiffness derived from both the static test and the gamma method led to underestimation. However, with accurate boundary conditions and connection stiffness, numerical modeling provided reliable predictions of natural frequencies for both the slab band beam and the full-scale floor system.

This research provides experimental results from both laboratory and field tests, along with a numerical modeling approach for the future application and design of this mass timber floor system. Further research will focus on performing modal response analysis on the full-scale floor numerical model.

7 – ACKNOWLEGEMENT

The financial support from the BC Forest Innovation Invest - Wood First program and the Natural Sciences and Engineering Research Council of Canada (NSERC) is gratefully acknowledged. The authors also appreciate the technical support provided by Fast + Epp.

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