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DYNAMIC RESPONSE OF STEEL-TIMBER COMPOSITE (STC) BEAMS

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Due to their recyclability and considerably lower embodied carbon, timber floors are advocated extensively as a more sustainable alternative to concrete slabs. Cross-Laminated Timber (CLT) is an engineered wood product with low variability in mechanical properties and therefore of high reliability and quality, presenting a very attractive alternative to concrete slabs. Replacing the reinforced concrete slabs in conventional steel-concrete composite with an engineered timber product (such as CLT) leads to a significant reduction in the overall weight of the floors, and consequently the weight of supporting structural elements including columns and beams. The combination of light CLT panels and steel may allow an increase in the load-carrying span of the floor systems which is highly desirable from an architectural viewpoint. However, one major drawback negatively affecting the serviceability and thus widespread adoption of such systems in practice is the high susceptibility of undesirable vibration in steel-timber composite (STC) floors under service load conditions due to low mass and damping ratio of timber slabs.

This paper presents the results of a series of experimental impact hammer tests conducted to investigate the vibrational characteristics of different STC beams. Three STC beams with different shear connector types are experimentally tested to extract their natural frequencies. Numerical models are generated and validated using the results of previously performed short-term failure tests. The validated numerical models are then used to extract the linear flexural stiffness of STC beams to determine the deflection of the beams under self-weight. The experimental results are compared against results from analytical models calculating the fundamental natural frequencies of the beams. Further, the obtained dynamic indices of STC beams are evaluated based on available standard regulations.

Keywords: Steel-Timber Composite (STC) Beams, Cross Laminated Timber (CLT), Vibration Serviceability of Floors, Impact Hammer Testing,

1. Introduction

Lightweight structures like timber structures are normally designed for serviceability criterion rather than strength. Therefore, it is common practice to perform dynamic testing to investigate and extract natural frequencies, damping ratios, and mode shapes of structures to be compared against residents discomfort threshold. The fundamental frequency of a structure is an important dynamic index used mainly to investigate the convenience level of occupants. For residents comfort, a fundamental frequency larger than 8 Hz is recommended [1, 2].

The high strength to weight ratio of timber has led to an increasing adoption of this material in the construction of mid-rise buildings. Due to its considerably lower embodied carbon and recyclability, timber is advocated commonly as a more sustainable alternative to concrete. The recyclability of timber may considerably reduce the negative end-of-life impact of buildings, contributing to life cycle sustainability of structures. Furthermore, due to their light weight, construction of wooden structures is generally less resource intensive (labor and equipment) and time-consuming than concrete structures. However, the same advantage, light weight of timber, is also the origin of a major serviceability drawback of timber floor systems, which is their poor performance under dynamic loadings. The dynamic response of timber floors has been studied by a number of previous studies [3-6]. The variety of available floor systems and joist joints, however, makes it highly challenging to predict the response of a particular floor system by relying on the results of the limited number of previous studies. Therefore, experimental tests, mainly impact testing, are generally recommended to evaluate vibration serviceability of timber floors. On the other hand, the complexity of the dynamic loading [7-9] and the human perception threshold of vibration [10-12] add to the difficulties associated with the prediction of the dynamic performance of different floors. A reliable prediction of vibration performance of flooring systems is highly important and may considerably affect the financial viability of the structures. Structural control of vibration including passive [13, 14], semi-active [15, 16], and active control [17, 18] are costly to be implemented in mid-rise residential floors. Composite floors have been studied as a new passive method to control the vibration of slabs [19, 20]. The innovative STC composite flooring system comprising of steel girders and Cross Laminated Timber (CLT) panels are part of the later group. In such systems, the use of steel girders significantly increases the load-carrying capacity and decreases elastic deflection of large span floors [21-25]. STC beams have been reported to show up to 90% composite efficiency and are the subject of ongoing research.

