COST Action FP1004: STSM Report

The vibration performance of round wood Timber-Concrete Composite floors

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Contents

Symbols

c, t, TCC	subscripts signifying concrete topping, timber and timber-concrete composite respectively in substitution of “ i ” throughout
a_i	the maximum accelerance of the beam (mean value)
b_c	the breadth of the topping
d_c	the depth of the topping
f_1	the fundamental frequency of vibration
l	the beam span
m_i	is the mass per unit area of the timber or topping
r	the mean radius of the log
s	the connector spacing
E_i	the mean modulus of elasticity of the material
EI_l	the equivalent bending stiffness of the beam about the axis perpendicular to the beam direction, in Nm^2/m.
I_i	the second moment of area of the component about the axis perpendicular to the longitudinal direction
K_e	the elastic slip modulus of the connectors following the first cycle of loading
K_{ser}	the serviceability slip modulus of the connectors
γ	the shear bond coefficient
ρ_i	the mean material density
ζ	the equivalent viscous damping ratio

1. Introduction

Timber-concrete composites are widely used as a technique for upgrading and enhancing existing timber floors. Whilst timber floors rarely fail because of insufficient strength they do suffer serviceability problems due to their relatively low stiffness and mass. Modern expectations are for floors which perform at higher standards than in the past with respect to footfall induced vibration. Adding concrete to a timber floor to form a composite structure is potentially beneficial to its vibration performance as it increases both its stiffness and mass.

The dynamic behaviour of composite structures is particularly interesting as the amount of composite action achieved dictates both the stiffness and damping properties of the structure which in turn affects its vibration response. Apart from composite action, the frequency at which a timber-concrete composite (TCC) floor vibrates is dependent on the mass-stiffness ratio of the components of the composite. A literature review has revealed that this aspect has not been well considered by previous studies, the inference being that the conventional dimensions of the timber and concrete elements in a TCC floor section may not be as well suited to its dynamic performance.

Current research at the University of Bath is developing a thin-topping solution for the upgrade of existing floors to enhance vibration performance. In addition to this research programme there are other significant TCC studies being conducted in Europe. At the University of Coimbra a research project is being undertaken to develop a round wood TCC with a low stiffness and strength topping. Part of the on-going testing programme is to construct and test multiple floor sections under static loads to serviceability and failure. Since dynamic testing is non-destructive, with the specimen only subjected to small loads and displacements, there has been an obvious opportunity to add additional value to the testing programme at Coimbra through collaboration with Bath.

A STSM under the direction of COST Action FP1004 has been undertaken at the University of Coimbra to improve the understanding of vibration performance of these TCC floor structures. This report documents the aims and objectives of the STSM, a description of the work carried out and the main results obtained during the STSM, the on-going and future collaboration with Coimbra University and plans for publications resulting from the STSM.

1.1 Aims and Objectives

Whilst the direction of the work being undertaken at the University of Bath is towards upgrading existing floors to enhance vibration performance it is acknowledged that the vibration performance of TCC floors is not a well-researched area and the findings of the STSM will be applicable to new construction. In defining the aims of the STSM the limitations of the experimentation must be stated. Firstly, the vibration performance of an insitu floor is difficult to replicate within a laboratory, particularly in relation to the support stiffness's which have a significant effect on the damping response. Secondly, single beams do not reflect the actual behaviour of a composite floor as a whole TCC floor will vibrate in a manner associated with a plate not a beam. However some of the differences in behaviour between the two floor types can still be observed in this testing and the simple nature of a single beam will aid the development of our basic understanding of this new floor type. With these points in mind the STSM has the following aims:

- To improve the general understanding of the vibration behaviour of TCC floors;
- To understand the change in vibration behaviour with the addition of a topping to timber floors.

To fulfil these aims the STSM has the following objectives :

- The prediction of the fundamental frequency of vibration of timber logs, topping and composite for comparison with experimental data;
- Vibration testing by impact of 12 timber logs;
- Vibration testing of 2 composite beams, by impact (a further 7 panels to be tested after the STSM).

2. Literature Review

A short review of the most relevant literature is presented here, ordered by date.

