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EXPERIMENTAL INVESTIGATIONS ON VIBRATION PERFORMANCE OF TIMBER-CONCRETE COMPOSITE BEAMS USING LIGHTWEIGHT AGGREGATE CONCRETE

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ABSTRACT: Better structural performances can be obtained by using concrete slabs instead of timber slabs in floor system of timber structures. The use of lightweight aggregate concrete (LWAC) in timber-concrete composite floors can reduce the self-weight of the slab. However, the vibration performance of timber-LWAC composite floors remains need to be studied. In view of this, an experimental programme was conducted to investigate the dynamic properties of the timber-LWAC composite beams. Three test specimens with different types of connections were designed and fabricated. The test results demonstrated that the timber-LWAC composite beams have good vibration performance with the fundamental natural frequency much higher than 8 Hz. Additionally, the vibration frequency of the composite beams with notch-screw connections or glued-steel plate connections is higher than that of the composite beams with crossed inclined screw connections.

KEYWORDS: Timber-concrete composite beams, Lightweight aggregate concrete, Vibration performance, Timber-concrete connections, Experimental investigations

1 INTRODUCTION

Floor system is the component with the closest contact between the human and building, which requires high structural performance both in ultimate limit state and serviceability limit state. The vibration performance is one of the crucial behaviours of floor systems, which significantly affects the comfort and safety of the structure. Due to the lightweight and low elastic modulus of timber, the traditional timber floor is prone to generate large vibration response. Excessive floor vibration will bring negative psychological effects to the occupants, and even affect the structural safety, which will restrict the development of modern timber structures [1].

Stiffness is the key factor affecting the vibration performance of floor system. Industry regulations control the vibration of timber floors by increasing the structural stiffness and limiting the deformation of timber members [2-4]. With the development of timber structures, the dynamic characteristic index is gradually used as an important parameter to evaluate the vibration performance of timber floors, such as the fundamental natural frequency $f_1 > 8$ Hz in the modal parameters of the floor, and the acceleration generated by human-induced load excitation [5-7]. In addition to the continuous development of vibration control methods, with the development of timber processing technology and structural construction, the types of timber floors are also changing. For the research work on the vibration performance of timber floors, the current main research object has changed from the traditional joist timber floor to the new types represented by cross-laminated timber (CLT) and timber-concrete composite (TCC) floor [1]. In recent years, some studies have proven that the timber-concrete composite (TCC) floors can significantly improve the vibration performance of the floor [8,9].

TCC structure has apparent advantages in stiffness, bearing capacity, sound insulation performance, and fire resistance when compared with traditional timber structures. Also, compared with concrete structures, TCC structure can effectively reduce the consumption of traditional building materials and promote the development of sustainable buildings [10,11]. Lightweight aggregate concrete (LWAC) has the characteristics of light self-weight, high stiffness, and good thermal insulation performance, which is more suitable for TCC structures than the traditional normal concrete [12].

However, few studies have been conducted on the vibration performance of timber-LWAC composite beams. In this study, the dynamic properties and vibration performance of the timber-LWAC composite beams were investigated, and the influences of different types of shear connectors on the vibration performances of the composite beams were evaluated.

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2 TEST SPECIMENS AND METHODS

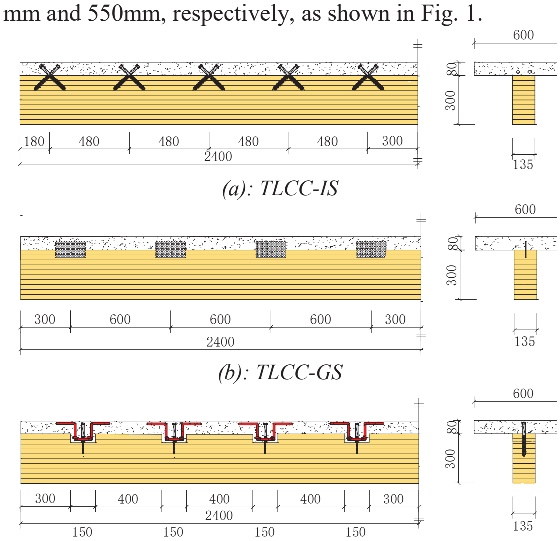
2.1 SPECIMENS

In this experimental programme, three timber-LWAC composite beams were designed, by considering different types of shear connectors. The connectors adopted in the composite beams include the crossed inclined screws, glued-in steel plates, and notched-screws. The specific component parameters were designed according to the Eurocode 5 [13], and the parameters of the specimens are shown in Table 1.