This study investigates the experimental dynamic response of different STC beams. Three STC beams with different shear connectors are fabricated and tested. The dynamic characteristics of the beams are extracted using an impact hammer as excitation source and accelerometers to record the structural response. Experimental findings are compared with available analytical prediction formula presented in the literature. The results of the tests are compared with recommended serviceability guidelines of available codes.

2. Methodology

2.1 Experimental Study

Three beams were fabricated comprising of CLT panels ($2\ panels\ of\ 3000 \times 1000 \times 120mm$, total length of 6.0 m (5.8 span)) and a steel girder ($standard\ 310UB32$) (Figure 1 and Figure 2). The beams were connected with different shear connectors, i.e. coach screws #16, dog screws #16, and pretension bolts #16 (Figure 3). The mechanical properties of the CLT panels are provided by the manufacturer as listed in Table 1. The moisture content and average density of the CLT panels were 12% and $490\ kg/m^3$, respectively.

Table 1 Mechanical properties of CLT panels (direction 1 is parallel to the CLT grain).

E_1 (MPa)	E_2 (MPa)	E_3 (MPa)	G_{12} (MPa)	G_{13} (MPa)	G_{23} (MPa)	μ_{12}	μ_{13}	μ_{23}	ρ (kg/m^3)
11000	370	370	690	690	50	0.48	0.48	0.22	490

The shear connectors were located with $250\ mm$ spacing as illustrated in Figure 1. The beams were simply supported with pin and roller supports at the ends. XA1020-B FGP accelerometers were directly attached to the timber surface using timber screws. Five accelerometers with a range of $\pm 5g$ with nominal sensitivity of $\pm 40mV$ were used to record the acceleration response of the beams at the centre line. The location of the accelerometers were at mid span, and $L/4$ and $L/6$ distance from the supports (Figure 1).

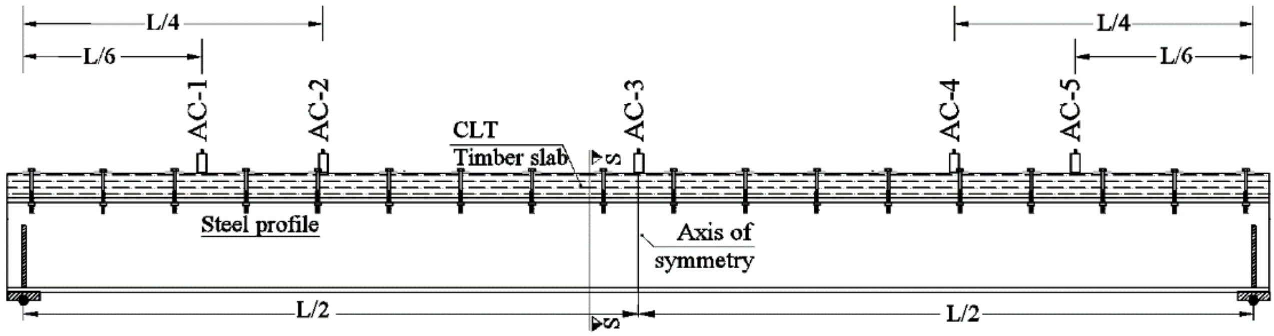


Figure 1 Typical layout of STC beams and location of accelerometers.

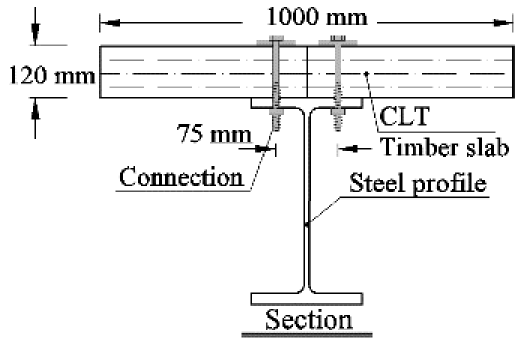


Figure 2 Cross-section of STC beams.

Figure 3 Shear connectors, left-to-right bolt #16, dog screw #16, coach screw #16.

