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Dynamic Properties of Timber–Concrete Composite Beams with Crossed Inclined Coach Screw Connections: Experimental and Theoretical Investigations

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Abstract: Due to the low density and stiffness of wood, traditional timber floor systems are prone to producing large vibration responses. By combining timber beams with concrete floors, timber-concrete composite (TCC) floor systems show stronger bearing capacity, higher bending stiffness, and better thermal and sound insulation behaviors when compared with traditional timber floor systems. In this study, the vibration performance of TCC beams with crossed inclined coach screw connectors was investigated using dynamic tests. The influence of the screw diameters and slab dimensions on the dynamic performance of the composite beams was evaluated. The test results demonstrated that TCC beams show good dynamic performance when used as a floor component and meet the preliminary requirements of floor vibration comfort for fundamental frequency. The fundamental frequency and damping ratio of TCC beams decreases with the increase in slab dimensions. The bending stiffness and natural frequency of TCC beams decreases smoothly when reducing the screw diameter from 16 to 12 mm. Additionally, two theoretical models were used to predict the natural frequencies of the TCC beams, and the predicted values show good consistency with the measured ones.

Keywords: timber–concrete composite beams; coach screws; dynamic properties; experimental study; theoretical analysis

1. Introduction

Timber members, characterized by light mass and high strength, are easily fabricated and assembled in construction [1–3]. However, compared to concrete or steel, timber shows apparent disadvantages in density and modulus of elasticity. Timber floors easily produce annoying vibrations, which affect the comfort of users, and even cause resonance that endangers the safety of the structure. Therefore, scholars have focused on the vibration problem of timber floors since the 1970s, forming a series of design methods and controlling indicators [4,5]. The controlling vibration factors include deformation modal parameters and excitation responses, such as deflection d, fundamental frequency f, speed v, and acceleration a, under dynamic load [6–10].

Existing investigations found that adding concrete to timber beams can significantly improve the vibration performance of the floor system. Compared to pure timber floors, timber–concrete composite (TCC) floors show significant improvement in the sound insulation effect and in reducing the sensitivity of vibration comfort, by means of increasing the stiffness of the components through the composite action [11–13].

Studies on TCC structures are mainly focused on static properties, but there are limited studies on vibration behavior. Deam et al. [14] experimentally investigated the dynamic performance of laminated veneer lumber (LVL)–concrete composite beams. Their



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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). study showed that the concrete slab is beneficial in reducing fundamental frequency and acceleration sensitivity when compared with pure timber floors, which can effectively avoid the sensitive perception range of people. Mertens et al. [15] conducted dynamic tests both on timber floors and TCC floors and evaluated vibration comfort according to the European standard EN 1995-1-1 (Eurocode 5) [10]. They found that TCC floors could meet the requirements of fundamental frequency and that TCC connections are crucial to the vibration response of TCC floors. Rijal et al. [16] discussed the influences of different connection types on the dynamic performances of TCC beams. Through experimental research, they found that different shear connectors influence beams' natural frequencies and damping ratios.

The interlayer connection is a crucial aspect of research in timber–concrete composite structures. Various types of fasteners have been reported for TCC structures. Chybiński and Polus [17] developed an aluminum-timber composite connection with hexagonal head wood screws and reinforced with toothed plates. Through an experimental study, it was found that bearing strength can be significantly improved after strengthening with a toothed plate. Lukaszewska et al. [18] developed a novel composite floor system by connecting prefabricated concrete slabs to timber joists. They developed and tested various types of shear connectors for the floor system, including metal plates, dowels, toothed metal plates, and hexagonal head wood screws with steel tubes. Through experiments and numerical analysis, they found that the connections all have good structural performance, especially the coach screws and notch connections. Szumigała et al. [19] developed new connectors for timber-concrete composite structures, consisting of a headed stud and a steel screw. Through experiments and analyses, it was found that the significant advantage of the new connection is ductility. Tao et al. [20,21] studied the feasibility of glued perforated steel plates in prefabricated timber-concrete composite structures. Their results showed that the glued perforated steel plate connections have high slip stiffness and shearing capacity. Gutkowski et al. [22] studied a composite concrete–wood floor system using a novel notched shear key/anchor connection. Their results indicated its structural merit compared with ordinary mechanical connectors.