Table 1: *The parameters of the specimens*

Specimens	Connector		
	Types	Spacing (mm)	Quantity
TLCC-IS	crossed inclined screw	480	10
TLCC-GS	glued-in steel plate	600	8
TLCC-NS(R)	notch-screw (reinforcing bar)	550	8

The dimensions of the timber beam are 4800 mm × 135 mm × 300 mm (length × width × height), while the LWAC slab are 4800 mm × 600mm × 80 mm (length × width × height). The spacings of the crossed inclined screws connections are 480 mm, while those of the glued-in steel plate connections and notch-screw connections are 600 mm and 550mm, respectively, as shown in Fig. 1.



(a): TLCC-IS

(b): TLCC-GS

(c): TLCC-NS(R)

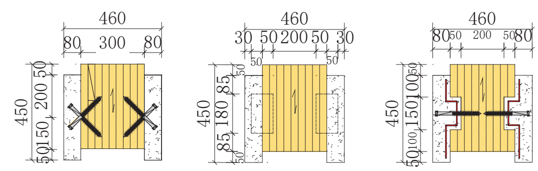
Figure 1: *Configurations of the specimens*

In order to obtain the basic mechanical properties of the connectors, the push-out tests on the connectors were carried out. The parameters of the push-out specimens are shown in Table2.

The push-out specimens adopted the symmetrical configuration, as shown in Fig. 2. For the specimens with crossed inclined screws, the inclination angle of the screw was 45°, and two screws with the diameter 16 mm and length 200 mm (M16L200) were adopted in each shear plane. For the specimens with glued-in steel plates, the length and width of the slots are 190 mm and 10 mm, respectively, and the glued-in depth is 50 mm. For the specimens with notch-screws, the length, width, and depth of the notch are 135 mm, 150 mm, and 50 mm, respectively.

Table 2: *The parameters of the push-out specimens*

Specimens	Connector	Metal Parts and Construction Methods
ISLC	crossed inclined screw	Two M16L200 screws, crossed and inclined at 45 °
GSLC	glued-in steel plate	A 180mm×100mm× 3.75mm steel plate was glued in the timber
NSLC(R)	notch-screw (reinforcing bar)	Reinforcing steel bars and M16L200 are set in the rectangular notch



(a): ISLC *(b): GSLC* *(c): NSLC(R)*

Figure 2:*Configurations of the push-out specimens*

2.2 MATERIALS

The glulam beams were made of North American Douglas Fir. The basic mechanical performances of the glulam are shown in Table 3.

Table 3: *The basic mechanical properties of timber*

Properties	Value (MPa)
Tension strength	69.7
Compressive strength	43.3
Shear strength	9.4
Modulus of elasticity	13100

The lightweight aggregate used in the LWAC slab is spherical shale ceramsite. The strength grade of lightweight aggregate concrete is LC30, and the mix design is shown in Table 4.

Table 4: *The mix design of LWAC*

Composition	Mass (kg/m^3)
Portland cement	490
Water	200
Coarse aggregate - shale ceramsite	485
Fine aggregate - sand	750

The standard cubic test blocks with a size of 150 × 150 × 150 mm³ and standard cylindrical test blocks with a diameter of 150 mm and a height of 300 mm were tested. The test results show that the average compressive

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strength of lightweight aggregate concrete is 28.15 MPa, and the elastic modulus is 18800 N/mm^2.

The screw connectors adopted in this experimental programme are galvanized hexagonal head self-tapping screws with a specification of M16L200, and the strength grade is Q235. Referring to ASTM F1575 [14], the yield bending moment of the screws was measured as 206430 N·mm. The strength class of the perforated steel plate in the glued-in steel plate connector is grade Q235, and the dimensions are 180 mm × 100 mm × 3.75 mm (length×width×thickness). The hole diameter is 10 mm, and the distance between the holes is 15 mm.

The adhesive used in the glued-in steel plate connector is a type of two-component epoxy resin, and the performance parameters are provided by the manufacturer, as shown in Table 5.