To clearly differentiate the natural modes, the beams were impacted using an ordinary hammer in three positions at the center line. The chosen positions present the maximum modal displacements of the first three mode shapes, i.e. at mid-span, and L⁄4 and L⁄6 distance far from the end support, respectively (H1 to H3 indicated by black dots in Figure 7). Acceleration-time data was recorded by means of a National Instrument data acquisition system with a sampling rate of 1500 data per second. To remove noise from the recorded data, a Butterworth filter was applied to the time domain data before transforming the data to the frequency domain. Fast Fourier Transforms (FFTs) were calculated and normalized for each test.

2.2 Analytical Prediction Models

In the literature, a number of analytical formulas were proposed to calculate the first fundamental frequency of a floor as listed in Table 2. To use the formulas, the elastic deflection under self-weight or flexural stiffness of the beams is required. Therefore, to calculate the flexural stiffness, first, the experimental results conducted by Hassanieh et al. [25] on beams with 800 mm width and different steel section were validated using a developed 1D finite element model by Khorsandnia et al. [26] (Figure 4). As shown in Figure 4, the numerical results are in good agreement with the experimental results; hence, the numerical model can be implemented to simulate the load-deflection curve of the available beams with 1000 mm wide slabs. By means of the validated numerical model, the flexural stiffness of the studied beams are extracted from the simulated load-deflection curve (Figure 5). The obtained secant flexural stiffness (EI) is used to calculate the deflection of the beams ($\delta = \frac{5\omega L^4}{384EI}$) under the self-weight ($\omega = 91\ kg/m$).

Table 2 Analytical models for predicting the first fundamental frequency of beam structures.

Name	Formula	Description of parameters
Wyatt [27]	$f_1 = 18/\sqrt{y_0}$ $f_1 = C_B\sqrt{EI/mL^4}$	y_0: maximum deflection due to the self-weight (mm) C_B: a constant (for pin supports is $C_B = 1.57$) EI: Flexural stiffness (Nm^2) m: the mass per unit length (kg/m)
Murray [28]	$f_1 = \pi/2\sqrt{g\,EI/\omega L^4}$	L: length of span (m) ω: uniform distributed mass load per unit length (N/m)
Allen [29]	$f_1 = 1\Big/2\pi\sqrt{\dfrac{g}{\Delta_s + \dfrac{\Delta_g + \Delta_G}{1.3}}}$	Δ_g: mid span deflection of beam (m) Δ_G: deflection of girder at the beam support (m) Δ_s: deflection of supports (m)
Eurocode-5 [1]	$f_1 = \pi/2L^2\sqrt{EI/m}$	m: the mass per unit length (kg/m)

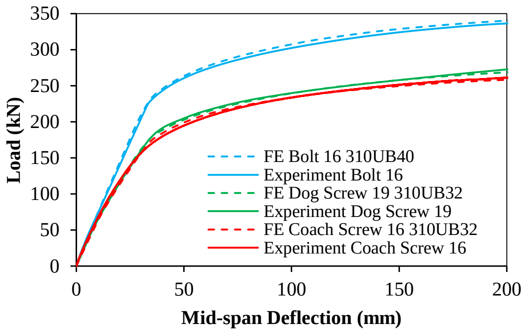


Figure 4 Validation of numerical model with experimental results of Hassanieh et al. [25].

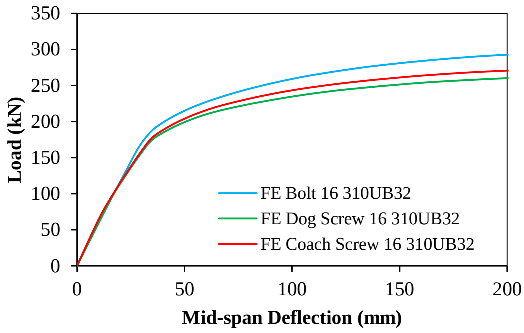
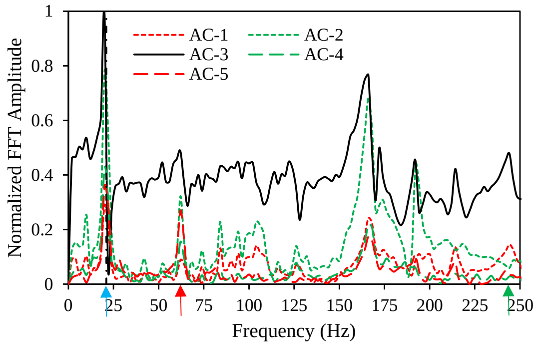