In this study, connections with crossed inclined coach screws were used for TCC beams considering their high construction efficiency and good shear performance [23]. Wen et al. [24] investigated the vibration performance of timber–lightweight aggregate concrete composite beams using three different connection methods. Among them, the natural frequency of composite beams connected with crossed inclined screw connections is lower than those with notch-screw connections or glued-steel plate connections. There are limited studies available in the literature on the dynamic performance of TCC beams with crossed inclined coach screw connections. Therefore, this study aimed to investigate the dynamic properties of TCC beams that utilize crossed inclined coach screws. Experimental investigations were conducted to evaluate the modal dynamic properties of TCC beams, including their fundamental frequency and damping ratio. Moreover, the effects of concrete slab dimensions and screw diameter on the dynamic performance of TCC beams are discussed.

2. Materials and Methods

2.1. Materials

2.1.1. Timber

The glulam beams were made with Douglas fir lumber from North America. The lumber has a density of 456 kg/m³ and a moisture content of 11.2%. Their moisture content was determined using tests according to GB/T 1931-2009 [25], and their density was measured following the GB/T 1933-2009 [26] guidelines. For the tests, a drying oven with machine model DHG-9140(A) (101-2), produced by Yiheng Scientific Instrument Co., LTD., Shanghai, China, was used. The basic mechanical properties of glulam were obtained using material tests according to EN 408 [27]. The dimensions of the samples used in the tensile, compressive, and shear tests were 30 mm \times 10 mm \times 300 mm (height \times width \times length),

50 mm \times 50 mm \times 300 mm, and 55 mm \times 32 mm \times 300 mm, respectively. A testing machine produced by MTS System (China) Co., Ltd. (Shanghai, China) with a maximum capacity of 300 kN, was used for the material tests. The corresponding test results are shown in Table 1.

Table 1. Mechanical properties of timber.

Properties	E _t (MPa)	$f_{\rm cl}$ (MPa)	f _{tl} (MPa)	f_{tp} (MPa)		
Value	13,500	38.2	39.4	9.4		

Notes: E_t is the modulus of elasticity, f_{cl} is the compression strength in the longitudinal direction, f_{tl} is the tension strength in the longitudinal direction, and f_{tp} is the shear strength parallel to the grain.

2.1.2. Concrete

The concrete slabs were poured with C40 grade cast in situ concrete. The compression tests were conducted on the concrete cubes with a side length of 150 mm under natural curing for 28 days. The Young's modulus and the tensile strength of the concrete were obtained via tests according to GB50010-2010 [28]. The tests were conducted using a Microcomputer-controlled automatic pressure tester produced by Sansi Instrument Manufacturing Co., Ltd. (Shanghai, China). The basic mechanical properties of the concrete are shown in Table 2.

Table 2. Mechanical properties of concrete.

Properties	E _c (MPa)	f _c (MPa)	f _t (MPa)	
Value	33,000	28.3	2.5	

Notes: E_c is the elastic modulus of concrete, f_c is the compression strength, and f_t is the tension strength.

2.1.3. Steel

The steels used in this test mainly include the reinforcing bars, bearing supports, and coach screws. The strength grade of the steel made for the reinforcing bars and coach screws was S355 with a yield strength of 345 MPa and a modulus of elasticity of 200 GPa. The bearing supports were manufactured with high strength steel with a yield strength of 640 MPa and a modulus of elasticity of 210 GPa. The diameter of the reinforcing bars was 8 mm at a spacing of 150 mm. The thickness of the bearing support plate was 30 mm. Coach screws with diameters of 12 mm or 16 mm and a length of 200 mm were used as the timber–concrete interfacial connections, as shown in Figure 1.



Figure 1. Coach screws.