Hu et al. (1998) reported the static and dynamic serviceability of three timber floors topped with 38mm thick concrete. All three floors had spans of 4.47m, widths of 3.60m and were constructed from 241mm deep I-joists at 600mm centres. Whilst the floors 1 and 2 had no shear connectors the third floor had double headed nails connecting the joists to the topping. Detailed results were not reported but the authors did comment that the stiffness of all increased with the addition of the topping whilst the natural frequency and r.m.s. acceleration of the floor vibration decreased. No significant difference between the performances of the floor with the double headed nails over those without was observed suggesting that the double headed nails provided relatively little shear connection. It was concluded that the technique used to transfer forces between the timber and topping needed to be investigated further.

Taylor & Hua (2000) tested normal weight, lightweight and gypsum-based concrete overlaid on TJI timber floors with 19mm OSB sheathing. The authors assumed full composite action between the toppings and timber but there is no report of connectors or adhesive being used. Results from the tests have been reproduced for clarity in Table 1 and demonstrate that the addition of mass to a floor without a shear connection will always reduce its fundamental frequency.

Table 1: TJI-concrete composite floor vibration results (Taylor & Hua (2000))

Floor case	Predicted f_1 (Hz)	Measured f_1 (Hz)
Floor 1 - Timber only	13.2	14.3
Floor 1 - Timber and 19mm Gypsum	13.6	11.3
Floor 2 - Timber only	13.1	14.3
Floor 2 - Timber and 38mm Lightweight	12.0	9.8
Floor 3- Timber only	23.0	22.9
Floor 3 - Timber and 38mm Normal weight	17.2	12.2
Floor 4 - Timber only	14.7	15.5
Floor 4 - Timber and 38mm Normal weight	11.2	8.0

Mertens et al. (2007) reported the findings of an investigation of the vibration performance of timber and TCC floor specimens. Four timber floors were constructed, 4.6m square with 68 x 240mm joists at 600mc/c and 18mm OSB nailed sheathing, supported on 140mm concrete blockwork walls. The second floor had a 40mm thick anhydrite topping overlaid without connectors. Floors 3 and 4 had 40mm anhydrite and 40mm C25/30 concrete toppings respectively. Connectors joining the timber joists and topping elements (a double row of screws spaced at 200mm c/c) were present in floors 3 and 4.

The floors were subjected to direct impact tests and their modal response, accelerations and damping were discussed. The authors commented that when the topping was connected to the joists, the modes separated as the behaviour of the floor changed from anisotropic to isotropic and that without the connectors the topping only provided additional mass to the floor. To take account of the isotropic behaviour, TCC floors should be analysed as a ribbed plate; a TCC beam, its behaviour largely orthotropic, can be analysed using the methods presented in Eurocode 5.

The summary of the results in Table 2, illustrates the dramatic improvement in the performance of the floor. Indeed floor 4 exhibits an acceleration which is far lower than required to conform to Eurocode 5, therefore there seems to be scope for reducing the thickness of the topping and allowing the accelerations to be higher.

Table 2: Softwood joist-concrete composite floor vibration results (Mertens et al. (2007))

Configuration	δ (mm)	f_1 (Hz)	ζ (%)	a_{max} (m/s^2/N)
1- Timber Floor (T.F.)	0.76	20.25	1.02	100
2- T.F. + anhydrite layer	0.26	16.50	1.96	50
3- T.F. + anhydrite layer + connectors	0.16	21.05	1.20	3.6
4- T.F. + concrete layer + connectors	0.14	20.00	1.20	0.00115

Ghafar et al. (2008) excited LVL-concrete composite beams with a continuous vibration. Although the absolute amount of energy dissipated by the composite beams was four times that of the bare LVL beam, the proportion of critical damping decreased from 2.3% to 1.3%. The fundamental frequency of the beam also decreased from 6.7Hz to 6.3Hz. Both the equivalent viscous damping ratio and the fundamental frequency are dependent on the stiffness and mass of the beam. For the beams tested the decrease in damping ratio reflects the smaller proportion of energy dissipated by the materials, connectors and supports whilst the decrease in frequency indicates that the additional mass of the topping was more significant than the increase in stiffness.

Rijal et al. (2011) presented the results of four TCC beams excited by an instrumented hammer. The beams had a span of 5.8m and were constructed from 48mm wide, 250mm deep LVL joists topped with 600mm wide, 75mm deep C30 concrete. SFS screws, notches with screws and birdmouth notches with coach screws were used as connection methods. The fundamental frequencies of the beams ranged from 8.93Hz to 10.08Hz. The damping ratios for all the beams were found to be at 1% apart from the beam with birdmouth and screw connectors at the closest spacing, which exhibited damping of 1.86%. These tests demonstrate the significant change in damping caused by the choice of connector. As yet there is no further information as to the energy dissipation capability of each connector type.