Table 5: *Basic mechanical properties of adhesive materials*

Properties	Value (MPa)
Tension strength	9.37
Bending strength	63.1
Compressive strength	110.1
Shear strength	16.7

The test specimens were fabricated in Nanjing Tech University. Fig. 3 and Fig. 4 show the fabrication processes of installing the connectors on the timber beam and pouring the concrete, respectively.

Figure 3: *Installed connectors on the timber beams*

Figure 4: *Poured concrete*

2.3 TEST DEVICE AND MEASUREMENT SCHEME

The test mainly attempts to extract the fundamental natural frequency f_1 of the vertical bending mode of the specimen [13]. In the modal test, the simply supported boundary conditions were used for the beam specimens. One end of the beam was adopted as fixed hinge, while the other end was set as sliding hinge. The span between the supports is 4500 mm. The beams were stroked by a pulse hammer, and the vibration responses were captured using accelerometers mounted on the beam, as shown in Fig.5. Experimental Modal Analysis (EMA) software was used to identify the fundamental natural frequencies in the modal parameters of the timber-LWAC composite beams. Fourier transform was used to convert the acquired time-domain signals into a frequency-domain signals. The modal parameters of beam specimens were extracted from the frequency response using the post-processing module of the software. In this test, the dynamic signal test system with the model of TST3828E was used for collecting the response signals, and the software with model of DASP was used for analysing the dynamic performance modal. In order to improve the accuracy and reliability of the data, three repeated tests were carried out for each beam specimen, and the dynamic performance was determined according to the average value from the three tests.

Figure 5: *Dynamic test for timber-LWAC composite beam*

3 TEST RESULTS AND ANALYSIS

3.1 INTERFACE PROPERTIES OF COMPOSITE BEAM

The shear performances of interfacial connectors for timber-LWAC composite beams were determined by push-out tests. Based on EN 26891-1991 [15], the test device and loading procedure are shown in Fig. 6 and Fig. 7, respectively. The interfacial slip was recorded by the displacement meters. The slip stiffness value (K_s) of the connector at serviceability limit state can be obtained by Eq.1. The results are shown in Table 6.

Figure 6: *Test set up of the push-out test*

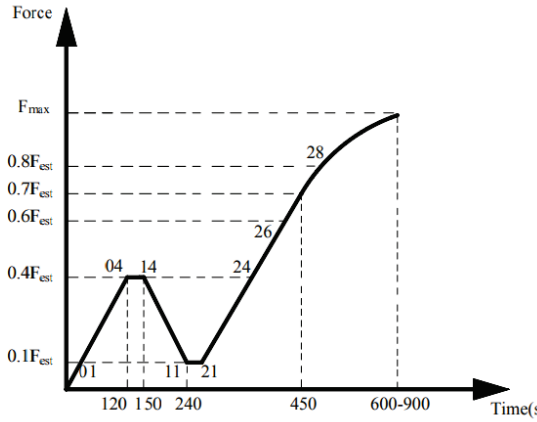


Figure 7: *Loading procedure*

$$K_s = \frac{0.4F_{est}}{4/3(\delta_{04} - \delta_{01})} \quad (1)$$

where F_{est} is the predicted value of the shear bearing capacity of the connector; δ_{01} is the corresponding slip value (mm) at $0.1F_{est}$; δ_{04} is the corresponding slip value (mm) at $0.4F_{est}$.