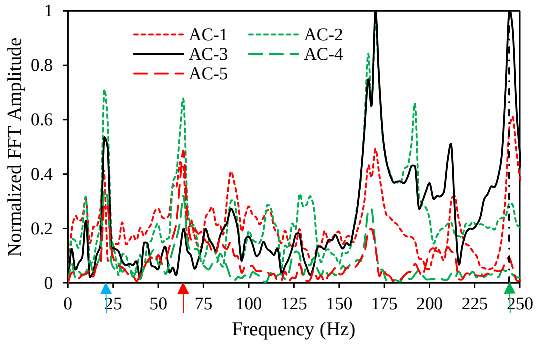
Figure 5 Numerical simulation of load-mid span deflection of the studied beams.

3. Results and Discussions

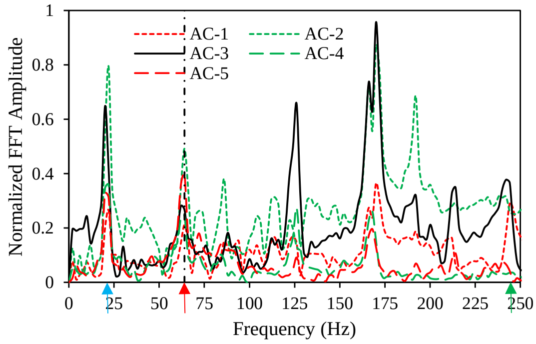
Figure 6 and Figure 8 show the calculated normalized FFTs of the three tests per specimen with impact at different locations (H1 to H3 in Figure 7). In the figures, the first flexural modes can clearly be identified by the first sharp peak in the FFT responses (indicated with blue arrows in Figure 6 and Figure 8). The second flexural mode is shown by the second sharp peak in the FFT responses (indicated by the red arrows). While the second mode can clearly be observed for impact excitation at locations H2 and H3 (Figure 6-b,-c and Figure 8-b,-c,-e,-f); due to impact location H1 being a node point of mode 2, this mode is marginally recognized for impact excitation at H1 (Figure 6-a and Figure 8-a), in particular for accelerometer AC-3 which is situated at the node point itself.



a) Pretension bolt – excitation at H1.



c) Pretension bolt – excitation at H3.



b) Pretension bolt – excitation at H2.

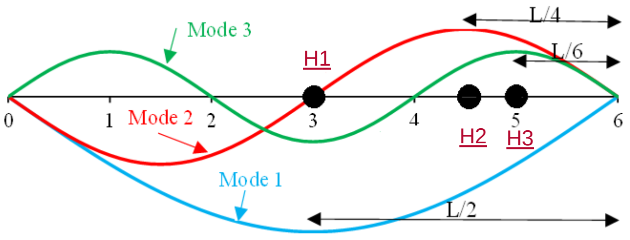
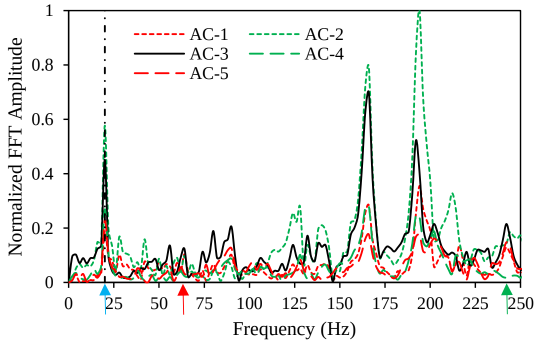


Figure 6 Normalized FFTs for the beam with pre-tension bolt connectors.