2.1 Summary

A brief review of the literature has demonstrated the need for further in-depth study of the vibration response of TCC composite floors. Whilst good composite action has been revealed as important to ensure that the frequency of the floor vibration does not decrease with the addition of the topping, equally as significant is the thickness of the topping. Too much mass can often negate the beneficial increase in stiffness gained with a topping.

The vibration response of timber floors has been shown to change from anisotropic to isotropic with the addition of a topping. TCC floors should be treated as ribbed plates rather than simply supported beams for analysis purposes.

Finally damping in TCC floors has been shown to vary with connector type. It may be the case that the energy dissipating capabilities of connectors could influence the choice of connector for a floor design when considering vibration response.

3. Analytical Predictive Models

Clause 7.3.3.4 of Eurocode 5 provides an equation for predicting the natural frequency for a timber floor simply supported on all sides. This equation, reproduced below as Equation 1, has been formed following several simplifications of the equation for the frequency of vibration of a rectangular plate simply supported on all sides. It has been simplified so as to not consider the effects of a floor spanning in two directions as the behaviour of timber floors is highly orthotropic. As this is also true for a simply supported beam, Equation 1 is appropriate for calculating the fundamental frequency of simply supported timber logs and TCC beams.

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

An alternative method for finding the frequency of a vibrating beam would be to use the equivalent mass method. The method finds the equivalent mass of a beam acting at its centre, by solving the kinetic energy equation for a beam loaded in three point bending, the solution is very close to Equation 1.

3.1 Timber Log Fundamental Frequency

The fundamental frequency of the example log, log 5, is estimated using Equation 1 and the properties listed in Table 3 as 38.4Hz.

Table 3: Properties of an example log

Log Property	
r	78.0 mm
I_t	14,02*10^6 mm^4
E_t	12080 N/mm^2
ρ_t	584 kg/m^3
l	2690 mm
m_t	10,9 kg/m length

3.2 Topping Fundamental Frequency

The fundamental frequency of the topping slab is estimated using Equation 1 and the properties listed in Table 4 as 9.9Hz.

Table 4: Properties of the topping slab

Topping Property	
d_c	50 mm
b_c	600 mm
I_c	$6{,}25 \times 10^6$ mm^4
E_c	26200 N/mm^2
ρ_c	1800 kg/m^3
l	2690 mm
m_c	54,0 kg/m length

3.3 Composite Fundamental Frequency

Annex B of Eurocode 5 describes the gamma method. The gamma method is used to calculate the effective stiffness of a composite beam based on the slip modulus and the spacing of the connectors, the dimensions and material properties of the timber and concrete components and the span of the beam. The predicted frequency of vibration for each composite beam is presented alongside the experimental results in Section 5.

For beam 5 the average slip stiffness of the connectors after the first cycle of loading is 57kN/mm and they are spaced every 100mm along the length of the beam, resulting in a shear bond coefficient of 0.732. Figure 1 is a plot of the change in fundamental frequency as the topping increases from 0 to 100mm, at 50mm the change in frequency is -3.8%. Results for 25%, 50% and 100% composite action are presented to illustrate how important establishing good composite action is to ensuring that the frequency of vibration does not significantly decrease when a topping is added to a timber log.

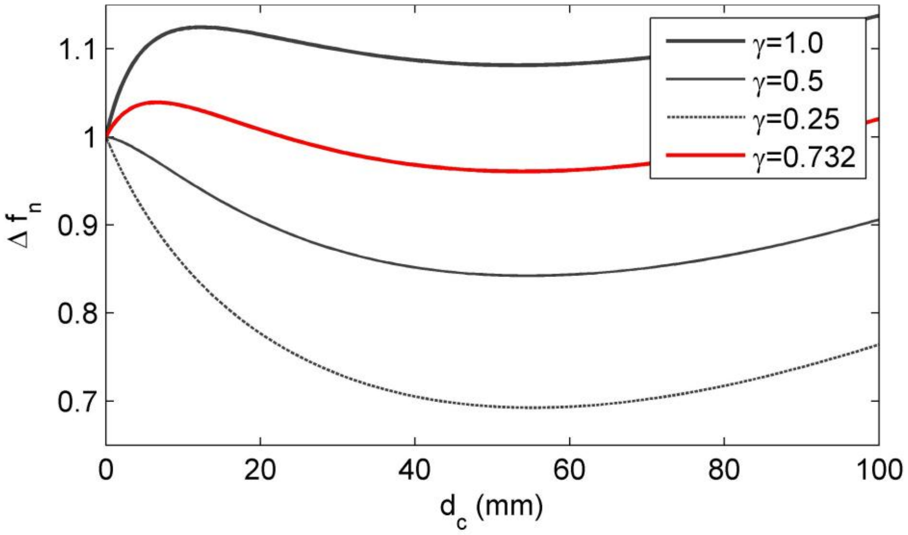

Figure 1: Beam 5, predicted change of fundamental frequency with addition of topping