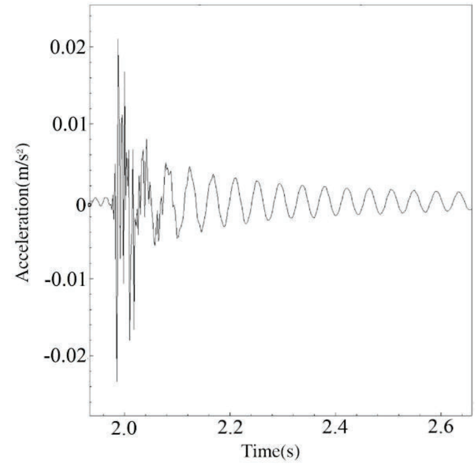
Table 6: *Push-out test results*

Specimen code	K_s (kN·mm^{-1})
ISLC	79.0
GSLC	220.5
NSLC(R)	264.5

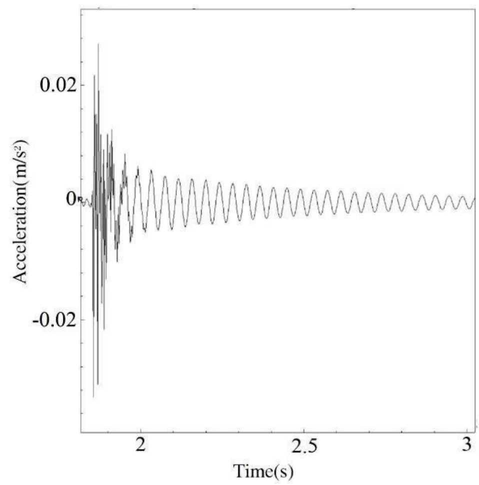
As shown in Table 6, the slip stiffness of the cross inclined screw, glued-in steel plate, and notched-screw connectors at the serviceability limit state are 79.0 kN/mm, 220.5 kN/mm, and 264.5 kN/mm, respectively.

3.2 DYNAMIC PROPERTIES OF THE TIMBER-LWAC COMPOSITE BEAMS

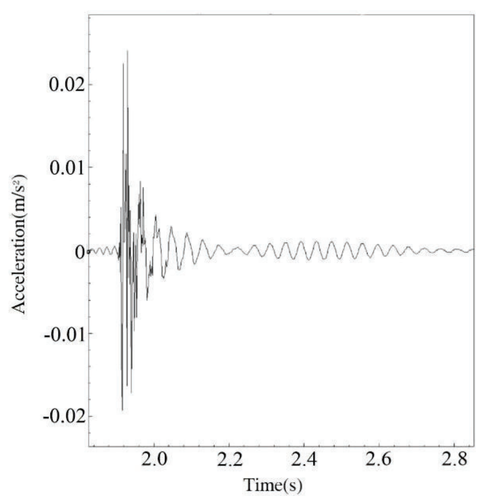
Fig. 8 shows the acceleration response time-domain signals of each timber-LWAC composite beam. The experimental value of the fundamental natural frequency $f_{1(exp)}$ of the timber-LWAC composite beams can be obtained by performing Fast Fourier Transform (FFT) on the time-domain signals through the analysis and processing software. The average values of $f_{1(exp)}$ obtained from 3 repeated excitation tests are listed in Table 7. At the same time, the damping ratios of the beams were calculated by the half-power method [16], and were listed in Table 7.



(a): TLCC-IS



(b): TLCC-GS



(c): TLCC-NS(R)

Figure 8:*Time-domain signals*

Table 7: *Dynamic properties of timber-LWAC composite beams*

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Beam code	$f_{1(\mathrm{exp})}$(Hz)	$f_{1(\mathrm{cal})}$(Hz)	Damping ratio
TLCC-IS	23.68	23.69	3.9%
TLCC-GS	23.93	26.13	1.7%
TLCC-NS(R)	24.17	26.78	3.5%

The timber-LWAC composite beam was used as the one-way slab. Therefore, the fundamental natural frequency of the beam could be considered as that of the floor. The estimation of the fundamental natural frequency of the composite beam mainly refers to the Equation (2) according to Eurocode 5 [13].

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

where l is the span of the floor (m), $(EI)_l$ is the effective bending stiffness of the floor (Nm^2/m), m is the mass per unit area of the floor (kg/m^2).

For timber-LWAC composite beams simply supported at both ends, the effective bending stiffness is calculated using Equation (3).

$$(EI)_{\mathrm{eff}} = E_{\mathrm{c}}I_{\mathrm{c}} + E_{\mathrm{t}}I_{\mathrm{t}} + \gamma_{\mathrm{c}}E_{\mathrm{c}}A_{\mathrm{c}}a_{\mathrm{c}}^2 + \gamma_{\mathrm{t}}E_{\mathrm{t}}A_{\mathrm{t}}a_{\mathrm{t}}^2 \qquad (3)$$

where $E_{\mathrm{c}}I_{\mathrm{c}}$ and $E_{\mathrm{t}}I_{\mathrm{t}}$ are the bending stiffness of the concrete slab and the timber beam of the composite beam, respectively; γ_{c} and γ_{t} are the reduction coefficients of the beam combination action, respectively; A_{c} and A_t are the cross-sectional areas of the concrete slab and the timber beam, respectively; a_{c} and a_{t} are respectively converts the distance from the section centroid to the concrete slab and timber beam centroid.