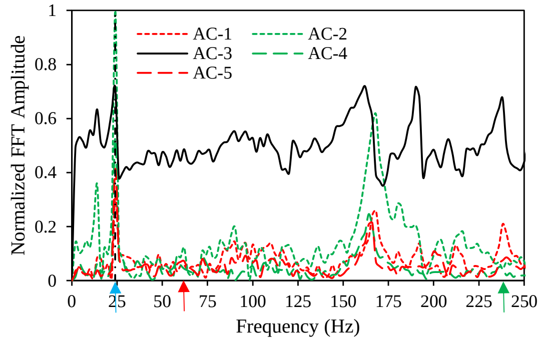
Figure 7 The first three mode shapes with indications of impact locations H1 to H3.

The third flexural mode shows the clearest in the tests with impact excitation at H3 with $L/6$ distance far from the support (Figure 6-c and Figure 8-c,-f (indicated by the green arrows)). Here, a dominant peak with large amplitude is seen in the normalized FFTs. Since the actual test beams are three dimensional (comprising of 1000 mm wide slabs), torsional and axial modes are also present in the FFT responses. For the current study, however, only the flexural modes are of interest. The values of the first three natural frequencies are provided in Table 3. It was expected to have the lowest fundamental frequency for the dog screw shear connectors, then coach screw connectors and the highest fundamental frequency for the pretension bolt connectors because of the initial flexural stiffness (EI) of the beams shown in Table 3. Although the seam between two CLT panels does not affect the ultimate load carrying capacity and the total deflection of the beams (proven both experimentally and numerically), it does have a significant influence on the dynamic response of the STC beams requiring a more detailed investigation of the seam effect.

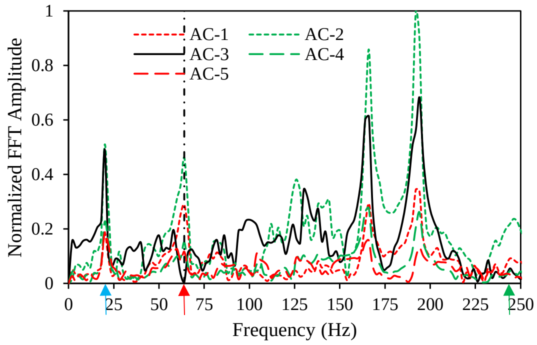
As a comparison, the results of the experimental natural frequencies (f_{1Exp}, f_{2Exp} and f_{3Exp}), the finite element simulation (EI and δ), as well as the analytical predication models (f_{1Wy1}, f_{1Wy2}, f_{1Mur}, f_{1All} and f_{1Eur}) are summarized in Table 3. All prediction models overestimate the fundamental frequencies. It is believed that the presence of multiple CLT panels attached to the beam in combination with the seam have a considerable effect on the dynamic behaviour of the STC beams. More detailed prediction models must be developed to consider the effect of multiple panels in deconstructible composite floors where the entire floor is not connected to form a unit slab.



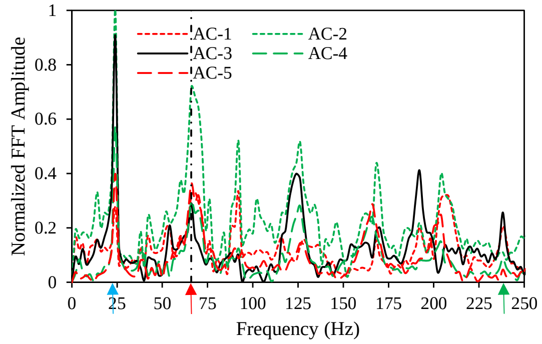
a) Coach screw – excitation at H1.