2.2. Specimens

2.2.1. Shear Connectors

To evaluate the shear performance of the crossed inclined coach screws, the push-out tests were carried out in preliminary tests according to EN26891 [29]. Two groups of

specimens with 3 samples in each group were analyzed in this study by adopting screws with different diameters. The specimens with 16 mm diameter screws were named CBIS16-200 and those with 12 mm diameter screws were named CBIS12-200. The length of the screws was 200 mm and the inclined angle was 45° . The test sample is shown in Figure 2. The predrilling diameter for CBIS16-200 was 12 mm, while that for CBIS12-200 was 9 mm. The screws were inserted using an electric wrench with a maximum torque moment of 200 N·m. A multifunctional testing device with a maximum load capacity of 250 kN produced by Hangzhou POPWIL electromechanical control engineering co., ltd., China was used for the test. The test setup for the push-out test is shown in Figure 3.



Figure 2. The pushout specimen.



Figure 3. The push-out test for the shear connector.

2.2.2. Timber-Concrete Composite (TCC) Beams

To evaluate the effects of concrete slab dimensions and screw diameter on the dynamic performance of the TCC beams, five TCC beam specimens were designed. The dimensions of the timber beams were 5000 mm \times 150 mm \times 400 mm (length \times width \times height), and the dimensions of the concrete slabs were 4800 mm in length with different widths and heights.

To explore the influence of concrete slab width on vibration performance, three slab widths of 930 mm, 1395 mm, and 1860 mm were designed under the clear span of 4650 mm. The parameter b_c/l is the width-to-span ratio, which was 0.2, 0.3, and 0.4 in this

study. Therefore, the TCC beams were named after b_c/l , which are TCC0.2, TCC0.3, and TCC0.4, respectively. Also, this study tested two different concrete slab heights, 100 mm and 120 mm. The TCC beam with a 100 mm high concrete slab was designated as TCC0.4; while the TCC beam with a 120 mm thick concrete slab was specified as TCC0.4-hc120.

The timber beams and the concrete slabs were connected with crossed inclined coach screws. The test explored two sizes of coach screws, the beam with 12 mm diameter screws was named TCC0.4-CO12, and the others were all 16 mm. The spacing between the connectors was 300 mm in length of beam and 70 mm in width. The details of the parameters of the TCC beams are listed in Table 3, and an example of the TCC beam is shown in Figure 4.

Table 3. Parameter details of TCC beams.

Specimen Code	$b_{\rm c}/l$	<i>b</i> _c (mm)	$h_{\rm c}$ (mm)	Connector
TCC0.2	0.2	930	100	CBIS16-200
TCC0.3	0.3	1395	100	CBIS16-200
TCC0.4	0.4	1860	100	CBIS16-200
TCC0.4-CO12	0.4	1860	100	CBIS12-200
TCC0.4-hc120	0.4	1860	120	CBIS16-200

Notes: b_c is the concrete slab width, h_c is the concrete slab height, l is the span of the beam, and b_c/l is the concrete slab width-to-span ratio.



Figure 4. Specimen of TCC0.4.

2.3. Test Set-Up

All of the TCC beam specimens were tested under the same boundary conditions, with one hinge support at one end and a roller support at the other end, as shown in Figure 5. The specimens were placed in the central line of the supports, and the clear span of all beams was 4650 mm.



Figure 5. The supports of the test: (a) the hinge support; (b) the roller support.

2.4. Equipment and Experimental Procedure

Acceleration sensors were arranged equidistantly along the central line of the upper surface of the concrete slabs, as shown in Figures 6 and 7. The dynamic test was stimulated using a pulsed hammer. The response signal was collected using the dynamic signal test system TST3828E, and the modal analysis of dynamic properties was performed using the signal processing software DASP-V11. To improve the accuracy and reliability of the data, each TCC beam was tested twice, and the dynamic properties were determined using the average values from the two tests.



Figure 6. Dynamic test of TCC beam.



Figure 7. Dynamic test set-up.