4. Testing Methodology and TCC Specification

4.1 Testing Methodology

Timber logs were tested in the test arrangement as illustrated in Figure 2. The testing equipment was located in a conditioning room at the University of Coimbra which maintained the temperature and humidity of the beams between 20^0C ±2^0C and 65% ± 5% respectively. The TCC beams were tested in the main structures lab also at the University of Coimbra, the test arrangement was very similar to that of the timber beams. Two methods of supporting the beams were used (Figure 3), Method A provided no rotational impediment whilst Method B provided some restraint.

Figure 2: Timber Beam, Vibration Test Arrangement

Figure 3: Support Types: a) Method A b) Method B

All the beams were subjected to a direct impact load. Timber beams were loaded by two methods either by striking a hammer against the top surface, Figure 4a, or by releasing a mass, Figure 4b. TCC beams were tested by the mass method only. The acceleration time response of the floors was measured by an accelerometer mounted on the top side of the beam. Data was sampled at 6400Hz to give good definition to the peaks of the acceleration-time response. A damping ratio for each beam was calculated from the time domain using the logarithmic decrement method. The fundamental frequency of each beam was found by transforming the data from the time domain to the frequency domain, using the Fast Fourier Transform method.

Prior to the vibration testing of the TCC beams, each beam was loaded in 4-point-bending to preload connectors with 30% of the beam's estimated design load. Three cycles of loading between 10% and 30% were applied. From the load-displacement behaviour the effective stiffness of each beam was calculated.

Figure 4: Vibration Excitation methods: a) Hammer b) Mass

4.2 TCC Beam Specification

The specification for each TCC beam is outlined in Table 6. Each beam had a 500mm wide, 50mm deep topping with the specification recorded in Table 4. Properties for timber logs 7 and 8 are recorded in Table 5.

Table 5: Properties of timber logs 7 and 8

Beam No.	l (mm)	r (mm)	E_t (N/mm^2)	ρ_t (kg/m^3)
7	2555	66	16254	554
8	2720	66	7787	568

Table 6: TCC Beam Specification

Beam No.	l (mm)	r (mm)	Connector Type	s (mm)	K_e (kN/mm)
7	2555	66	8mm Dowel	100	57
8	2720	66			

5. Results

5.1 Timber Beam Results

The following graphs and tables record the results of the log vibration tests. Figure 5 and Figure 6 present a typical vibration response in the time and frequency domains. Figure 7 shows the correlation between predicted and experimental results. The correlation between the results is weak as some of the results do not fit with the overall relationship. Generally the predictive method over predicts the fundamental frequency for both support types.

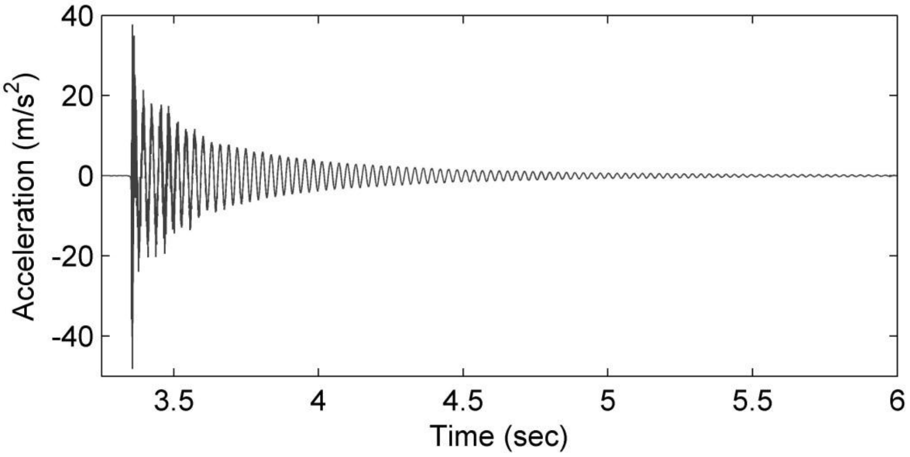

Figure 5: Beam 9, Vibration Response (Time Domain)