The subscripts c and t stand for concrete and timber, respectively. When calculating the value of the γ coefficient, the value of the slip stiffness K_{s} of the corresponding connectors determined by the push-out test was used.

The theoretically predicted fundamental natural frequency $f_{1(\mathrm{cal})}$ of each beam was calculated by Eq. 2, and were also listed in Table 7.

3.3 DISCUSSION

The theoretically predicted and the measured fundamental natural frequency are listed in the Table 7. It can be found that the fundamental natural frequency values estimated by Eurocode 5 method have a very small difference compared with the measured values, and the accuracy can meet the needs of engineering design.

It can be seen from the test data that if the timber-LWAC composite beams in this test are directly used as a one-way floor, the measured fundamental natural frequency values are all between 23 and 25 Hz, which can meet the general requirement of 8 Hz [13]. At the same time, the frequencies of the timber-LWAC composite beams are far away the frequencies range (1.0-4.0 Hz) of human-induced loads (such as walking, jumping, running, etc.) [17], which can effectively prevent the occurrence of resonance caused by people in the use of the floor.

The differences between the theoretically predicted values of the fundamental natural frequency and the experimentally measured values are 0.04%, 9.2%, and 10.8% for the timber-LWAC composite beams connected by crossed inclined screws, glued-in steel plate, and notch-screw connections, respectively. The calculation method in the Eurocode 5 showed the relatively high prediction results. This phenomenon may be caused by the overestimated values in effective bending stiffness for all beam specimens.

The fundamental natural frequencies of the beam specimens TLCC-NS(R) and TLCC-GS are bigger than that of TLCC-IS. This is because the glued-in steel plate (GSLC) and notched-screw (NSLC(R)) showed higher slip stiffness compared with cross inclined screw connection (ISLC). This result lead to the higher values in effective bending stiffness for beam specimens TLCC-NS(R) and TLCC-GS, compared with the beam specimen TLCC-IS. Investigating the reason, in the case of the same beam span and the same quality, it can be seen from the push-out test results that the slip stiffness value of the crossed inclined screws connector is smaller than that of the glued-in steel plate and notch-screw connector. On the other hand, there are also differences in the number of connectors. The number of crossed inclined screw connectors is 10 groups, while the number of glued-in steel plate and notch-screw connectors is 8 groups. The number of crossed inclined screw connectors is less than the other two, which further shows that the decisive factor is still the slip stiffness value of the connector. From this phenomenon, it can be deduced that the slip stiffness value of the connectors is a very important factor of the vibration performance for timber-LWAC composite beams.

In terms of damping ratio, the specimen TLCC-GS showed the value of 1.9%, which is much smaller than specimens TLCC-IS and TLCC-NS(R). There is no direct relationship between the connector stiffness and the damping ratio. The above results were only preliminary inferences obtained through sample tests, and the influence of sample size and test accuracy cannot be ruled out.

4 CONCLUSIONS

In this study, the dynamic tests were carried out on the timber-LWAC composite beams using three different connectors. The fundamental natural frequencies of beams were predicted by the calculation method suggested in Eurocode 5, and the predicted values were compared with the experimental values. By analyzing the modal parameters, such as the fundamental natural frequency and damping ratio, the basic vibration performances of the timber-LWAC composite beams were obtained. The main conclusions are summarized as follows:

The fundamental natural frequencies of the timber-LWAC composite beams in this study are in the range of 23.68 to 24.17 Hz, which meet the primary requirement in Eurocode 5. The fundamental natural frequency of the timber-LWAC composite beam is much higher than 8 Hz [13], which means the vibration performance meets with the preliminary comfort requirements.

From the test results, it can be preliminarily inferred that the number and slip stiffness of shear connectors can significantly affect the fundamental natural frequency of timber-LWAC composite beams.

The theoretical fundamental natural frequency of the specimens calculated according to Eurocode 5 show good agreement with the test results. However, there is still a certain difference between the predicted and experimental values, which might be caused by the overestimation of the bending stiffness of composite beams.

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