The TCC beams were tested under bending load, and the test set-up is shown in Figures 8 and 9. The testing equipment comprises a hydraulic jack and a load cell produced by OVM Machinery Co., Ltd. in Liuzhou, China and Jiangsu Guo Yan Li Zhun Detection Instrument Technology Co., Ltd. in Nanjing, China, respectively. The hydraulic jack with counter-force frames provided the load, and the values of the applied forces were recorded with the load cell. The deflections of the TCC beans were recorded with linear variable displacement transducers (LVDTs).



Figure 8. Bending test of TCC beam.



Figure 9. Bending test set-up. Reprinted with permission from Ref. [30]. 2023, Elsevier.

3. Experimental Results

3.1. Push-Out Test of Connectors

According to the European standard EN26891 [29], the load, interfacial slip, and the slip stiffness of the connector were obtained. The shear properties of the connections are listed in Table 4.

Connector Code	Screw Diameter (mm)	Screw Length (mm)	Penetration Depth (mm)	K _s (kN/mm)	K _u (kN/mm)	F _{max} (kN)
CBIS16-200	16	200	135	42.92	39.31	73.50
CBIS12-200	12	200	135	40.54	34.30	58.40

Notes: K_s is the slip modulus of the connection at the serviceability limit, K_u is the slip modulus of the connection at the ultimate state, and F_{max} is the shear capacity of the connection.

3.2. Dynamic and Bending Test of the TCC Beams

The TCC beams were stimulated with a hammer, and the time domain signals of acceleration responses (as shown in Figure 10) were collected from sensors. The time domain signals were subjected to fast Fourier transform (FFT); then, the natural frequencies (as shown in Figure 11) and damping ratio of the TCC beams could be calculated. The

symbol $f_{1(exp)}$ denotes the measured values of fundamental frequencies of the first flexural modal, and ζ_1 was used to indicate the first modal damping ratio of the TCC beams. The specific test results are listed in Table 5.



Figure 10. The time domain signals of acceleration response: (a) TCC0.2; (b) TCC0.3; (c) TCC0.4; (d) TCC0.4-CO12; (e) TCC0.4-hc120.



Figure 11. The frequency spectrum: (**a**) TCC0.2; (**b**) TCC0.3; (**c**) TCC0.4; (**d**) TCC0.4-CO12; (**e**) and TCC0.4-hc120.

Specimen Code	(<i>EI</i>) _(exp) (×10 ¹² N⋅mm)	P _u (kN)	$P_{\rm u}$ (kN) d (mm)		ζ ₁ (%)
TCC0.2	25.6	313.7	9.3	25.60	2.9
TCC0.3	27.4	310.6	8.5	21.85	2.7
TCC0.4	28.8	316.7	8.3	19.54	2.2
TCC0.4-CO12	28.2	273.2	7.1	19.04	2.8
TCC0.4-hc120	28.3	242.2	6.6	18.07	2.1

Table 5. Measured values of bending and dynamic properties of TCC beams.

Notes: $(EI)_{(exp)}$ is the bending stiffness, *d* is the mid-span deflection at 0.4 P_u , P_u is the ultimate load, $f_{1(exp)}$ is the measured values of fundamental frequencies of the first flexural modal, and ζ_1 is the first modal damping ratio of the TCC beams.

The load (P) was applied at the rate of 20 kN/min using a hydraulic jack with counterforce frames. The deflections were recorded via the LVDTs, and the load–deflection curves are shown in Figure 12. The bending properties at the serviceability state of the TCC beams are also listed in Table 5, including the mid-span deflection *d* and the bending stiffness (*EI*)_(exp). The beams were tested to the ultimate load; P_u is the ultimate load and presents the failure mode, as shown in Figure 13.



Figure 12. Load–deflection curves. (Exp.: experimental results). Reprinted with permission from Ref. [30]. 2023, Elsevier.



Figure 13. The failure mode.