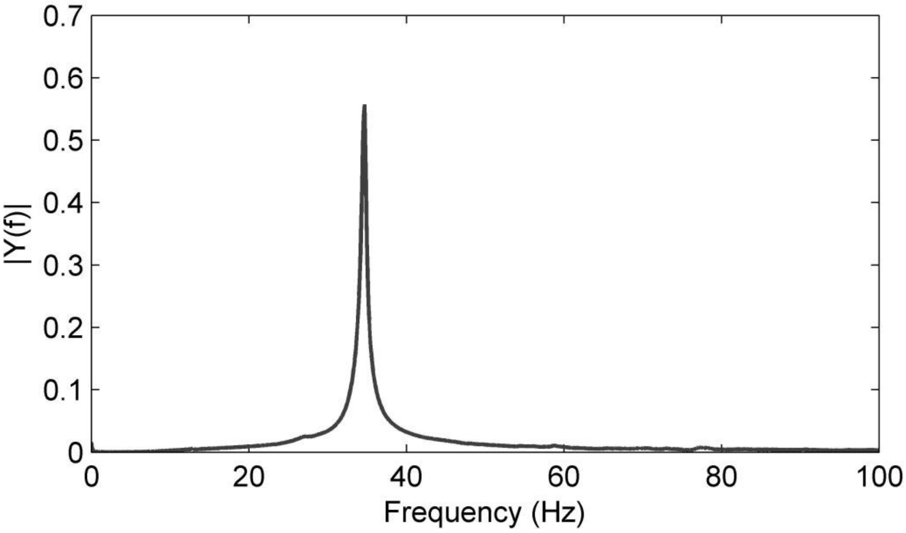

Figure 6: Beam 9, Vibration Response (Frequency Domain)

Table 7: Timber Beam Results, Frequency, Damping and Maximum Accelerance

Beam No.	Hammer Method, Support A		Mass Method, Support B		
	Log f_1 (Hz)	Log ζ (%)	Log f_1 (Hz)	Log ζ (%)	a_t (mm/s^2/N)
1	31.1	1.42	37.5	0.69	172.9
2	35.4	1.04	34.2	0.80	252.7
3	33.3	1.19	38.0	0.82	237.0
4	36.6	1.26	32.2	0.86	213.9
5	31.7	1.06			
6	34.2	1.21	38.6	0.81	179.2
7	33.9	0.96			
8	28.1	1.03			
9	28.1	1.21	34.7	0.83	176.6
10	29.9	1.24	37.3	0.78	267.5
11	27.8	1.35	34.5	0.93	130.3
12	28.1	1.22	37.8	0.55	145.5

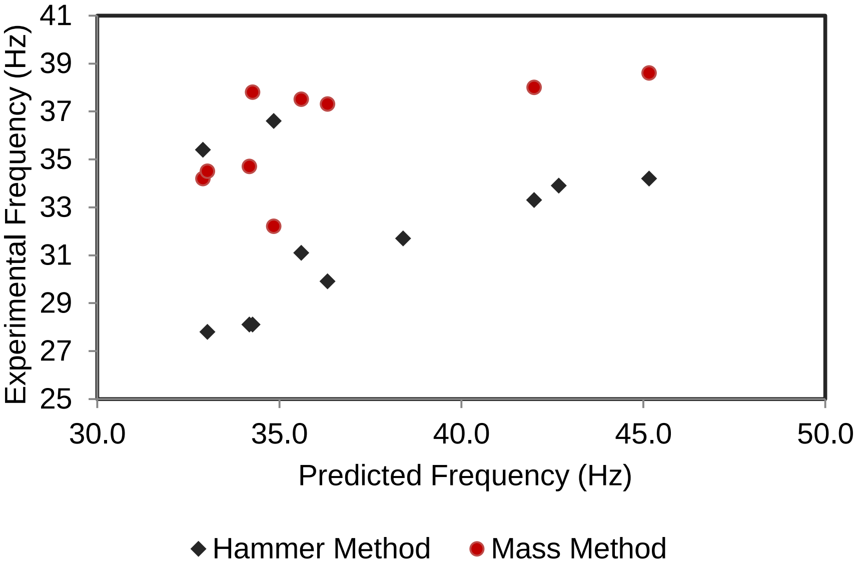

Figure 7: Correlation between predicted and experimental fundamental frequency

5.2 TCC Beam Results

The following graphs and tables record the results of the TCC beam vibration tests. Plots of time domain and frequency domain responses are presented as well as the fundamental frequencies and maximum accelerance. Figure 11 illustrates the overall difference in performance between the timber and TCC beams as according to the EC5 criteria.