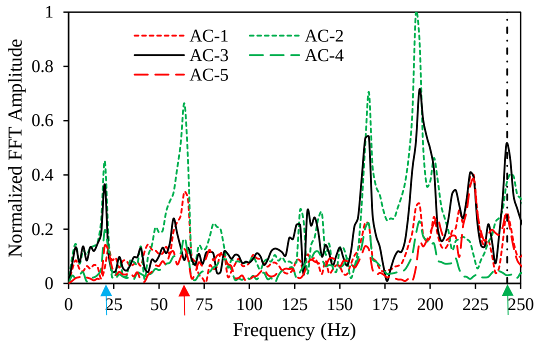
d) Dog screw – excitation at H1.



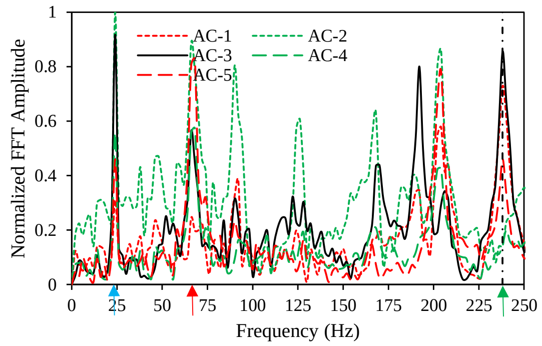
b) Coach screw – excitation at H2.



e) Dog screw – excitation at H2.



c) Coach screw – excitation at H3.



f) Dog screw – excitation at H3.

Figure 8 Normalized FFTs for beams with coach screw and dog screw connectors.

Table 3 Natural frequencies of experimental & analytical/numerical prediction models.

Beam	Experimental			Numerical		Analytical				
	$f_{1_{Exp}}$ (Hz)	$f_{2_{Exp}}$ (Hz)	$f_{3_{Exp}}$ (Hz)	EI (MNm^2)	δ (mm)	$f_{1_{Wy\,1}}$ (Hz)	$f_{1_{Wy\,2}}$ (Hz)	$f_{1_{Mur}}$ (Hz)	$f_{1_{All}}$ (Hz)	$f_{1_{Eur}}$ (Hz)
Coach screw	20.31	63.6	222.13	29.68	0.443	27.04	26.65	26.67	27.00	26.67
Dog screw	24.01	66.03	238.07	29.01	0.453	26.73	26.35	26.37	26.69	26.37
Pretension bolt	21.47	64.03	244.24	31.21	0.421	27.73	27.33	27.35	27.69	27.35

The ISO 2631-2 standard [30] recommends to avoid the range of 4-8 Hz for the fundamental frequency which humans are sensitive to. Outside of this frequency range, the serviceability is a function of the peak floor acceleration, with higher acceleration amplitudes resulting in more discomfort. The fundamental frequency of the investigated STC beams is significantly larger than the 8 Hz threshold, highlighting the favorable dynamic serviceability characteristics of the tested STC beams. A comprehensive study should be undertaken to record and calculate the weighted average acceleration of STC floors at different positions on the surface of the flooring system to accurately specify vibration performance of the overall system.

4. Conclusion

Three experimental STC beams with a 5.8 m span length were tested to extract the natural frequencies as a main dynamic characteristic influencing the serviceability performance of the flooring system. In addition to the experimental study, five analytical prediction models were correlated with the test results. The following observations were made based on the experimental data and analytical models:

- The fundamental frequencies of the investigated STC beams were found to be considerably larger than 8 Hz, which is outside the recommended frequency range to avoid residents discomfort, highlighting the capability of the STC beams investigated in this study to meet the vibration serviceability requirements.
- STC beams with different shear connectors showed the same vibration frequency range for the first three flexural modes. Therefore, the connector type was found not to be a determining factor in the dynamic response of the STC beams.
- In spite of strength criterion, the seam between CLT panels was found to significantly affect the vibration response of the STC beams and should, therefore, be taken into account in the design of STC beams.
- The five analytical prediction models studied in this research were found to overestimate the fundamental frequencies of the STC beams. Murray's and the Eurocode-5 models resulted in the same fundamental frequency estimations, while Wyatt's first and second prediction models yielded the lower and upper limits of the predictions, respectively.

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