4. Analytical Investigation

Studies have shown that people are most likely to feel uncomfortable when the floor is characterized by low-frequency vibrations, especially for frequencies in the range of 4–8 Hz [31]. Combined with research and ISO standards [32,33], scholars have given relevant indicators to control the vibration of timber floors for comfort. An important one of which is that the fundamental frequency (f_1) should be greater than 8 Hz. If f_1 is lower than 8 Hz, it is easy to cause discomfort to the users, and even footfall will cause resonance of the floor, causing safety problems [6,7,32,33]. For example, Eurocode 5 [10] stipulates that the f_1 should be greater than 8 Hz. If the f_1 of the floor is estimated to be lower than 8 Hz, special analysis and design should be carried out. As one of the important indicators of the dynamic properties of the floor, the fundamental frequency is an important indicator to evaluate whether the vibration performance of the floor is good. Therefore, the analysis of the f_1 of the TCC beam is an important task of this study.

4.1. Theoretical Calculation

Eurocode 5 provides a calculation model for estimating the fundamental frequency (f_1) of the floor system, as shown in Formula (1):

$$f_1 = \frac{\pi}{2l^2} \sqrt{\frac{EI}{m}} \tag{1}$$

where *EI* is the bending stiffness of the TCC beam; *l* is the span of the TCC beam; and *m* is the unit length mass of the TCC beam, including the beam self-weight and other permanent loads. In addition, the bending stiffness of the partially composite beams uses the effective bending stiffness (*EI*)_{eff}, which is based on the ' γ -method', as shown in Formula (2):

$$(EI)_{eff} = E_c I_c + E_t I_t + \gamma E_c A_c a_c^2 + E_t A_t a_t^2$$
⁽²⁾

$$\gamma = \frac{1}{1 + \frac{\pi^2 E_c A_c s}{K I^2}} \tag{3}$$

where the subscripts *c* and *t* designate the concrete and timber, respectively; *E* is the modulus of elasticity; *I* is the moment of inertia; γ is the reduction coefficient for the combined action; *A*_c and *A*_t are the section area of concrete slab and timber beam, respectively; *a*_c and *a*_t are the distance between the centroid of concrete slab or timber beam to the neutral axis of the composite section, respectively; *s* is the distance of shear connectors; *K* is the slip stiffness of shear connections; and *L* is the clear span of beams.

Murray [34] also provides a calculation model that could estimate the fundamental frequency (f_1) of the simply supported beams, as shown in Formula (4):

$$f_1 = \frac{\pi}{2} \sqrt{\frac{gEI}{wL^4}} \tag{4}$$

where *g* is the acceleration of gravity; *EI* is the bending stiffness of the TCC beam; *L* is the clear span of the beam; and *w* is the uniformly distributed load in unit length.

The parameters adopted in the theoretical calculation are shown in the previous text. It is worth noting that Table 4 shows the shear properties of the connectors. K_s and K_u are the slip moduli of the connector at the serviceability limit and the ultimate state, respectively. When studying the vibration behavior of beams, the values of K_s were used to calculate the $(EI)_{eff}$ of TCC beams in the serviceability limit state. Using the Eurocode 5 and Murray methods, the semi-theoretical predicted values $f_{1(EC5)}$ and $f_{1(M)}$ of the fundamental frequencies of the TCC beams can be obtained, respectively, as shown in Table 6. Additionally, Tao et al. [23] have provided a theoretical calculation method of connector stiffness. Based on the connection stiffness calculation method, the full-theoretical predicted values of the fundamental frequencies can be obtained, as the values of $f'_{1(EC5)}$ and $f'_{1(M)}$ shown in Table 6.

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	Specimen Code	(EI) _{eff} (×10 ¹² N·mm)	(<i>EI</i>) _(exp) (×10 ¹² N⋅mm)	f _{1(EC5)} (Hz)	f' _{1(EC5)} (Hz)	$f_{1(\mathrm{M})}$ (Hz)	f' _{1(M)} (Hz)	f _{1(exp)} (Hz)	ζ ₁ (%)
	TCC0.2	26.5	25.6	23.08	23.71	22.85	23.47	25.60	2.9
	TCC0.3	28.1	27.4	19.78	20.23	19.58	20.11	21.85	2.7
	TCC0.4	29.5	28.8	17.74	18.21	17.56	18.03	19.54	2.2
	TCC0.4-CO12	29.0	28.2	17.58	17.25	17.40	17.08	19.04	2.8
	TCC0.4-hc120	34.5	28.3	17.58	18.02	17.40	17.84	18.07	2.1

Table 6. Bending stiffness and dynamic properties of TCC beams.