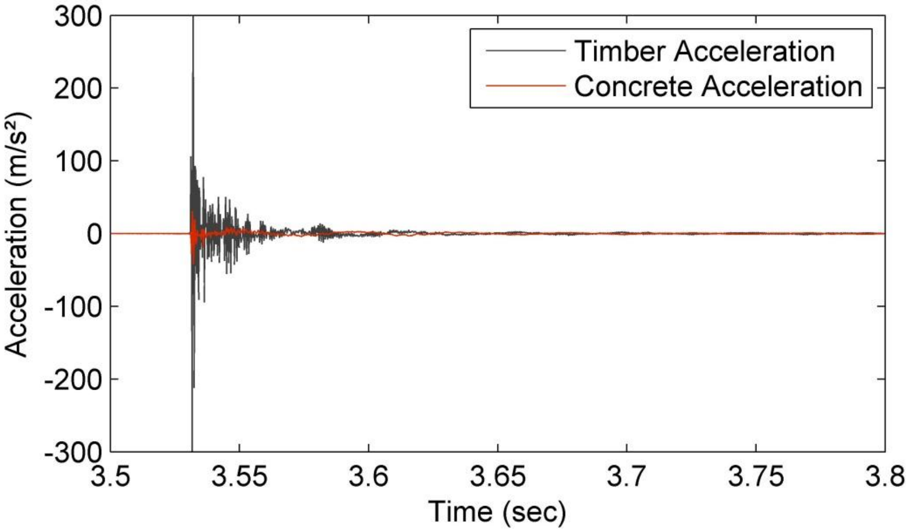

Figure 8: TCC Beam 7, Vibration Response (Time Domain)

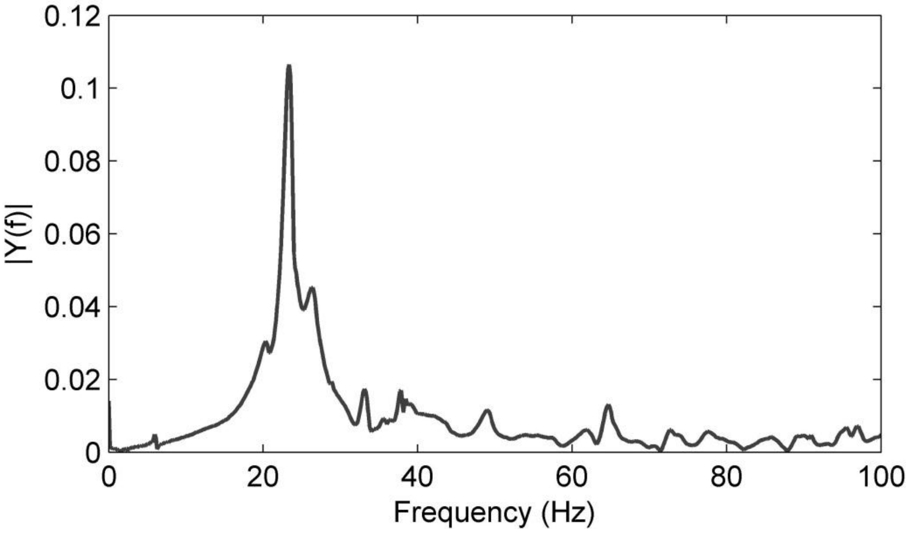

Figure 9: TCC Beam 7, Vibration Response (Frequency Domain)

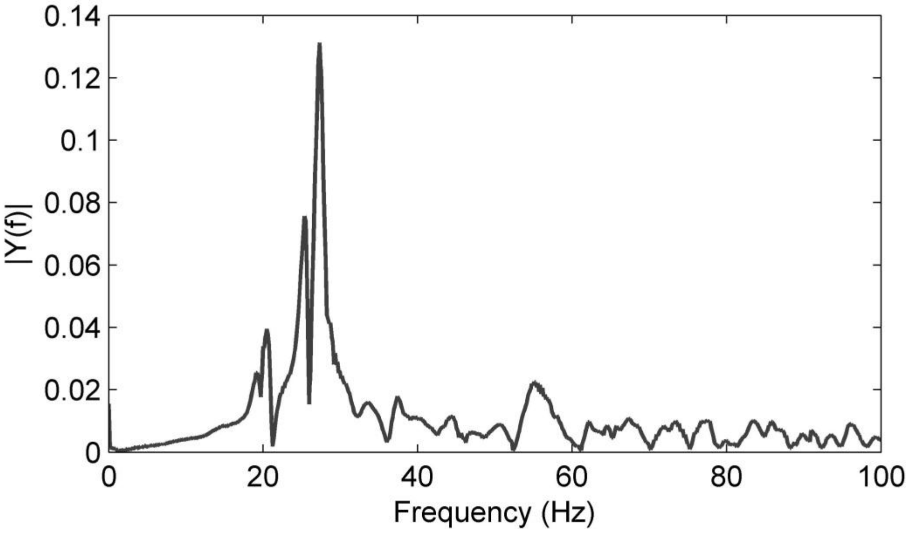

Figure 10: TCC Beam 8, Vibration Response (Frequency Domain)

Table 8: TCC Beam Results, Frequency, Damping and Maximum Accelerance

Beam No.	TCC f_1 (Hz)	TCC ζ (%)	a_{TCC} (mm/s^2/N)
7	23.2	---	104.4
8	27.3	---	60.5

Table 9: Comparison between Predicted and Experimental Fundamental Frequency

Beam No.	Predicted Log f_1 (Hz)	Experimental Log f_1 (Hz)	Predicted Δf_1 (Hz)	Experimental TCC f_1 (Hz)
7	42.7	33.9	-14.9%	25.8
8	26.0	28.1	-0.1%	27.3

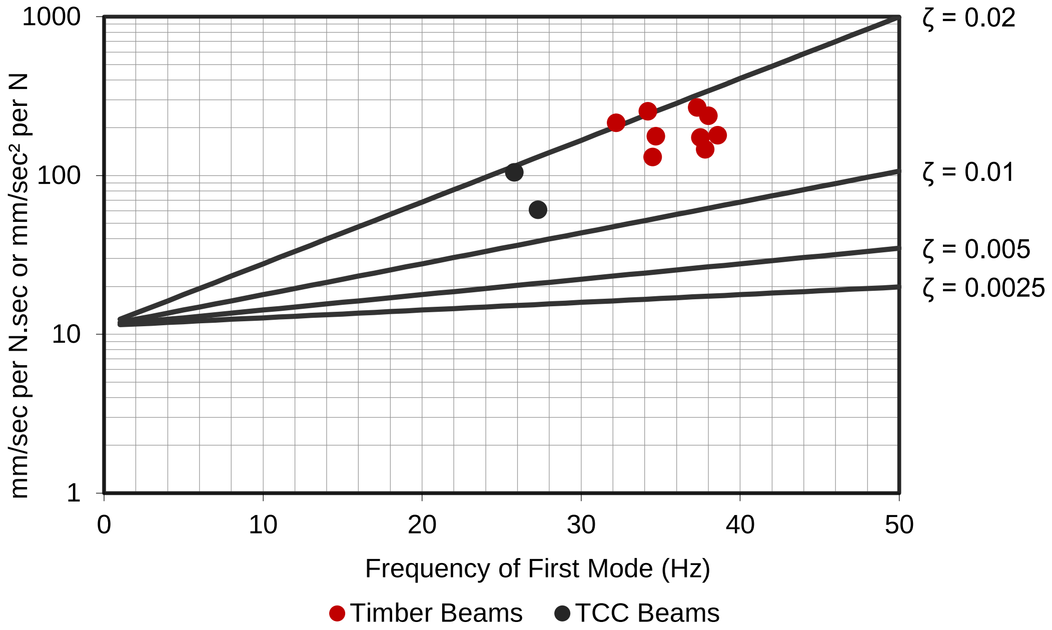

Figure 11: Vibration Response of TCC and Timber Beams (EC5)

6. Discussion

A short discussion of the timber log and TCC beam results are presented here.

The prediction of the fundamental frequency of vibration for each timber logs was reasonable considering the irregular shape of the logs. Not only do the logs taper but the rate of change in diameter along the length of each log does not remain constant. Only the experimental fundamental frequencies of logs 2 and 4 had an unacceptable variation with the predicted values. Peaks for the fundamental frequency were simple to identify from the very clean frequency domain response whilst damping was more difficult to find from the time domain.