Notes: $(EI)_{eff}$ is the bending stiffness of the TCC beams calculated based on the γ -method, $(EI)_{(exp)}$ is the experimental bending stiffness of the TCC beams, $f_{1(EC5)}$ is the fundamental frequency calculated according to Eurocode 5 with the experimental stiffness of the connector, $f_{1(M)}$ is the fundamental frequency calculated according to Murray [34] with the experimental stiffness of the connector, $f'_{1(EC5)}$ is the fundamental frequency calculated according to Eurocode 5 with the theoretical stiffness of the connector, and $f'_{1(M)}$ is the fundamental frequency calculated according to Murray [34] with the theoretical stiffness of the connector.

4.2. Discussion

4.2.1. Fundamental Frequency

As shown in Table 6, the fundamental frequencies of the five composite beams ranged from 18 Hz to 26 Hz. If the TCC beams are considered as one-way floors, the control requirements of $f_1 > 8$ Hz for the floor can be satisfied. From the comparison between the measured values and the calculated values, the value of the maximum difference between experimental frequency and full calculated frequency is 2.13 Hz, it can be seen that the calculation methods in the Eurocode 5 and Murray methods have good reliability.

4.2.2. Effect of the Dimensions of Concrete Slabs

From the data in Table 6, as the width of the slab increases, the flexural stiffness $(EI)_{eff}$ and $(EI)_{(exp)}$ of TCC beams increases, while the fundamental frequency decreases both in the calculated value and in the measured value. According to Equation (1), although the stiffness of the concrete slab increases with the increase in the slab width, the increase in self-weight caused by the increase in slab width still reduces the fundamental frequency of the TCC beams. Similarly, when the slab heights of the concrete are increased from 100 mm to 120 mm, the flexural stiffness (*EI*)_{eff} of the TCC beam also increases significantly, but its fundamental frequency still decreases. Therefore, it can be preliminarily identified that the self-weight of concrete slab changes, caused by the dimension change, has a greater effect on the fundamental frequency of the TCC beams than the flexural stiffness (*EI*)_{eff}, and the values of fundamental frequency using the Murray method have a similar pattern. In addition, the damping ratio decreases significantly as the width and height size of the concrete slab increase.

4.2.3. Effect of the Connection

This study tested two different connectors for the TCC beams. It can be seen in Tables 4 and 6 that the flexural stiffness $(EI)_{eff}$ and $(EI)_{(exp)}$ of the TCC beam decreases when reducing the shear stiffness of the connectors. Meanwhile, when changing the screw diameter from 16 mm to 12 mm, the fundamental frequency of the TCC beams decreases smoothly, but the damping ratio increases notably, according to Table 6. This indicates that under the same conditions, the natural frequency of the specimen is inversely proportional to the damping ratio.

5. Conclusions

In this study, five TCC beams with a clear span of 4650 mm were tested under dynamic excitation. The vibration behavior of the TCC beams was evaluated based on the fundamental frequency and damping ratio. The fundamental frequency of the TCC beams was predicted and calculated using the calculation models in Eurocode 5 and the Murray method, respectively. The calculated values and the experimental values were compared and discussed. The generalized conclusions are as follows: The TCC beams in this study can be used as the one-way floor unit and meet the requirement of $f_1 > 8$ Hz for floor comfort.

The increase in the dimensions of the concrete slab can increase the flexural stiffness of the TCC beams, but the consequent increase in the self-weight of concrete causes a reduction in the fundamental frequency. The fundamental frequency of the composite beams decreases with the decrease in the connection shear stiffness, while the damping ratio increases with the reduction in the connection stiffness.

Both the methods provided by Eurocode 5 [10] and Murray [34] have certain reliability in predicting the vibration behavior of the TCC beams, but their calculation values are smaller than the experimental values. Therefore, a more in-depth study needs to be conducted, and our next research plan will try to optimize the existing predictive method.

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