The response of TCC beams 7 and 8 to the impact type load is shown in Figure 8, Figure 9 and Figure 10. The time-acceleration response is characterised by a quick discharge of energy after the initial acceleration, followed by an approximately sinusoidal wave with a slower decay. Unlike the timber logs the responses have more than one frequency component. Whilst this could be the 2nd and 3rd modes of vibration being captured, it would seem more likely that the separate responses of the timber and concrete components as well as the combined TCC response are being observed. The first peak at 20Hz is attributed to the concrete part of the beam's structure. The second and third peaks are close together at 23.2Hz and 25.8Hz; one is the frequency response of the timber log and the other the composite behaviour. Identifying which peak corresponds to which component is difficult as the peaks are close together.

Predicted values (Table 8) for the change in fundamental frequency when the logs were formed into TCC beams were inaccurate for two reasons. Firstly the effective stiffness of the beam, calculated by the gamma method was inaccurate by 50%. Secondly it was incorrect to assume that following several cycles of loading the connectors would then act in a stiffer manner, as they vibrated, compared to the first time they were loaded in a static test. Consequently the beams exhibited a lower effective stiffness than calculated and the predictions regarding the change in fundamental frequency were incorrect. Revised predictions, based on the experimental stiffness are recorded in Table 10 and show very good correlation with the experimental results.

Table 10: Revised Predictions of Fundamental Frequency

Beam No.	Experimental Log f_1 (Hz)	Predicted Δf_1 (Hz)	Predicted TCC f_1 (Hz)	Experimental TCC f_1 (Hz)
7	33.9	-24.5%	25.6	25.8
8	28.1	-2.8%	27.3	27.3

Compared to the timber logs it was difficult to decide on the correct damping ratio for the TCC beams. Instead of recording values in Table 8, generalised comments about the change in energy dissipation capabilities of the beams are given. From the time domain responses it is clear to see that the duration of vibrations of the TCC beams was significantly shorter than the timber logs. The duration for timber logs was approximately 2.5 seconds compared to 0.3 seconds for TCC beam 7, indicating that the damping ratio for the TCC beams is much higher than that of the timber logs.

Figure 11 describes how the overall performance has changed in relation to the criteria of EC5. Whilst the frequency decreased there was improvement in the maximum accelerance of the beam. The biggest difference which cannot be recorded is the improvement in damping; damping for the TCC beams is probably significantly in excess of the 0.8% for the timber beams.

7. Conclusions

Twelve timber logs and two TCC beams have been tested to observe their vibration response to an impulse load. The tests have been valuable in enhancing our knowledge and understanding of the vibration performance of TCC beams. It has been demonstrated that an improvement in performance is possible even with a low shear bond coefficient. For longer floor spans, more susceptible to poor vibration performance, composite action will be more easily assured and the improvement in performance greater.

The vibration response of the TCC beams contained multiple frequencies which are thought to be the frequency response of the separate components and their combined frequency response. Higher composite action should cause the part of the response attributable to the composite to become more significant and the separate components less influential. Calculating the change in fundamental frequency from the timber log to composite beam was possible once the effective stiffness of the TCC beams was found from experimental testing.

The damping ratio of the TCC beams was difficult to assess from the time domain plot. It is recommended that future testing of TCC beams and floors uses two types of testing, the method used for these tests and a continuous vibration sine sweep method. Damping ratios could then be calculated from the frequency domain of the continuous vibration test using the half power bandwidth method. The advantage of the current method is its simplicity, short time required to perform and low cost.

Whilst beams cannot represent the actual behaviour of a whole floor they do let our understanding of the basic behaviour of TCC floor types to be quickly improved without the added complexity of two-way action. Nonetheless, future vibration testing should include testing of complete floors to answer the following key questions:

- How does the modal mass of a timber floor change with the addition of a topping?
- How do the support conditions of the floor affect its vibration response?
- How does the stiffness of the floor perpendicular to the joists change with the addition of a topping?
- How does the damping ratio of a floor change with the addition of a topping?

8. Future Collaboration and Publications

This STSM is the beginning of an on-going collaboration between the participants. In addition to the two TCC beams tested, a minimum of 7 and up to a maximum of 13 further beams will be constructed and tested at the University of Coimbra with the collected data analysed at the University of Bath. A range of connector types will be tested and it is hoped that the large data set collected will lead to a future publication.

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